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Optimal State-of-Charge Value for Charge-Sustaining Mode of Plug-In Hybrid Electric Vehicles

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ABSTRACT For plug-in hybrid electric vehicles or extended range electric vehicles, battery stored energy often cannot fully meet the travel needs, and the battery needs to stay in a charge-sustaining mode to allow for backup sources such as gasoline or diesel to power the vehicle. It is crucial to identify the optimal state-of-charge (SOC) value for the battery to maintain this charge-sustaining mode since this SOC has significant impact to battery degradation. In existing studies, Just-in-Time control proposes that this SOC should be maintained at 55% but without theoretical justification. With the help of a battery degradation model based on solid electrolyte interphase growth, this article develops a method to decide the optimal SOC value for charge-sustaining mode. Following the principle of superposition, degradation during the battery discharging process is divided as a fixed degradation caused by the drop of SOC from maximum to minimum values during charge-depleting mode, and a dynamic degradation caused by the oscillation at the charge-sustaining SOC value. Then this oscillation-caused degradation is further modeled and minimized through the investigation of the side reaction current density. The optimal SOC value obtained will be the SOC at which the side reaction current density has the slowest changing rate. This SOC value indeed relies on battery parameters, charging/discharging current and ambient temperature, and a case study shows that the best range of SOC value is 36%~38% for a 1.8Ah SONY 18650 cell. An average SOC of 37% is therefore recommended for charge-sustaining mode considering the possible errors in SOC estimation.

INDEX TERMS Plug-in hybrid electric vehicle, state-of-charge, charge-sustaining, solid electrolyte interphase.

I. INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) are powered by both engines and batteries which provide great flexibility to cover long distance travels. Since electricity cost is always cheaper than gasoline, and electricity from renewable sources can provide clean energy for PHEVs, it is preferred to use electrical energy as much as possible from the Li-ion battery during the energy control of a PHEV. In a conventional PHEV energy control, battery energy is often used up first so that the battery state-of-charge (SOC) is kept at a minimum level during the remaining part of a trip, in case this trip is long enough so that battery stored energy cannot cover the total trip. That is, the PHEV is under charge-depleting mode in the beginning until the SOC reaches the minimum level

(e.g., 25%), then the vehicle is under charge-sustaining mode where the power is provided by the engine to complete the remaining part of the trip. This conventional control method will put the battery under a low SOC for a long time which is bad for battery life. To solve this problem, [1] presents the 'Just-in-Time' control for PHEV and extended range electric vehicles so that the vehicle is first run in charge-depleting mode until the SOC of a fully charged battery SOC drops to 55%, which is maintained using charge-sustaining operation, changing back to charge-depleting mode near the end of the trip so that the remaining trip is powered by battery only. Finally, the SOC reaches 25% at the end of the trip where a recharging facility is available to recharge the vehicle. This Just-in-Time control relies on accurate trip estimation, and it significantly reduces the possibility of exposing the battery to low SOC, therefore effectively extending battery life. However, it is unclear why this 55% SOC value is chosen

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in Just-in-Time control, and why other values are not chosen. In this article, an electrochemical battery degradation model will be applied to explain this phenomenon, and in particular, a general method to identify such optimal charge-sustaining SOC values for PHEV energy operations will be provided too.

In other PHEV energy management studies, a charge-sustaining SOC value is usually not properly maintained since many studies only focus on fuel consumption minimization and often ignore battery degradation. For example, supervisory control of charge-sustaining hybrid EVs is discussed in [2] to save the total energy consumption, but battery degradation is not considered. Reference [3] also does not consider degradation in the energy management of PHEV using traffic preview information. Reference [4] proposes a new adaptive fuzzy logic energy management strategy for plug-in hybrid electric city bus, and again battery degradation is not considered. Reference [5] applies a nonlinear model predictive control approach to series-parallel hybrid electric bus energy control without considering degradation. The above PHEV energy management strategies only maintain the battery SOC within its allowable minimum and maximum bounds, and ignore the corresponding impact of an optimal charge-sustaining SOC to battery life.

