# Robust Control Solutions for Electric Vehicle Promotion Including Charging Infrastructure Development

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**Abstract:** In this paper the authors propose to determine the amount of public subsidies for the promotion of electric vehicles (EVs) by applying a feedback control model. The following three features are assumed on the growth model for the electric vehicle market for a controlled target: (1) The charging station is assumed to be public installation and private management; (2) The break-even point is calculated from the maintenance cost of the charging station; (3) The target numbers of electric vehicle sales are set as growth patterns. To achieve such target numbers and to follow the changes, we propose the application of robust control. In this research, an uncertainty is supposed in the model when the EV market growth is simulated, and fuzzy logic control is applied for better understanding by the decision-makers who exercise the policy measures and for the improvement of the target following capability. The simulation results show the effectiveness of the control based on the fuzzy logic even if some uncertainties are assumed in the growth model.

**Keywords:** Electric Vehicles, Battery Charging Infrastructure, Subsidies, Fuzzy Logic Control, Uncertainty

## 1. Introduction

In this research, the growing use of the battery-operated electric vehicle is regarded as an object of control, and by adjusting the amount of public subsidy with the feedback control, the proposed model aims at supporting the achievement of targeted market size for sustainable growth.

The wide-spread adoption of electric vehicles (EVs) is expected and promoted for the exhaust gas reduction from the vehicles that is one of the causes of the global warming and for achievement of low carbon society [1]. However, the following two points are major obstacles against consumer's interest in EV purchases [2]:

(i) High cost of vehicles and additional investment of charging facility at home compared with conventional vehicles with similar functions;

(ii) Because the drivable ranges are much shorter than the gasoline-operated vehicles, there is a concern that EVs run out of battery and become stranded unless there is a charging station nearby (the "range anxiety"). Therefore, until the self-sustainable scale of EV market is achieved, public support is strongly needed for consumers and charging station entrepreneurs. For example, the government of Japan established the support budget both for the introductory expense toward EV purchases and for the charging station construction expenses [3]. Although the sales price of a popular EV was reduced and the drivable range has expanded [4], the numbers of sales did not increase remarkably [5].

To examine the public policy measures for promoting the EV market growth a simulation model has been developed [6-8]. In such a model the number of EVs and the charging station availability are the main variables, and the dynamics of the market growth is estimated by a scenario analysis. The research examines the effects of subsidies for the EV purchase support and charging station installation.

In reality, because the number of EVs on the road is quite limited, and what the EV users pay for the recharging at the station is low, the entrepreneurs do not feel an interest in investing in the EV charging business. Therefore, the installation of charging stations is not advancing except for highway rest areas, the dealerships, major shopping centers and so on. Due to the above-mentioned background, both the EV market and the charging station growth are slow.

To address these issues, the authors raise three points as below:

i) Let us assume a public-funded private management of the charging stations. That is, the public-sector, such as a

local government, bears the full cost of the charging station installation, and entrust an entrepreneur on operation and maintenance after that [9]. Therefore, in this proposed model, the cost recovery of the charging station construction is not considered, and only the operation and maintenance cost comes into the scope of model after the charging station is transferred to the private sector. The results of recent survey [10] indicate the effectiveness of public subsidy towards the charging infrastructure, particularly in the early stages of EV market development, and they support the view of this paper.

ii) The subsidy measure to support the EV market growth is considered to continue for several years, and at each year the target number of the EV addition is set to be followed. The target number of EV addition is given in the quarterly periods in consideration of the common practice of accounting intervals of the private-sector enterprises.

iii) To achieve the target following capability, the authors propose that the public-sector policy makers adjust the amount of subsidies by observing the EV proliferation conditions. That is, if the number of EVs increases more than the target, the subsidy may be reduced, and vice versa. To decide the amount of funding, the feedback control is applied. The control method proposed here is fuzzy logic [11] which is applied to address deficiencies observed in the PID control widely used in industry. Because the control logics are expressed in rules, the control logic is assumed to be easily understood by the decision-makers (policy-makers and consumers considering purchases of EVs). Also, there is an advantage of robustness against the parameter changes. Even if the targeted value is changed, the readjustment of the parameters of the control model is not necessary. Fig. 1 shows the control block diagram.

