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HEV Cruise Control Strategy on GPS (Navigation) Information

Beomsoo Kim[1], Yong-gi Kim[2], Talchol Kim[2], Yeong-il Park[3], Suk Won Cha[1]
[1] School of Mechanical & Aerospace Engineering, Seoul National University, Seoul, Korea,
zepplin9@snu.ac.kr
[2] Hyundai Motor Company, 772-1 Jangduk-Dong, Hwaseong-Si, Gyeonggi-Do, 445-706, Korea
[3] School of Mechanical Design and Automation Engineering, Seoul National University of Technology, Seoul, Korea

Abstract

The main objectives of this paper are to demonstrate the development of the hybrid vehicle control system with the GPS (navigation) system of a vehicle travelling a pre-planned driving route. To verify the improvement in vehicle fuel economy, we developed the forward-facing simulator, which can be applied to the proposed HEVs control system. The proposed HEVs control system recognizes upcoming driving patterns because it has terrain (uphill, downhill) and speed information. The controller calculates the parameters related to pattern recognition during a sampling time to choose a comparable driving cycle and to classify into three driving modes (Urban/ Extra-urban/ Highway mode). Moreover, a dynamic programming approach is proposed to obtain the optimal fuel economy and the state of charge (SOC) trajectory. For this approach, we developed a rule-based controller to manage the battery SOC according to the target SOC range. The amount of the target SOC range depends on the driving pattern recognition during a specific time period. The conventional HEV control system sustains the battery SOC within a limited range. Compared with the conventional controller, the proposed control system, by using road slope and speed information, gives results that confirm improved fuel economy.

Keywords: HEV (hybrid electric vehicle), navigation, controller, state of charge, simulation,

1 Introduction

As an alternative to conventional vehicles, Hybrid Electric Vehicles (HEVs) can achieve better fuel economy and reduce pollution emissions. HEVs can use gasoline (or diesel) engine energy to generate electric energy through a motor-generator system with a rechargeable energy storage system. Compared to similar conventional vehicles, Hybrids has more advantages: it can operate the combustion engine closer to the highest efficiency range; can capture the wasted energy from deceleration through the regenerative braking system and convert it into electrical power; and can use the electric power to charge the batteries, which in turn can propel the electric motor for hill climbing, acceleration, and high power demand conditions.

The conventional HEV control system commonly monitors and maintains the battery state of charge (SOC) at the upper (approximately 60%) and the lower (approximately 40%) limit range. The battery needs to provide propulsive power for unexpected hill climbing and/or acceleration conditions. The battery requires a sufficient charge storage space for regenerating mechanical potential and/or kinetic energy during downhill and/or deceleration conditions. When the battery SOC falls below the lower limits, in the conventional control system, the engine power will engage and provide electrical charging power to the battery immediately via the commands that increase engine torque and speed. However, this conventional control system is advantageous for obtaining adequate results when the vehicle operates on a flat terrain travelling route (without road slope information). When HEVs are operating at a relatively high altitude and/or high speed, more power may be required and the battery may be discharged faster than when HEVs are operating at a relatively low altitude and/or low speed. In such a case, the battery SOC control using GPS (navigation) information can be applied.

Arun Rajagopalan investigated an instantaneous, control strategy for a parallel HEV. This strategy continuously modifies itself based on future driving conditions, when speed or elevation changes. Traffic and elevation information from GPS is used in an adaptive fuzzy logic controller [3]. Erik Hellstrom studied how information about future road slopes can be utilized in a heavy truck. A model predictive control scheme is used to control the longitudinal behavior of the vehicle. And computer simulations showed that fuel consumption can be reduced by 2.5% [2]. Yoshitaka Deguchi proposed a charge/discharge control system, which uses fuel efficiency as the control parameter. The parameter is updated according to the magnitude of the difference between the predicted SOC and the actual SOC and whenever traffic information is updated. Fuel economy was improved by 3.5% on the test route, by 7.8% on the downhill route and 0.5% on a congested route [4].

Accordingly, we developed the forward-facing simulator,which can be applied to the proposed HEVs control system. The proposed HEVs control system recognizes future driving patterns based on information about the travelling terrain (uphill, downhill) and speed. This rule-based controller manages the battery SOC according to the incoming target range. The target SOC range depends on pattern recognition during a specific time period. Moreover, a dynamic programming approach is proposed to obtain the optimal fuel economy and the optimal SOC trajectory. The results of the proposed control system are presented and conclusions are described in comparison to those of the conventional control system.