There do exist studies that consider battery degradation in PHEV energy management, but these studies do not specifically consider the optimal charge-sustaining SOC like [1] and apply simple degradation models in the cost calculations. For instance, a capacity loss model based on ampere-hour calculation is converted into equivalent hydrogen consumption in the energy control of a hybrid fuel cell electric bus in [6], and this capacity loss model is also applied in [7] to evaluate the impact of control strategies to battery degradation for electric buses. The same ampere-hour based capacity loss model is applied in [8] to minimize the PHEV energy consumption cost. A similar semi-empirical capacity fade and resistance increase model is also applied in [9] to study the battery downsizing problem for PHEVs. Further to these PHEV studies, [10] applies a degradation model characterized by SOC, current, and current-changing rate in the power split control between battery and ultracapacitor for a pure electric vehicle. In all these studies, the battery degradation models applied are not accurate electrochemical models, and the only reference which discusses the optimal SOC for charge-sustaining mode is [1] which does not explain why a 55% SOC is the best value.

In literature, there are many accurate electrochemical models which can describe well the Li-ion battery degradation phenomenon. For example, it is found that the continuous growth of solid electrolyte interphase (SEI) on the negative electrode is the main reason accounting for the capacity fade of Li-ion batteries [11]. SEI growth has been modeled by full order partial differential equations in [11]. Simplified reduced order single particle models are also presented in [11], [12]. Reference [13] presents an SEI growth theory to account for capacity fade and accelerated aging. Reference [14] applies a Monte Carlo simulation method to model the early stage

SEI formation. The above SEI models, such as the single particle models, are also applied in [15] to characterize the degradation mechanism of the battery of a 48V hybrid electric vehicle, and in [16] to derive battery state of health (SOH) estimations. However, these accurate battery degradation models have not yet been applied in the identification of SOC value for PHEV charge-sustaining operations.

In this article, the SEI growth model from [11], [12] will be applied to identify the best SOC value to maintain charge-sustaining mode for PHEVs. The degradation process is divided as a fixed degradation occurred in the charge-depleting mode and an oscillation-related degradation happened in the charge-sustaining mode. Then this oscillation degradation is further minimized by studying the derivative of the side reaction current density. The best SOC value is further described through the critical point of this side reaction current density. Usually the obtained optimal SOC value will change if the corresponding battery specifications are changed. Furthermore, it is also observed that this SOC value relies on the charging/discharging current and ambient temperature, therefore, an acceptable range of this SOC value can be obtained that is applicable to different current and ambient temperatures. From this sense, the existing 55% SOC value in Just-in-Time Control could be better improved by calculating the corresponding optimal SOC range for specific types of batteries, current, and weather conditions.

The remaining of this article is organized as follows. The next section will review the SEI growth model used in this article and present the mathematical models relating degradation and SOC changes. Section III will provide simulation studies to identify the best SOC value range under different temperatures, while Section IV will conclude the paper with some observations.

II. OPTIMAL SOC VALUE FOR CHARGE-SUSTAINING MODE

To identify the optimal SOC value for PHEV charge-sustaining modes, the following electrochemical battery models are needed.

A. ELECTROCHEMICAL MODELS NEEDED

The electrochemical SEI growth model used in [12] is briefly reviewed here. First, let SOC_{cell} be the cell SOC and θ_n the lithiation state of the anode, then

$$\theta_n = \theta_{n,min} + SOC_{cell} * (\theta_{n,max} - \theta_{n,min}), \quad (1)$$

where $\theta_{n,min}$ and $\theta_{n,max}$ represent the minimum and maximum stoichiometric limits of anode lithiation, respectively. The following equation calculates the equilibrium potential U_n^{ref} (in V) for the battery cell [12]:

$$U_n^{ref} = 0.7222 + 0.1387\theta_n + 0.029\theta_n^{\frac{1}{2}} - \frac{0.0172}{\theta_n} + \frac{0.0019}{\theta_n^{1.5}} + 0.2808 \exp(0.90 - 15\theta_n) - 0.7984 \times \exp(0.4465\theta_n - 0.4108). \quad (2)$$

The side reaction current density J_s [N] satisfies the following implicit equation, which can be solved either by iteration or by the direct solution from Chapter 7 of [11].