(Note that the model reflects only the electric vehicles powered by on-board batteries which need recharging from external electrical sources.)

## 2. EV Market Growth Model with Charging Infrastructure

### 2.1. EV Market Growth Model

The dynamic model of EV market growth was developed in the earlier research [6]-[8] and summarized in (1). The parameters are listed in Table 1 and the values follow those identified in [6]. Details are found in the reference document.

$$dy/dt = k\beta(am - BU(t)^{-1})u(t)y(t) \qquad (1)$$

### 2.2. EV Sales Target and Charging Station Installation

The target number of EV sales is assumed to be in the following two scenarios:

(a) Modest scenario: Total of 600,000 units in ten years, from the results of [6].

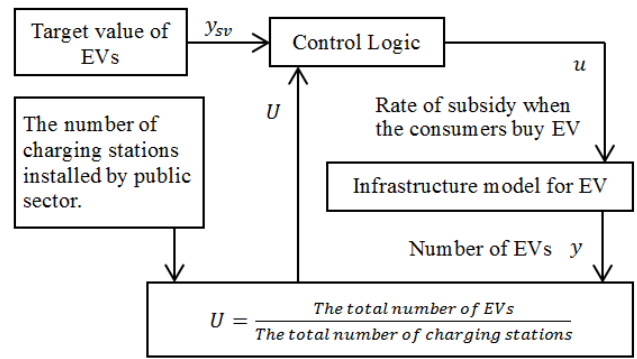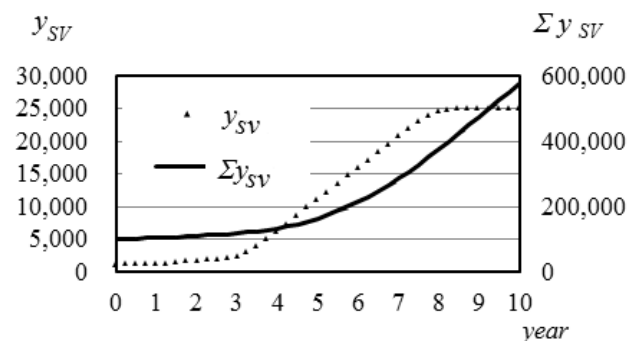(b) Challenging scenario: Total of two million units in ten years [12]-[14].



Figure 1. Block diagram of the proposed control for subsidy policy.
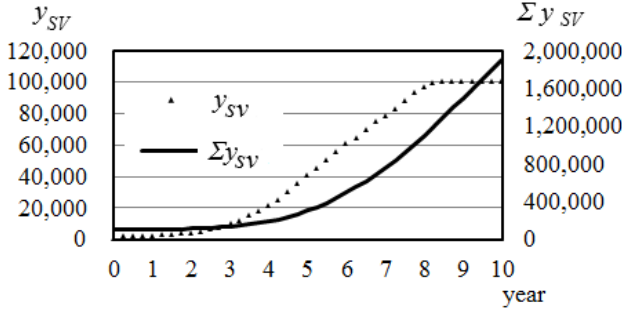
Table 1. Nomenclature.

| Symbol | Value | Remarks |
|---|---|---|
| y | [units] | The number of EVs added in a year; The numbers of vehicles manufactured, sold, and registered are assumed to be the same. |
| k | 2.5 | Period of cost recovery of initial cost of station business |
| β | 0.65 | Elasticity coefficient of the demand for EV increasing as the value of U reducing |
| a | 10 [US$] | Cost paid at single recharging of EV battery |
| m | 80 | Frequency of recharge during the year of one EV |
| B | $1.67 \times 10^4$ [US$] | Break-even revenue for the EV charging station; The cost of maintenance is assumed to be 20% of the initial investment cost from [9]. |
| U | 104 | Availability index of EV charging infrastructure, measured as the ratio of the total number of EVs to the total of number of stations. At the equilibrium U = 104. |
| u | [%] | The rate of subsidy toward the EV purchase price. |
| t | [year] | The period of the simulation is ten years (t=0-10). |
| $y_{sv}$ | [units] | Quarterly targeted value of new EV sales |

To satisfy the total number of accumulated EVs sold, a quarterly targeted value is assumed for each period as shown in Fig. 2. The target number is set to become a smooth curve to avoid a sudden production increase and additional capital investment. Hereafter, figures indicated as (a) show the modest estimate, and those with (b) assume more challenging growth.