2 Road slope and vehicle speed information

The Global Positioning System (GPS) is a common vehicle navigation system. It offers a signal that contains the longitudinal and latitudinal position information of the vehicle on a route. When the departure and destination points are specified, the driver drives the hybrid vehicle along the planned route and obtains information along this path from the GPS. Once the vehicle receives information on the future driving condition in advance, the control system can operate the vehicle to reduce fuel consumption. For example, Figure1 shows an illustration of the SOC control management scheme with or without slope information. When an HEV is to travel on an uphill in the near future at a relatively high speed and high altitude (c-d region), the motor/generator (MG) will require more power to satisfy the power demand and the battery SOC may drop. In the conventional control system, if the battery SOC falls below the threshold lower limit, the motor/generator (MG) will prevent the discharge of the battery.

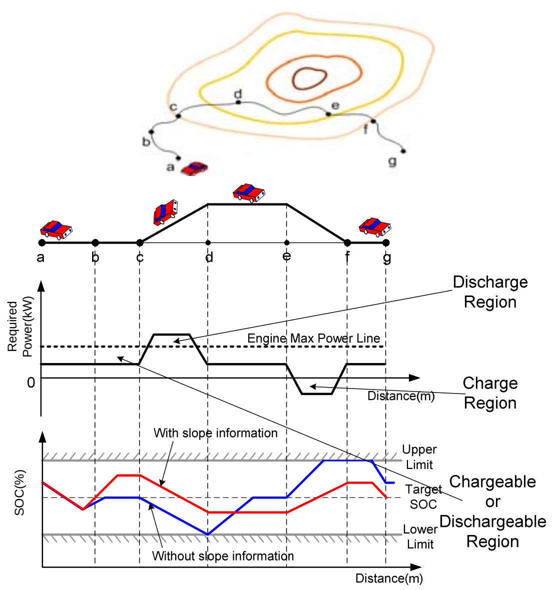


Figure1: Control scheme of road slope (altitude) information

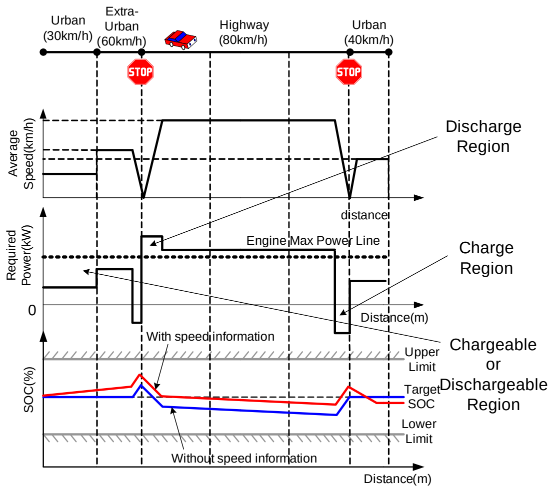


Figure2: Control scheme of average speed information

However, the battery SOC discharging can be postponed or omitted in the Chargeable/ Dischargeable region (b-c region) when an uphill condition is expected in the near future (c-d region) before the battery SOC has reached the limit bounds. On the other hand, when an HEV is to travel downhill (e-f region) in the near future, this is an opportunity to recharge the battery SOC from regenerating applications. Therefore, the control system needs to secure a greater space in the battery to store the regenerating power before the threshold upper limit is reached. Future vehicle speed cannot be predicted in realty and cannot be guaranteed along the HEV planned route. Therefore, a realistic alternative to future speed prediction is to use an average speed of a representative road characterized according to the road classification (urban: 10~50km/h, extra-urban:50~70km/h, highway: 70~km/h).

3 Application of GPS (Navigation) information to HEVs control strategy

3.1 Driving cycles classification

Driving cycles are the standardized driving patterns, which are described by a velocity-time table. As shown in Table 1, two kinds of parameters can be calculated from the velocity during a fixed time interval. According to the duration times of idle speed (equation (1)) and average speed, the nine most common driving cycles can be divided into three groups: Urban, Extra-Urban, Highway.