$$J_s [N] = -i_{0,s} a_n \exp \left(\frac{-F * (U_n^{ref} - U_{ref,s})}{2R_g T} \right) * \exp \left(-a \sinh \left(\frac{-\frac{i_{app}[N]}{Vol_n} - J_s [N]}{2a_n i_0} \right) \right), \quad (3)$$

where $i_{0,s}$ is the exchange-current density for side reaction (in Am^{-2}), a_n is the specific surface area of negative electrode (in m^{-1}), F is Faraday's constant, R_g is the universal gas constant and equals $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$, T is temperature (in K), $U_{ref,s}$ is the equilibrium potential of the side reaction (in V), i_{app} is the applied cell current (in A), Vol_n is the volume of the negative electrode (in m^{-3}), and i_0 is the exchange-current density for intercalation reaction (in Am^{-2}).

The following equation (4) on film thickness (in m) δ_{film} shows the degradation during the charging process [12]

$$\frac{\partial \delta_{film}}{\partial t} = -\frac{M_p}{a_n \rho_p F} J_s, \quad (4)$$

where M_p is the average molecular weight of the constituent compounds of the SEI layer (in Kg mol^{-1}), and ρ_p is the average density of the constituent compounds (in Kgm^{-3}).

B. OPTIMAL SOC VALUE

With the above electrochemical models, we are ready to discuss the optimal charge-sustaining SOC value for a PHEV.

Assume that in the beginning of a trip, the SOC is initially $a\%$ (e.g. 85%), and the SOC at the end of the trip is $b\%$ (e.g. 25%). During the driving process, the battery starts with the charge-depleting mode, then enters into the charge-sustaining mode at a fixed SOC value, which is assumed to be $x\%$ SOC. Now the battery SOC slightly oscillates around this $x\%$ due to the necessary electricity consumptions like lights, and the charging from regenerative braking or generators. For simplicity, assume that this oscillation is repeated for m times, and at each time the SOC changes about a small increment/decrement $\pm \Delta x\%$. That is, SOC changes about m rounds from $(x - \Delta x)\%$ to $(x + \Delta x)\%$. After the oscillation at charge-sustaining mode, it is assumed that the battery goes back to charge-depleting mode until it reaches $b\%$ SOC and in the meanwhile it arrives its travel destination with charging facilities (e.g. returning home).

By the superposition principle, the overall degradation during the trip can be decomposed into two parts: one part is a fixed degradation coming from the direct decrease of the SOC from $a\%$ to $b\%$, and the other part comes from the oscillation degradation, i.e., the m rounds of discharging/charging between $(x - \Delta x)\%$ and $(x + \Delta x)\%$. Note that the fixed degradation part from $a\%$ to $b\%$ is a constant and does not rely on the $x\%$ optimal charge-sustaining SOC, therefore, this part can be ignored in identifying the best SOC. Hence, this optimal SOC is decided exclusively by the oscillation

degradation. During each round of oscillation, the battery is understood to be discharged first from $(x + \Delta x)\%$ to $(x - \Delta x)\%$ and then charged back to $(x + \Delta x)\%$. Although both the charging and discharging processes within this small SOC interval will cause degradation, the charging process has a much more significant degradation than the discharging process, and this is why the discharging degradation is ignored in many studies [12], [17]. During the charging process, SEI grows much faster than in the discharging process [17], which makes it sufficient to consider the dominant charging degradation. This implies that we can apply equation (4) to model the charging degradation during oscillation and ignore the corresponding discharging degradation within oscillation.

Now the problem to identify the best charge-sustaining SOC value is to identify the best $x\%$ value that can minimize the oscillation charging degradation around $x\%$. The result from the Just-In-Time Control method in [1] simply states that this $x\%$ should take the value of 55% in order to reduce the oscillation degradation. In the following, we shall only focus on oscillation-caused degradation.

When the SOC oscillates m rounds, i.e., being charged m times from $(x - \Delta x)\%$ to $(x + \Delta x)\%$, the corresponding J_s will also oscillate m times around $J_s(x)$ if we treat J_s as a function of SOC. We may understand this as J_s oscillates from $J_s((x - \Delta x)\%)$ to $J_s((x + \Delta x)\%)$ if we further assume J_s is a monotone function of SOC around $x\%$, which is usually a reasonable assumption if Δx is small enough.

