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A Predictive Energy Management Strategy Using a Rule-Based Mode Switch for Internal Combustion Engine (ICE) Vehicles

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ABSTRACT

With fuel efficiency becoming an increasingly critical aspect of internal combustion engine (ICE) vehicles, the necessity for research on efficient generation of electric energy has been growing. An energy management (EM) system controls the generation of electric energy using an alternator. This paper presents a strategy for the EM using a control mode switch (CMS) of the alternator for the (ICE) vehicles. This EM recovers the vehicle's residual kinetic energy to improve the fuel efficiency. The residual kinetic energy occurs when a driver manipulates a vehicle to decelerate. The residual energy is commonly wasted as heat energy of the brake. In such circumstances, the wasted energy can be converted to electric energy by operating an alternator. This conversion can reduce additional fuel consumption. For extended application of the energy conversion, the future duration time of the residual power is exploited. The duration time is derived from the vehicle's future speed profile. The future speed profile is non-deterministic in real driving environment. Therefore, the proposed EM applies a Markov chain model to stochastically predict the vehicle's speed. Based on the predicted duration time of the residual power, a rule-based mode switching strategy is established. There are three types of control modes defined according to the target amount of battery charge. The proposed strategy of this paper was validated through simulation, and simulation results show an improvement in fuel efficiency compared to the results of a conventional EM.

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INTRODUCTION

The demand for electric power consistently increases as the number of electric components in the ICE vehicles grows [1]. In the ICE vehicles, an alternator is mechanically attached to the engine and rotates with a crankshaft by a pulley. The alternator generates electric energy through rotational motion of the crankshaft. In this process, the operation of the alternator affects the operating point of the engine [2]. In effect, this causes an increase in fuel consumption when supplying the electric energy for electric power systems. Therefore, research on an EM system that can limit the associated fuel consumption is necessary.

In order to improve the fuel economy, residual kinetic energy is used in this paper. The residual energy occurs when a vehicle decelerates and is usually consumed by brake force or friction. The wasted energy can be recycled to generate electric energy. Several systems have been developed to exploit residual energy, such as the kinetic energy recovery system (KERS) [3], [4] and hybrid electric vehicles (HEVs). For example, in a Formula One racing car, the Flywheel KERS has been applied [3]. In this system, a flywheel stores the kinetic energy as rotational energy from a driveshaft. For reuse of the kinetic energy, the KERS generally uses additional components as a low-friction flywheel. In the case of HEVs, a regenerative brake system has been installed [5], [6]. It converts the heat energy of brakes into electric power. The additional devices are also installed to the HEVs, as an electric motor is equipped for conversion and recovery of the electric energy.

This paper presents an EM strategy which can improve fuel economy without additional equipment for ICE vehicles. The EM strategy switches the control mode of the alternator according to predefined rules. The rules are based on the future duration time of the residual engine power. Electric energy production is varied along the control mode to reduce fuel consumption.

The proposed EM strategy progresses in two main stages. In the first stage, the future vehicle speed is predicted based on the Markov chain model that is derived from the driving database. The predicted speed is then used to estimate the future duration time of the residual engine power. In the second stage, an alternator control mode switch is operated based on the results of the first stage. There are three main modes for the switch: normal charge mode, high-rate charge mode, and low-rate charge mode. In the normal charge mode, the alternator operates in the same manner as it would in a conventional system. When there is residual engine power, the mode is switched to the high-rate charge mode. In this mode, the amount of electric power generation increases. Lastly, the low-rate charge mode is activated when the generation of residual energy is estimated in the near future.

In this mode, the alternator supplies minimum operating capacity. This strategy allows for the effective usage of residual power, and as a result, it reduces additional fuel consumption.

The remainder of this paper is organized as follows: Section II gives an overview of the EM system along with its system architecture. Then, Section III presents the stochastic prediction model for vehicle driving information. In Section IV, an EM using a rule-based mode switch is explained. In Section V, simulation results are presented. Finally, in Section VI, the conclusion is given.