Based on the target values of EVs we obtain the number of charging stations required. These values are to satisfy the availability index (the number of EVs per each station) $U = 104$ at the equilibrium point of market growth as described in [6].



(a) Modest scenario

(b) Challenging scenario

**Figure 2.** *Target values of EV addition.*

## 2.3. Uncertainties in the Model

Here, the uncertainty of the parameters included in (1) is examined. First, because the elasticity β is influenced by consumers' interest, fluctuation of 25% is assumed such as

$$\Delta\beta = (0.65*0.25)\ \sin\ (4t) \qquad (2)$$

Then, the uncertainty of recharge frequency *m* away from home is considered. Actual frequency of recharging outside of home parking is not publicly available at this point of writing. Because the drivable range of EVs is much shorter than those of gasoline-powered vehicles, it is clear that the uncertainty exists in this value. Therefore, the fluctuation of 25% is assumed in the simulation as below.

$$\Delta m = (80*0.25)\ \sin\ (10t) \qquad (3)$$

Similarly, the break-even revenue *B* is subject to the uncertainty due mainly to economic cycle, therefore,

$$\Delta B = (1.67*0.25)\ \sin\ (6t/5) \qquad (4)$$

Consider the influence of annual business cycle on the number of EV sales *y* such as

$$\Delta y = -y_{sv}*0.25*\cos\ (6t) \qquad (5)$$

By reflecting the above uncertainties (1) is modified as

$$dy/dt=k(\beta+\Delta\beta)[a(m+\Delta m)-(B+\Delta B)U(t)^{-1}]u(t)(y(t)+\Delta y) \quad (6)$$

## 2.4. Control by Fuzzy Logic

To achieve the target-following capability, the application of fuzzy logic control is examined.

In fuzzy logic control the amount of subsidy is adjusted by the output of the controller $\Delta u$ as shown in the next equation assuming a quarter-yearly control interval.

$$u(t)=u(t-0.25)+\Delta u,\ t \geq 0.25 \qquad (7)$$

The algorithm of the fuzzy logic control is as follows:

i) The controller uses the present error $e(t)$, the error $e(t-0.25)$ at one step before, and the error $e(t-0.5)$ at two steps before as input.

ii) The input into (1) is normalized to the range of -1 to +1 by the upper and lower bounds.

iii) Membership functions of antecedent and consequence

parts are shown in Fig. 3 and Fig. 4, respectively.

iv) The membership functions are simply made symmetric with 0 in center.

v) The fuzzy production rule is shown in Table 2.

vi) The fuzzy logic operation uses the most popular max-min center of gravity method.

vii) With the upper bound of EV subsidy amount of 50%, by the proportion calculation and output from -1 to +1 obtained by the fuzzy inference, the control is applied within the range of 0~50%.

Figs. 5-8 show the simulation results. To examine the performance of the fuzzy logic control the root mean squared error (RMSE) of deflection *e* over ten years is shown in Table 3. In the table comparison between the proposed fuzzy logic and conventional PID control [15] is shown. As observed by the amount of adjustment, a large subsidy is given in the initial period, and the smaller amount is given later on.
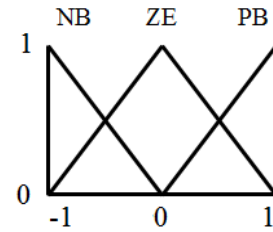