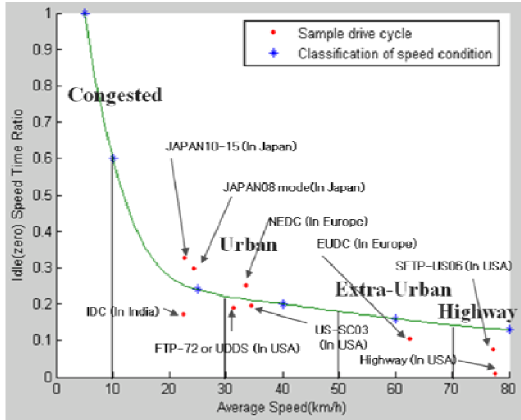


Figure3: Classification of the representative driving cycles

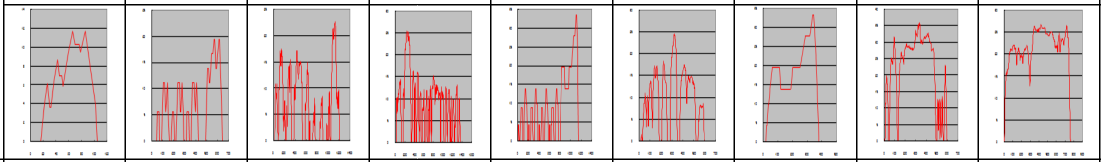
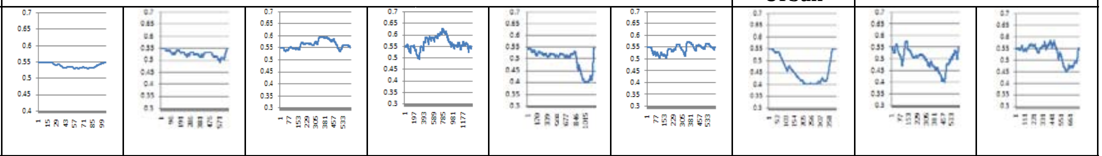
$$Idle\ speed\ ratio = \frac{Zero\ speed\ duration\ time(\mathrm{sec})}{Total\ time(\mathrm{sec})} \quad (1)$$

These groups will be utilized to categorize the future circumstances of vehicles travel. Additional information that will be utilized is the boundaries of the road sections from an urban road to a highway road. Although the navigation system can provide the road classification, it cannot predict the actual road condition such as congestion and intermittent stop-and-go's. Therefore, the driving speed information (idle speed ratio and average speed) during the past time interval is stored in the memory devices and is extracted to determine the vehicle road groups and boundary points. Nine representative driving cycles were classified according to two main parameters, as shown in Figure3.

3.2 Pattern recognition

The output data of vehicle speed in the sampled time are used to predict the future state of the vehicle. If the sampled time interval is assumed to be 150 seconds, the future state of the vehicle will be updated every 150 seconds. The 'speed' and 'slope' information from the GPS (navigation) system are used separately for different approaches, as seen in figure 4. Pattern A considers only the 'speed' information, obtained by calculations of average speed, idle speed ratio and maximum speed during the past 150 seconds. The controller calculates the three parameters during a sampled time to choose a driving cycle comparable to the above representative driving cycles and to classify the road groups.

Table1: Characteristics of representative driving cycles for recognizing the patterns

	IDC	Japan10-15	JAPAN08	FTP-72	NEDC	US-SC03	EUDC	SFTP-US06	HWFET
Driving Cycle									
Avg. speed(kph)	22.50504	22.7196	24.39504	31.50036	33.59952	34.5564	62.5932	77.31	77.6736
Idle speed ratio	0.17143	0.32526	0.28821	0.18964	0.24894	0.19468	0.10474	0.74875	0.78329
Groups	Urban						Extra-Urban	Highway	
Optimal SOC traj. Dynamic Programming (Init. 0.55)									
Max. SOC	0.550	0.550	0.594	0.626	0.550	0.572	0.550	0.575	0.584
Min. SOC	0.529	0.489	0.489	0.492	0.400	0.504	0.400	0.401	0.452
Avg. SOC	0.539	0.527	0.548	0.563	0.500	0.543	0.461	0.500	0.533

When one representative driving cycle is selected, the maximum, minimum and average SOC in Table l are used to control the target input data and the allowed SOC range. This target SOC is calculated by Dynamic Programming (DP), which is used for the optimization of the backward-facing simulation for given driving cycles. Pattern B considers the 'slope' information. If the driver indicates destination points in a navigation system, all of the slope information in the planned route can be uploaded to the controller and a non-dimensional parameter can be calculated. The weighing function derives the offline map data based on average speed and idle speed ratio. Vehicle speed in the sampled time on the route affects this weighing value. Pattern B includes a function of slope information.