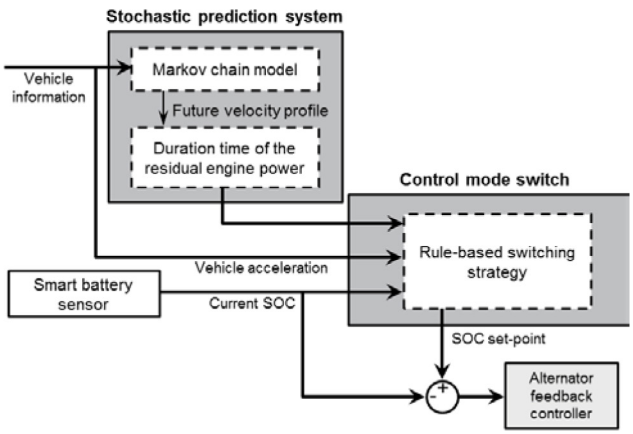


Figure 1. System architecture of the energy management strategy

ENERGY MANAGEMENT STRATEGY

System Overview

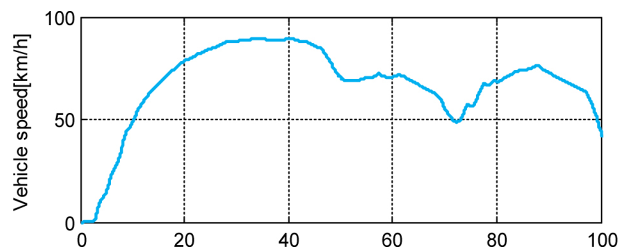
The proposed EM strategy is applied to the electric system of conventional ICE vehicles. In the target electric system, the alternator is controlled by a negative feedback controller using SOC value as a reference input. The proposed strategy provides a variable SOC setpoint to the feedback controller of the alternator.

As shown in Fig. 1, this EM consists of two sub-systems: a stochastic prediction system and a control mode switch. First, the prediction system estimates future duration time of the residual engine power based on input of current vehicle measurements. The prediction is based on a Markov chain model that is one of the representative stochastic models. Then, the control mode of the alternator is switched based on predefined switching rules. The rule determines the control mode according to the predicted information and the SOC of the battery. As the control mode switches, the set-point of the SOC changes as well. Finally, the error between the SOC set-point and current SOC values are used by the feedback controller of the alternator.

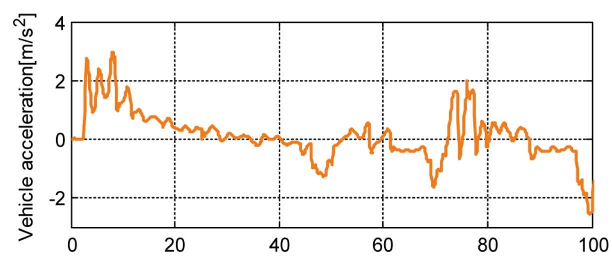
PREDICTION OF RESIDUAL ENGINE POWER

Relationship between Vehicle Speed and Residual Kinetic Energy

As mentioned in the previous section, the prediction system aims to estimate the future duration time of residual kinetic energy. However, it is difficult to predict the residual energy directly. Therefore, we used vehicle speed to predict the occurrence of residual energy. Correlation between the vehicle speed and the residual kinetic energy is shown in Fig. 2. It is observed that the residual power occurs when the vehicle decelerates. However, the deceleration does not always result in the residual power as shown in Fig. 2(c). Therefore, we applied a threshold for the magnitude of vehicle deceleration to distinguish the driver's demand. The threshold value was determined empirically. Consequently, the residual power is indicated by the value of vehicle acceleration under the threshold.



a.



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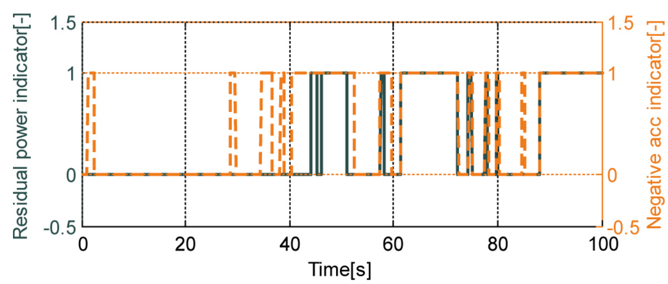

c.