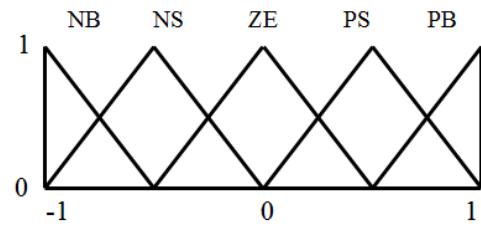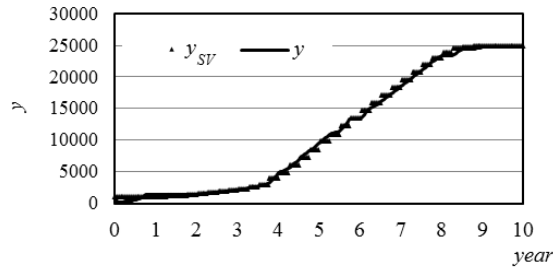
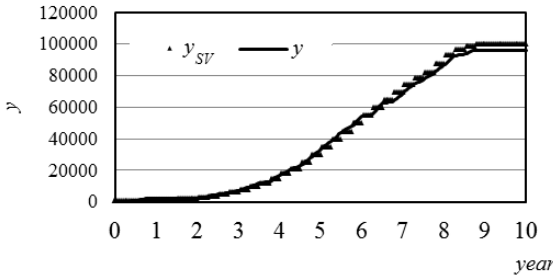**Figure 3.** *Antecedent membership function.*



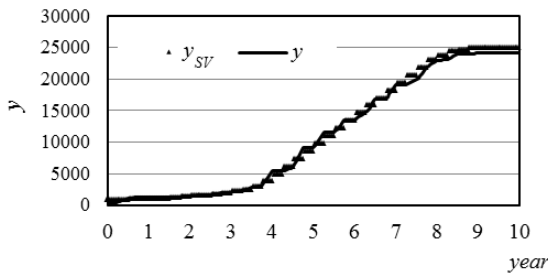**Figure 4.** *Consequence membership function.*

**Table 2.** *Fuzzy production rules.*

(a)

| 0.25 < e(t-0.5) | | e(t-0.25) | | |
|---|---|---|---|---|
| | | NB | ZE | PB |
| e (t) | NB | PS | PB | PB |
| | ZE | NS | ZE | PS |
| | PB | NB | NS | NS |

(b)

| -0.25 < e(t-0.5) < 0.25 | | e(t-0.25) | | |
|---|---|---|---|---|
| | | NB | ZE | PB |
| e (t) | NB | PS | PS | PB |
| | ZE | NS | ZE | PS |
| | PB | NB | NS | NS |

(c)

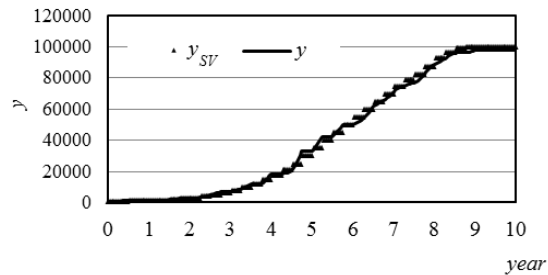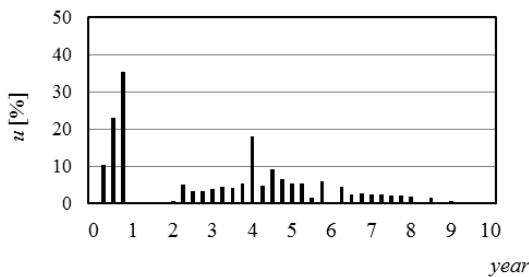| e(t-0.5) < -0.25 | | e(t-0.25) | | |
|---|---|---|---|---|
| | | NB | ZE | PB |
| e (t) | NB | PS | PB | PB |
| | ZE | NS | ZE | PS |
| | PB | NS | NB | NS |

(a) Modest scenario



(b) Challenging scenario

**Figure 5.** *EV market growth by fuzzy logic control (with no uncertainty).*
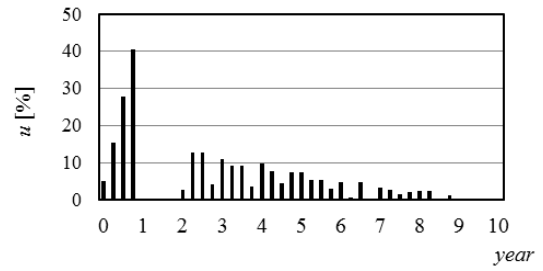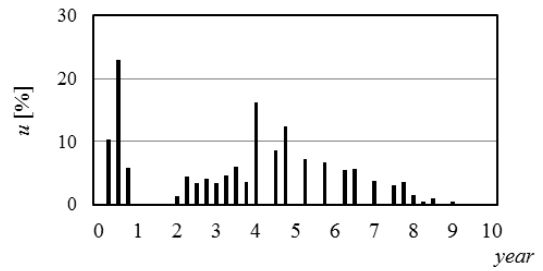