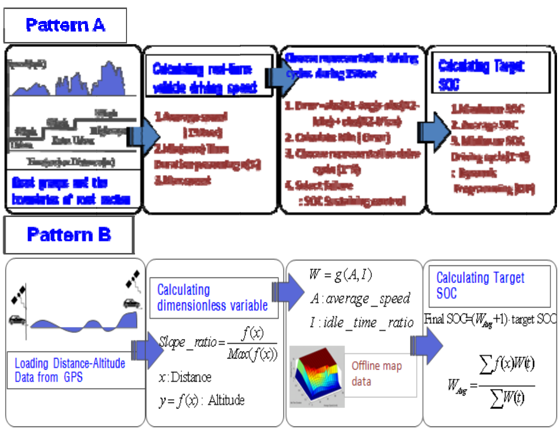


Figure4: Application of the control logic system with 'slope' and 'speed' information

4 Development of forward-facing control system

4.1 Implementation of rule-based controller

HEV controller design for cruise control can be divided into two parts. The rule-based control system is one of the HEV control design methods. Driving in all situations is controlled by a set of constraints and rules. This method can be used as a static approach for determining the ideal operating points of an engine and electric motor. These strategies mainly consist of a pre-determined map based on a representative driving condition. On the other hand, real-time control strategies adjust operations based on the current driving condition. The HEV model components in the simulator are shown in Figure5. This model has a parallel HEV depending on the engine clutch engagement and the specification of the components seen in Table 2. [6-8]

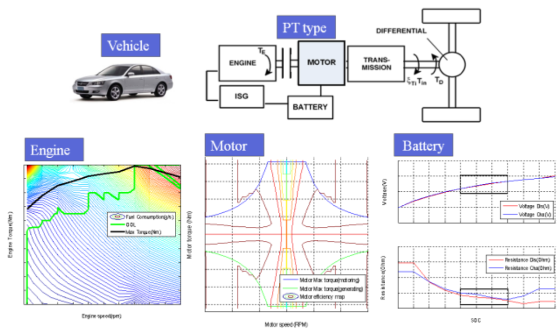


Figure5: Configuration of powertrain structure and components of HEV system model

Table2: Specification of the HEV components

Engine	2.4L gasoline engine
Motor	PMSM
Transmission	6-gear Automatic Transmission without torque converter
Battery	Li-PB

4.2 Simulation

The vehicle model for simulation used the commercial software program, AVL cruise. The control logic system was built using Matlab-Simulink. Figure 6 shows the conventional SOC control logic that maintains the SOC at the upper (70%) and the lower limit (40%) range. When the battery SOC falls below the mid-lower (48%) limit, the basic control system will cause a negative motor torque and provide electrical charging power to the battery immediately. When the battery SOC rises above the mid-upper (62%) limit, the basic control system will cause a positive motor torque and draw electrical power from the battery. But the additional motor torque does not work between 48%~62% SOC range.

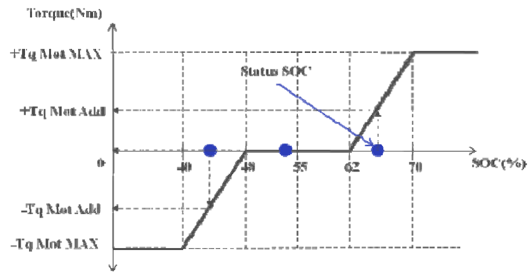


Figure6: The conventional SOC control logic (Controller1)

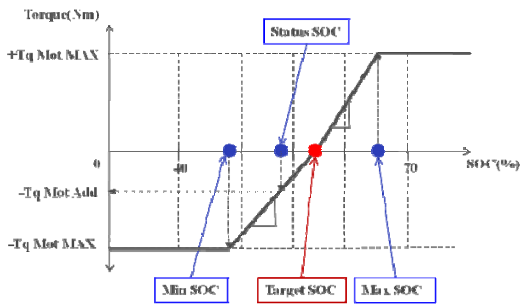


Figure7: The proposed SOC control logic (Controller2)

Regardless of the driving conditions, this controller applies to the HEV cruise control. The proposed SOC control logic in Figure7 will change a magnitude of the additional motor torque according to the target, max and min SOC.

The proposed controller 2 will be applied to each pattern A and pattern B, or together.