Figure 2. The relationship between vehicle speed and residual engine power: (a) vehicle speed profile, (b) acceleration profile, and (c) indicators of residual power (solid line) and negative acceleration (dotted line)

Markov Chain Model

In real driving, the prediction of vehicle speed is not deterministic, since the behavior of a vehicle is determined by the driver as well as various driving environment factors [7]. To model a non-deterministic system, a stochastic approach is used. In this paper, a Markov chain model is applied for prediction. This Markov chain model is based on an interval encoding method and multivariate Markov chain [8], [9].

We defined the state space X and partitioned it into a finite set with equal intervals. Each interval is assigned to Markov state $\overline{x}_j$, which is the midpoint of the interval. With $\overline{x}_j$ and predefined transition probabilities π_{ij}, a deterministic next state x^+ is predicted as

$$x^{+} = \sum_{j=1}^{M} \pi_{ij} \bar{x}_j \, . \tag{1}$$

Based on this interval encoding, the continuous real-valued state can be calculated [4]. In order to improve predictive accuracy, we selected three vehicle measurements as the Markov states: vehicle speed, vehicle acceleration, and engine speed.

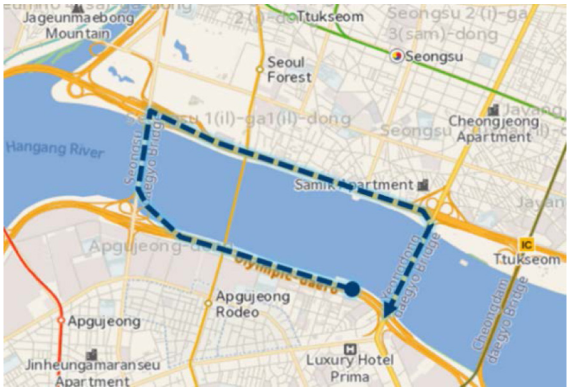

Figure 3. Map of the route for data collection

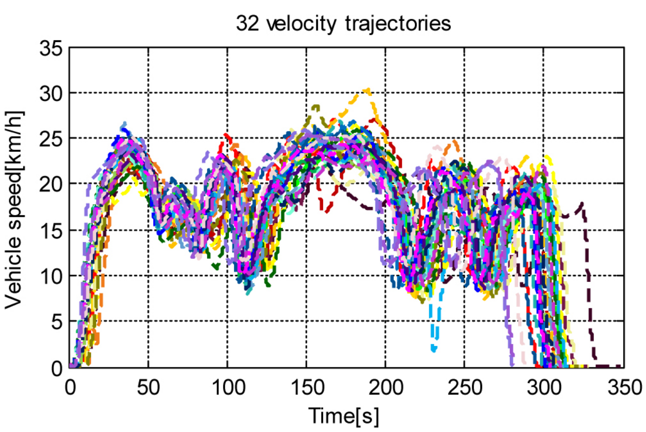

Figure 4. 32 measured velocity trajectories

Actual driving data were collected to design the Markov chain model. The data collection was repeated 32 times on the route of Fig. 3 in Seoul, Korea. The data was measured under similar conditions; no traffic jams were encountered, and there was a low volume of traffic. Fig. 4 shows the 32 velocity trajectories of the vehicle measured. 31 of the trajectories were used as training data for the Markov chain model, and the last one was used for verification simulation.

Evaluation Results

The Markov chain model of vehicle speed was evaluated through the simulation. The maximum prediction horizon (PH) of the Markov model is 10 seconds. PH indicates how long the prediction model can look ahead into the future. Fig. 5 shows the results in time domain. Each graph figures out different performances for each PH. As the PH increases, the accuracy of the prediction decreases. Quantitative analysis results are given in Table 1.

Table 1. RMSE and R-squared values for each PH

PH [s]	RMSE [km/h]	R-squared
1	1.68	0.9998
4	4.72	0.9861
7	7.99	0.9686
10	10.29	0.9452