(a) Modest scenario



(b) Challenging scenario

**Figure 6.** *EV market growth by fuzzy logic control (with uncertainty).*
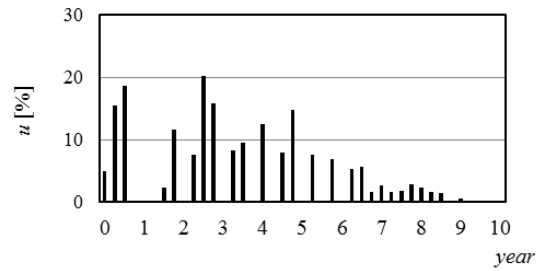


(a) Modest scenario



(b) Challenging scenario

**Figure 7.** *Changes of control variable u by fuzzy logic control (with no uncertainty).*



(a) Modest scenario



(b) Challenging scenario

**Figure 8.** *Changes of control variable u by fuzzy logic control (with uncertainty).*

**Table 3.** *Comparison of RMS errors.*

| Target value | Control Logic | without uncertainty | with uncertainty |
|---|---|---|---|
| $\Sigma y_{SV} = 600,000$ | PID | 775 | 860 |
| | Fuzzy | 395 | 607 |
| $\Sigma y_{SV} = 2,000,000$ | PID | 3,925 | 4,387 |
| | Fuzzy | 2,166 | 2,051 |

### 2.5. Comparison of Total Amount of Subsidies

To show the effects of the proposed method, the total amount of the subsidy from the simulation results is compared with the subsidy of conventional policy measures. From [6] the typical installation cost of charging station (equipment purchases and construction expense) is assumed to be $83,300. The total number of charging stations will be 5,769 places in ten years. The subsidy amount by the conventional measure is assumed to support 50% of the charging installation cost reflecting a present policy of Japan. EV price is based on the sales price of Nissan Leaf and the purchase subsidy is assumed to support the amount of cost to become equal with the price

of Toyota Prius. Although the sales price changes by the vehicle grade and the region, based on the typical subsidy of 22% or US$6,400 is assumed.

To calculate the total subsidy by the proposed approach the number of addition $y$ is multiplied by the subsidy per vehicle and the subsidy amount at each time is obtained. From the subsidy amount multiplied by the number of EVs, the total subsidy amount in the entire period is obtained.

For example, the total cost of subsidy $C_A$ by the conventional measure with the fixed rate of vehicle subsidy (based on the 22% subsidy rate) is calculated as follows:

$$C_A = 83,300*5,769*0.5 + \Sigma\, y*6,400$$

$$= 83,300*5.769*0.5 + 463,205*6,400$$

$$= 3,205*10^6\ [\$] \tag{8}$$

Table 4 summarizes the total amount of subsidies for comparison. The proposed control results in about 75% reduction of the total subsidy.

***Table 4.*** *Comparison of total amount of subsidies [US$10^6].*

| Target | Uncertainty | Conventional | Controlled |
|---|---|---|---|
| Modest | Not | 3,205 | 775 |
| | included | 3,126 | 751 |
| Challenging | Not | 11,882 | 2,741 |
| | included | 12,031 | 2,740 |

## 3. Conclusion

To achieve the target number of electric vehicles this paper has proposed a public policy measure which applies the feedback control and adjusts the amount of subsidy accordingly. The control method applied is based on fuzzy logic, and some parameter uncertainties are considered. Even if the uncertainty is given to the model, the results show the robustness of the control and good target following capability.