5 Simulation results

The simulation results were obtained from a real driving cycle in Korea. In the time domain, the vehicle driving speed and the surrounding terrain data are shown in Figure 8. The entire driving cycle is composed of the urban mode, extra-urban mode and highway mode. On the route, the altitude rose slightly and dropped repeatedly until the extra-urban mode.
A dynamic programming approach is proposed for hybrid system optimization.[13] This approach is demonstrated to design a control strategy for optimal driving performance, emissions, an dfuel economy. Also, the optimal SOC trajectory can be found additionally. As shown in Figure 9, we obtained the optimal SOC trajectory for a vehicle travelling in a given driving cycle in Figure8 by the backward-facing simulation. In the case of the same vehicle system model, the battery SOC trajectory in Figure 9 is the optimal solution for the control of the HEVs. However, a dynamic programming approach can be applied exclusively to the backward-facing control system, which is not connected to real-time driving signals and data. This DP is, therefore, not available to implement the conventional/proposed SOC control design but profitable to achieve reliable results compared to the forward-facing control system.

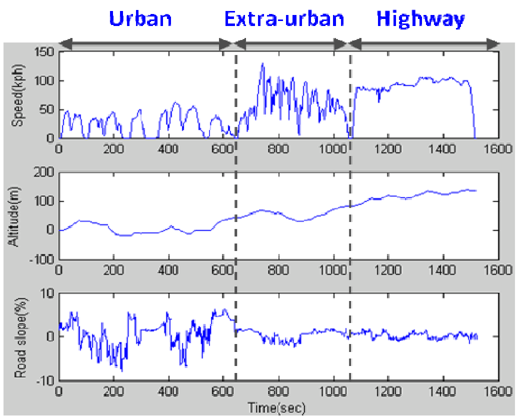


Figure8: Simulation driving cycle (urban, extra-urban, highway route)

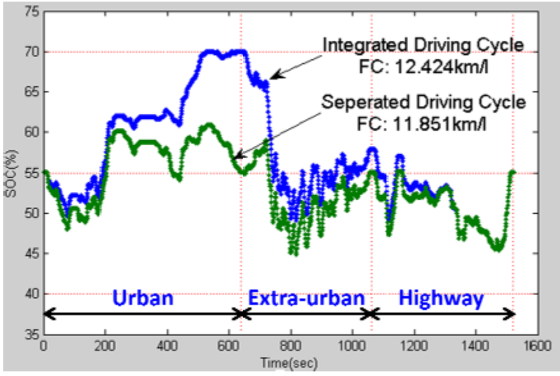


Figure9: Results of DP optimal SOC trajectory to estimate the potential fuel economy with road slope data (DP: initial SOC and final SOC: 55 %)

In addition, it contributes the instuctions in which the forward-facing controller guides the vehicles to obtain a comparable optimal solution.

Consequently, we need to evaluate the theoretical maximum of improving fuel economy using the dynamic programming results. The separate driving cycle in Figure 9 gives the optimal SOC trajectory for calculating the driving cycles individually through a DP method at the initial SOC(55%) condition. And the ideal fuel economy by optimal control is 11.851km/l. On the contrary, the integrated driving cycle for all of the driving cycles together achieves 12.424km/l fuel economy. A dynamic programming assures the best solution for the optimal control HEVs. The ideal potential of fuel efficiency can be expected to be approximately 4.84% enhancement.

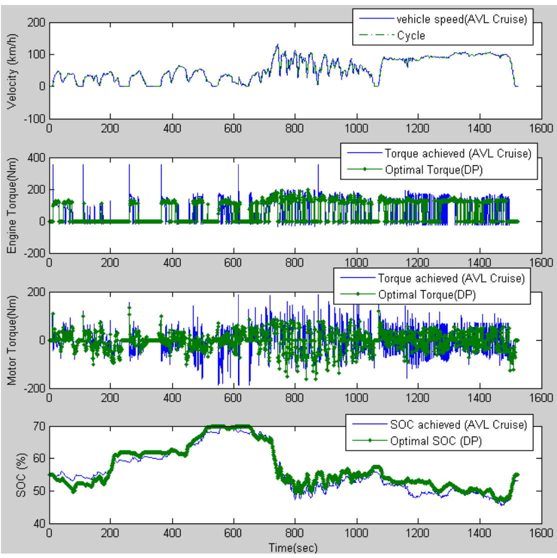


Figure10: Forward-facing simulation results: the optimal SOC from DP was used instead of the target SOC

Moreover, the optimal SOC trajectory at the transition of the road section boundaries in Figure9 provides the control strategy rules of Figures 1,2.