*RMSE: root mean square error

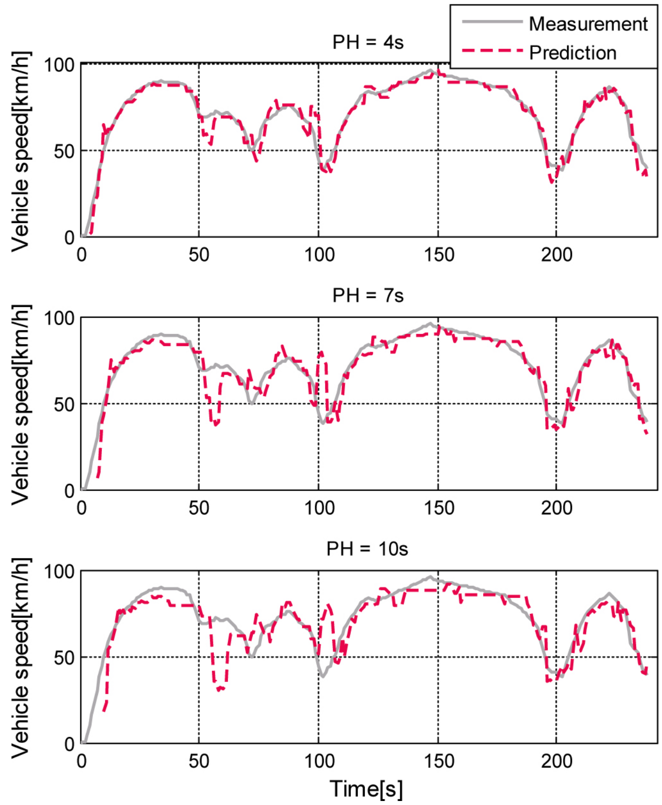

Figure 5. Prediction results of vehicle speed for PH = 4, 7, 10 seconds

RULE-BASED CONTROL MODE SWITCH (CMS

In the switching strategy of the alternator control mode, three modes are defined:

1. Mode 1 = normal charge mode (NC)
2. Mode 2 = high-rate charge mode (HC)
3. Mode 3 = low-rate charge mode (LC).

The control mode of the alternator is determined according to predefined rules, which is expressed by the “if-else” language as follows:

If $a_{veh}(t) < \theta_a$
  Mode$(t+1)$ = HC mode
Elseif a_{veh} (t) > θ_a and $SOC_{ResPwr} > SOC_{Err}$
  Mode$(t+1)$ = LC mode
Else
  Mode$(t+1)$ = NC mode

At first, this EM basically runs in the NC mode. In the NC mode, the alternator operates identically to that of the conventional vehicles. It tries to maintain the SOC value in the stable region. The normal operating range for the batteries is usually 50-80% [10]. Therefore, the basic SOC set-point for NC mode is set to 70%.

At the next stage, the residual kinetic energy is confirmed through the current acceleration (a_{veh}). If a_{veh} is lower than the threshold (θ_a), it implies the occurrence of residual power, and the mode is shifted to HC mode. In the HC mode, the SOC set-point is set to high value and electric power production is increased. In this condition, the electric energy generation causes minimum fuel consumption by using the portion of the residual power.

Then, when a_{veh} is higher than θ_a, the amount of SOC charged by the HC mode in near future (SOC_{ResPwr}) is estimated. In other words, the SOC_{ResPwr} is calculated based on the duration time of residual power, which is estimated through the prediction system. Since the alternator generates maximum electric power with the residual power, SOC_{ResPwr} is calculated as

$$SOC_{ResPwr} = \dot{SOC}_{max} \times t_{ResPwr}, \tag{2}$$

where $\dot{SOC}_{max}$ is maximum charge rate of SOC and t_{ResPwr} is the predicted duration time of residual power. The $\dot{SOC}_{max}$ is a coefficient which is dependent on specifications of the alternator and battery capacity. When $SOC_{ResPwr} > SOC_{Err}$, it is confirmed that the residual energy recovery can supplement the lack of current SOC in the near future. SOC_{Err} is calculated as

$$SOC_{Err} = SOC_{set} - SOC_{meas}, \tag{3}$$

where SOC_{set} is the normal SOC set-point and SOC_{meas} is current measured SOC. In the LC mode, the SOC set-point is changed to low value. In this case, the electric energy generation is minimized to prevent unnecessary fuel consumption.

Finally, when there is no chance for residual energy recovery, the EM keeps the NC.

SIMULATION RESULTS

Simulation Environment

The proposed EM strategy was validated through simulation using the Autonomie which was developed by Argonne National Laboratory (ANL) [11]. Specifications of the vehicle model are as in the following table.