Equation (4) means that the increment rate $\frac{\partial \delta_{film}}{\partial t}$ is proportional to the absolute value of J_s . When $\frac{\partial \delta_{film}}{\partial t}$ is also treated as a function of SOC, then $\frac{\partial \delta_{film}}{\partial t}$ oscillates between its values at $\text{SOC} = (x - \Delta x)\%$ and $\text{SOC} = (x + \Delta x)\%$, i.e., between $\frac{\partial \delta_{film}}{\partial t} \Big|_{\text{SOC}=(x-\Delta x)\%}$ and $\frac{\partial \delta_{film}}{\partial t} \Big|_{\text{SOC}=(x+\Delta x)\%}$, where we assume that J_s is locally monotone with respect to SOC. During m rounds of oscillation, the total changes of $\frac{\partial \delta_{film}}{\partial t}$ equals the following:

$$m \left(\frac{\partial \delta_{film}}{\partial t} \Big|_{\text{SOC}=(x+\Delta x)\%} - \frac{\partial \delta_{film}}{\partial t} \Big|_{\text{SOC}=(x-\Delta x)\%} \right) = -\frac{mM_p \Delta t}{a_n \rho_p F} (J_s((x + \Delta x)\%) - J_s((x - \Delta x)\%)). \quad (5)$$

In the above equation (5), the left-hand side represents the changes of $\frac{\partial \delta_{film}}{\partial t}$ during the oscillation. From the J_s v.s. SOC relation developed in [12], J_s is always negative and also decreasing when SOC increases. Thus the right-hand side of (5) is always positive. This is equivalent to saying that the left-hand side of (5) is positive, and if its value turns big, then $\frac{\partial \delta_{film}}{\partial t}$ will have a bigger increment, and δ_{film} will also have a bigger increment. When the left-hand side becomes smaller, δ_{film} will have a relatively smaller increment, but it still increases. In order to reduce degradation speed, it is necessary for the left-hand side of (5) to be small, which is equivalent to making the right-hand side of (5) be small. Since $\frac{mM_p \Delta t}{a_n \rho_p F}$ is a positive constant, it suffices to make $-(J_s((x + \Delta x)\%) - J_s((x - \Delta x)\%))$ small in order to reduce the degradation speed,

which also shows that the degradation speed is related to the optimal charge-sustaining SOC value $x\%$. From the first order approximation of derivatives, we have

$$-(J_s((x + \Delta x)\%) - J_s((x - \Delta x)\%)) \approx -2\Delta x\% * \left. \frac{dJ_s(SOC)}{dSOC} \right|_{SOC=x\%} \quad (6)$$

Therefore, a minimum degradation speed happens if and only if $\left. \frac{dJ_s(SOC)}{dSOC} \right|_{SOC=x\%}$ is at a minimum.

This is to say, when the derivative $\frac{dJ_s(SOC)}{dSOC}$ has a smaller value at $x\%$, or equivalently when the J_s v.s. SOC curve turns to be flat, then the corresponding charge-sustaining mode at $x\%$ will have a lower oscillation degradation.

The above reasoning shows the following conclusion.

Proposition If the battery of a PHEV vehicle maintains the charge-sustaining mode at $x\%$ SOC, then the corresponding degradation will be minimal at the point $x\%$ which minimizes $\frac{dJ_s(SOC)}{dSOC}$, where $J_s(SOC)$ implies that J_s is treated as a function of SOC, and $\frac{dJ_s(SOC)}{dSOC}$ is its derivative with respect to SOC.

From this Proposition, it suffices to calculate the minimal $\frac{dJ_s(SOC)}{dSOC}$ in order to identify the best SOC to maintain charge-sustaining mode, and this is equivalent to finding the flattest area of the $J_s(SOC)$ curve. Since $J_s(SOC)$ is also affected by charging current and temperature (T), the minimal value of $\frac{dJ_s(SOC)}{dSOC}$ will also change against current and temperature. Therefore, the best charge-sustaining SOC value changes with current and temperature, and an optimal range of SOC can be obtained as a general guide for charge-sustaining operations. For the PHEV vehicle cruise control, this best charge-sustaining SOC value can be applied to minimize degradation cost under real-time operating conditions.