In the proposed approach, steady addition of charging station is assumed by the public funding. In addition to the EV consumers' benefit, the proposed approach has the following advantages for the charging station entrepreneur: The target numbers of EVs for several years ahead are shown and they become the indicator of the managerial decisions; and the hurdle of the business entry is low because of the public-sector installation coupled with private management. Lastly, if the decision-makers of public policy measures use the proposed approach, there is a possibility of reducing the total amount of subsidies more than a conventional fixed-rate approach.

## Acknowledgements

## References

[1] A. G., Boulanger, A. C. Chu, S. Maxx, D. L. Waltz, "Vehicle Electrification: Status and Issues," Proceedings of the IEEE," Vol.99, No.6, June 2011, pp.1116-1138.

[2] A. Wiederer and R. Philip, Policy Options for Electric Vehicle Charging Infrastructure in C40 Cities. Harvard Kennedy School, Cambridge, MA, 2010. [Available online: http://www.innovations.harvard.edu/policy-options-electric-vehicle-charging-infrastructure-c40-cities].

[3] EV and PHV Charging Infrastructure, EV and PHV Town Report in Japan 2013, Next Generation Vehicle Promotion Center, 2013 [Available online: http://cev-pc.or.jp/event/pdf/evphvtown_report2013_en.pdf.].

[4] Updated Nissan LEAF Available in Japan, November 20, 2012. [Available Online: www.nissan-global.com/EN/NEWS/2012/_STORY/121120-01-e.html].

[5] Electric Drive Sales Dashboard, Electric Drive Transportation Association, Aug. 2014. [Available online: http://www.electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952].

[6] D. Yamashita, T. Niimura, H. Takamori, R. Yokoyama, "A Dynamic Model of Plug-in Electric Vehicle Markets and Charging Infrastructure for The Evaluation of Effects of Policy Initiatives", presented at IEEE Power Systems Conference and Exposition, Phoenix, Arizona, USA, March 2011.

[7] D. Yamashita, R. Yokoyama, T. Niimura, H. Takamori, "A Model for Policy Assessment to Facilitate the Proliferation of Electric Vehicles ; For Strategic Evaluations of Infrastructure Investment", Journal of Real Options and Strategy, Vol.4, No.2, pp.143-157, 2011.

[8] D. Yamashita, T. Niimura, H. Takamori, T. Wang. "Plug-in Electric Vehicle Markets and Their Infrastructure Investment Policies under Fuel Economy Uncertainty", International Journal of Real Options and Strategy, 1, pp.39-60, 2013.

[9] J. Snyder, Financial Viability Of Non-Residential Electric Vehicle Charging Stations, UCLA Luskin School of Public Affairs, Luskin Center for Innovation, August 2012. [Available Online: http://luskin.ucla.edu/news/school-public-affairs/winter-2013-luskin-forum-features-electric-vehicle-charging-stations-la].

[10] GSGF Report on Large-scale Rollout of Electric Vehicles, Global Smart Grid Federation, June 2014. [Available online: http://www.globalsmartgridfederation.org/2014/07/23/the-first-global-view-on-the-progress-of-clean-vehicle-technology/].

[11] H. T. Nguyen, N. R. Prasad, C. L. Walker, E. A. Walker, A First Course in Fuzzy and Neural Control, Chapter 3, Chapman and Hall/CRC, 2002.

[12] J. Barras, "Nissan CEO Carlos Ghosn Promises 1.5 Million EVs by 2020", 2013 September, 2013. [Available online: http://gas2.org/2013/09/13/nissan-ceo-carlos-ghosn-promises-1-5-million-evs-by-2020/].

[13] I. S. Nam, "Nissan May Hit Electric-Car Sales Target Before 2020 Japanese Car Maker Is Looking to Emerging Markets for Growth", The Wall Street Journal, March 15, 2014.

[14] Jeff Cobb, "How Nissan and Renault are Dominating the Electric Car Game", June 11, 2015. [Available online: http://www.hybridcars.com/how-nissan-and-renault-are-domin ating-the-electric-car-game/].

[15] N. Sakamoto, et al., Robust Feedback Control for the Subsidy Policy about Plug-in Electric Vehicle using Sliding Mode Control, IEEJ Transactions on Electronics, Information and Systems (in Japanese), Vol.134, No.12, pp.1855-1861.