For evaluation, the proposed strategy—that is, the CMS—was compared to a proportional control strategy whose SOC set-point is constant. The proportional control strategy is provided by the Autonomie alternator control model.

The test driving cycle is one of the collected velocity trajectories in the Fig. 4, as mentioned in Section III. Total time and distance of the cycle are 238 seconds and 17.11 km respectively. The other analysis results of the test driving cycle are shown in the Fig. 6.

Table 2. The specification of the target vehicle model

Component	Specification
Engine	110kW 2.2L Spark Ignition Direct Injection (SIDI)
Transmission	Automatic transmission (AT)
Alternator	2kW
Battery	12V 66Ah lead-acid battery
Electric load	200W

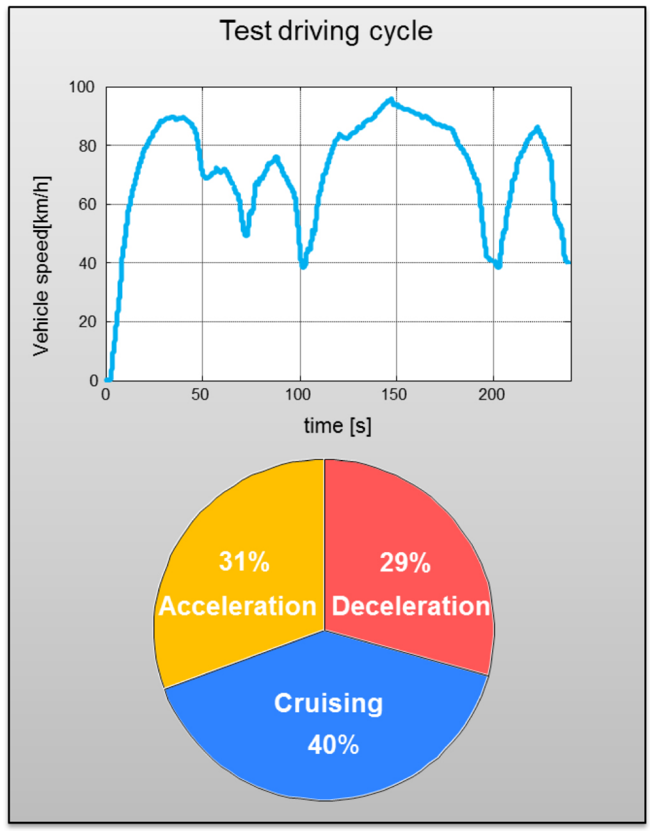

Figure 6. Analysis of test driving cycle: velocity trajectory and proportion ratio of acceleration

Simulation Results

Simulation results show that the proposed EM can improve fuel economy. Fig. 7 presents trajectories of normalized alternator command and SOC according to change of control mode. The alternator command is maximized when the residual power occur (Residual power indicator = 1). The alternator is turned off by the CMS when the residual kinetic energy is detected in future. On the other hand, it operates for the entire duration of time in results of the proportional control strategy. Both of the two strategies keep SOC values in the stable range.

As a result, Fig. 8 and Table 3 show that total fuel consumption is reduced by 0.48%. In terms of electric energy production, the fuel consumed by the alternator is reduced by 42.86%.