III. CASE STUDY

The parameters for a 1.8Ah SONY 18650 battery cell are taken from [12] in this case study (see Table 1), and the models in (3)-(5) are applied to calculate the relation between SOC and J_s under different temperatures and charging current. The corresponding calculation results are given in the figures below.

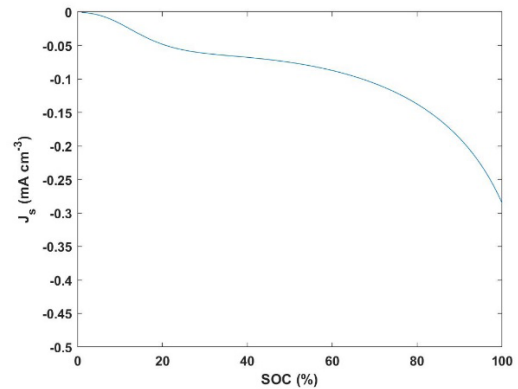
Fig. 1 (a) shows how the side reaction current density J_s changes against the SOC under 1C (i.e. 1.8A) current and 25°C. It is observed that the area within 30~50% SOC is relatively flat, and indeed the derivative of $-J_s$ in Fig. 1(b) shows that 36% is the SOC that has the lowest rate of change for J_s in the allowed SOC range (e.g., from 20 % to 90% SOC).

The above Fig. 1 assumes that the charging current is fixed. Now consider the impact of the charging current, and Fig. 2(a) shows a 3D graph of the side reaction current density J_s under 25°C where the SOC changes from 0% to 100% with a step increase of 1% while the charging current varies from 0C to 3C.

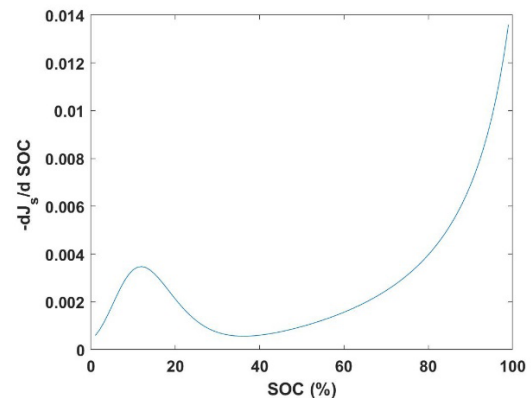
From Fig 2(a), it can be observed that roughly within the area of 30-60% SOC, the curve is relatively flat. In order to

TABLE 1. Battery parameters used in the case study [12].

Parameter	Value
$i_{0,s}$	$1.5 \times 10^{-6} \text{ A m}^{-2}$
a_n	147000
$U_{ref,s}$	0.4 V
Vol_n	$5.2448 \times 10^{-6} \text{ m}^3$
$\theta_{n,min}$	0.03
$\theta_{n,max}$	0.886



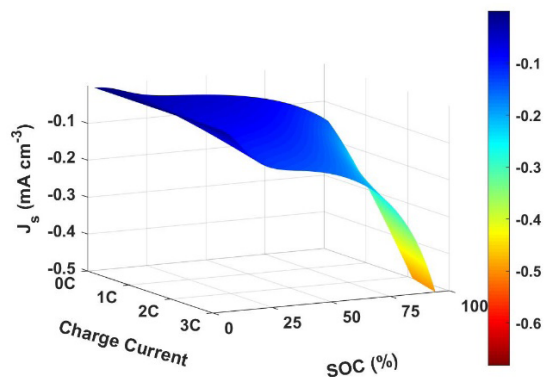
(a) Side reaction current density



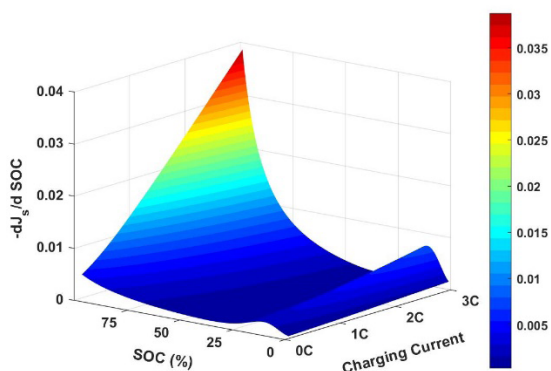
(b) Derivative of $-J_s$

FIGURE 1. Side reaction current density versus SOC under 1C and 25°C.

find the minimum $\frac{dJ_s(SOC)}{dSOC}$, the SOC's are changed from 0% to 100% on a step in crease of 1% to search for the optimal SOC ($x\%$) that minimizes $-(J_s((x + 1)\%) - J_s(x\%))$. The corresponding results are plotted in Fig. 2(b). From the calculated results, the optimal SOC values under 25°C are 38%, 37%, 37%, 36%, 36%, and 36% for the charging current 0.5C, 1C, 1.5C, 2.5C and 3C, respectively.