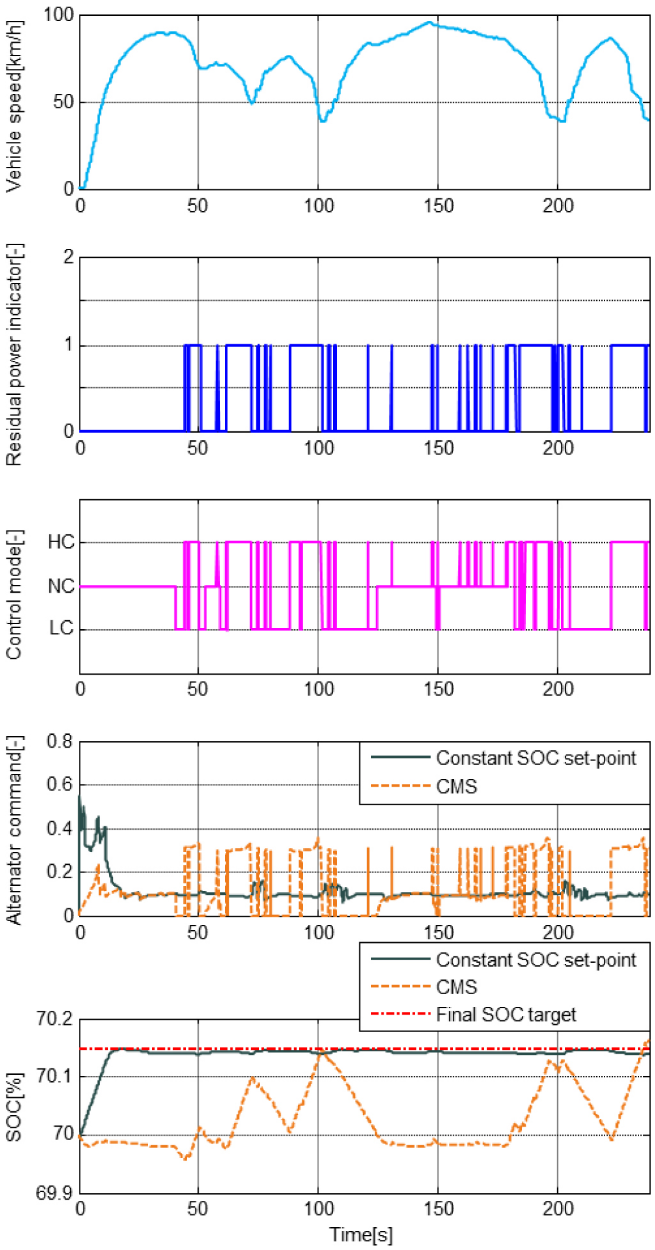

Figure 7. Results of CMS: velocity trajectory of the test driving cycle, residual power indicator, alternator control mode profile, normalized alternator command, and SOC

Table 3. Comparison of the two strategies in terms of fuel consumption reduction

Control strategy	Fuel consumption [g]	
	Total	By alternator
Constant SOC set-point	264.6	2.80
CMS	263.4	1.60
Saving	0.48%	42.86%

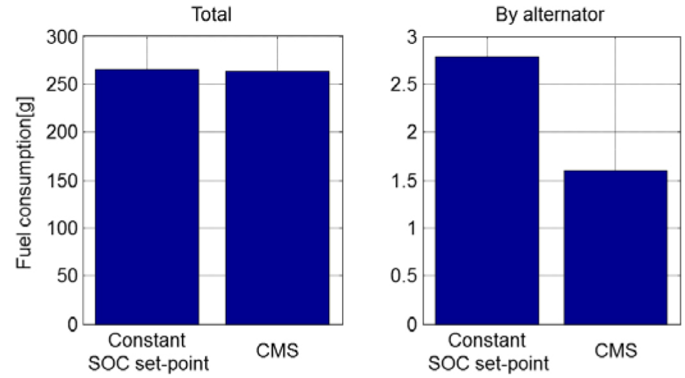

Figure 8. Final fuel consumption in two perspectives: total fuel consumption and fuel consumed by alternator

CONCLUSIONS

Advanced energy management strategies are developed to efficiently supply electric energy while reducing fuel consumption. In this paper, the energy management strategy based on the mode switch of the alternator control has been proposed. The alternator control mode is switched according to predefined rules. The rules are based on the residual kinetic energy for energy recovery. In order to estimate the duration time of residual energy, this strategy uses future vehicle speed predicted by a Markov chain model. The proposed strategy is evaluated through simulation and compared with the conventional strategy. The total fuel consumption is reduced by 0.48%. In the case of the fuel consumed based on the operation of the alternator, the proposed EM achieves fuel saving by 42.86%. This method is suitable for implementation in the conventional vehicle because it does not require the additional hardware. There is also the potential for expansion in HEVs.

The future work will focus on application of intelligent traffic system (ITS). ITS information such as traffic signs and traffic lights can improve performance of the stochastic prediction system.

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DEFINITIONS/ABBREVIATIONS

ICE - Internal combustion engine

HEV - Hybrid electric vehicle

SOC - State of charge

CMS - Control mode switch

ITS - Intelligent traffic system

EM - Energy management