(a) Side reaction current density



(b) Derivative of $-J_s$

FIGURE 2. Side reaction current density versus SOC under 25°C.

Similarly, the above optimal SOC values under other temperatures such as -15°C, -10°C, -5°C, 0°C, 5°C, 10°C, 15°C, 30°C, 35°C, 40°C, 45°C, 50°C are also calculated and shown in Table 2.

From the results of Table 2, it can be concluded that charge-sustaining mode is best maintained at a SOC between the range of [36%, 38%]. However, the above ranges only make sense if the SOC values can be accurately found. In real applications, this is often difficult as the SOC is usually estimated from real time monitoring of battery current, voltage and temperature. This kind of SOC estimation often has certain limitations. For example, the mean error in the method of [18] can be as high as 1.64%, the maximum error in a recent method of [19] is at least 0.46%, and these errors could exceed 2% under certain driving cycles [18]–[20]. For this reason, it is advised to take the average value of the above SOC range, i.e., 37% as the best SOC value. Even if under a 2% SOC estimation error, the working range of 35%~39% still provides a good guide in minimizing the oscillation degradation.

When the battery rated capacity is changed to 2Ah, the results in Table 2 only change slightly, and the best SOC range is still between [36%, 38%]. Again, considering the SOC estimation errors, an average value of 37% SOC is

TABLE 2. Optimal SOC value.

Temp. (°C)	Optimal SOC Value (%)					
	0.5C	1C	1.5C	2C	2.5C	3C
-15	38	37	37	37	36	36
-10	38	37	37	37	36	36
-5	38	37	37	37	36	36
0	38	37	37	37	36	36
5	38	37	37	37	36	36
10	38	37	37	37	36	36
15	38	37	37	36	36	36
20	38	37	37	36	36	36
25	38	37	37	36	36	36
30	38	37	37	36	36	36
35	38	37	37	36	36	36
40	38	37	37	36	36	36
45	38	37	37	36	36	36
50	38	37	37	36	36	36

recommended as the best SOC value. Although this result is different to the 55% SOC recommended in the Just-in-Time Control of [1], the curves in Fig. 1(b) and Fig. 2(b) still show that 55% SOC is an acceptable choice and performs better than a lower SOC such as 20%.

IV. CONCLUSION

With the help of a reduced order solid electrolyte interphase layer growth model, this article presents a general method on identifying the best SOC value for maintaining a charge-sustaining mode for plug-in hybrid electric vehicles. That is, the optimal SOC value is found to be the SOC which maximizes the derivative of the side reaction current density. From this result, the 55% SOC for charge-sustaining mode in Just-in-Time control is not optimal for the popular battery SONY 18650 cell, and the corresponding best SOC should be 37% considering the potential SOC estimation errors.

The above optimal SOC value is obtained by investigating the degradation of a battery cell, however, the degradation of a whole battery pack may be quite different to an individual cell. This is because that the degradation of the whole battery pack is related to the worst-degraded battery cells as well as the battery balancing methods within the battery management system. In order to simplify the discussions, the diverse performance among individual battery cells has been ignored in this article, and the above obtained optimal SOC value is applicable only when all the battery cells within a pack have roughly the same level of degradation and performance, such as in new batteries. For our immediate next step of work, the optimal SOC value for a battery pack will be investigated.

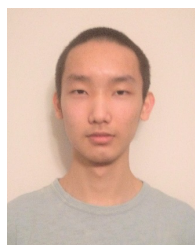
Since this article uses only the battery cell parameter for the SONY 18650 cell, the obtained SOC values will change when the type of battery cell changes. More types of batteries and the application of this optimal SOC value in PHEV cruise control will be investigated as a future study.

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