Figure10 shows that the comparison of backward-facing simulation (DP) results and the forward-facing simulation results to verify the reliability of the proposed forward-facing control system and the vehicle components model. The engine torque, motor torque and SOC achieved by AVL cruise simulator implemented the proposed SOC control logic (controller2) which used the optimal SOC from DP instead of the target SOC. We confirmed that the implementation of the forward-facing controller is practical for following the target SOC. As referred to in Figure 4, pattern A, which only related to the vehicle speed information, is applicable to the proposed SOC control system (controller2). The result of fuel economy was 11.121km/l, which was an insignificant outcome compared to the result of the conventional control system (controller1). In the case of Pattern B, which is associated with road slope information, fuel economy improvement was increased up to 1.35%, which was not a remarkable quantity. Considering pattern A and pattern B simultaneously, we can improve fuel economy by 1.16%, according to simulation results. The SOC trajectory results are seen in each case of Figure11.

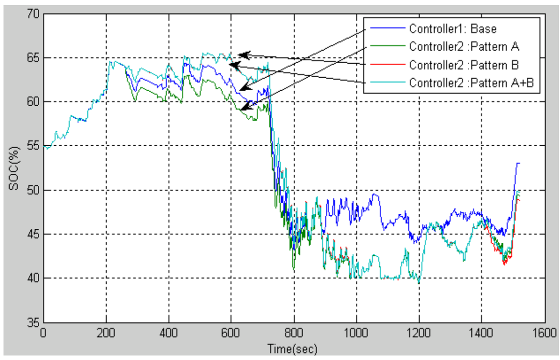


Figure11: SOC trajectories of the proposed control system applied with the rule-based controller1.2

Table3: Results of fuel economy in the simulation

Optimal FC(km/l) (Dynamic Programming)	12.424 (Initial: 55% final: 55%)
Controller1 (conventional)	11.059 (calibration)(*) (Initial: 55% final: 55%)
Controller2 (proposed)	
Pattern A (Speed info.)	11.121 (calibration) (Initial: 55% final: 55%) ***+0.56% (*)***

Pattern B (Slope info.)	11.208 (calibration) (Initial: 55% final: 55%) ***+1.35% (*)***
Pattern A+B	11.187 (calibration) (Initial: 55% final: 55%) ***+1.16% (*)***

** Standard*

6 Conclusions

This paper presents the hybrid vehicle control algorithm with GPS (navigation) system for vehicles travelling a pre-planned driving route. To verify fuel economy improvement, we developed the forward-facing simulator applicable to the proposed HEVs control system.

To predict the future state of a vehicle, the proposed HEV control system recognizes the future driving patterns from information on the terrain (uphill, downhill) and speed. The controller calculates the parameters during a sampled time in order to choose a driving cycle and to classify three driving modes (Urban/Extra-urban/Highway mode)

This rule-based controller commands manage the battery SOC according to an incoming target range. The target SOC range depends on pattern recognition during specific time period. Moreover, a dynamic programming approach was proposed to obtain the optimal fuel economy and the optimal? SOC trajectory. Dynamic programming is well-known for finding the best solution for optimal control of the HEV. In the simulation, ideal fuel efficiency can be expected to be approximately 4.84% enhancement. The optimal SOC trajectory at the transition of road section boundaries suggests rules of control strategy based on the ideas described. In addition, the backward-facing simulation (DP) and the forward-facing simulation results were compared to verify the reliability of the proposed forward-facing control system and vehicle components model. Compared with the conventional controller, the proposed control system gives results that confirm improved fuel economy, using road slope and speed information in the simulation.

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References

[1] Gerald D. conover, (2006). ITS Technology in Automotive - Who's on First?, SAE, 2006-01-0095.

[2] Erik Hellstrom, Anders Froberg, Lars Nielsen, A Real-Time Fuel-Optimal Cruise Controller for Heavy Trucks Using Road Topography Information, SAE, (2006). 2006-01-0008.

[3] Arun Rajagopalan, Gregory Washington, (2002). Intelligent Control of Hybrid Electric Vehicle Using GPS Information, SAE, 2002-01-1936

[4] Yoshitaka Deguchi, Kouichi Kuroda, Makoto Shouji, Taketosh Kawabe (2004). *HEV Charge / Discharge Control System Based on Navigation Information, SAE*, 2004-21-0028.

[5] Michiel Koot, J. T. B. A. Kessels, (2005). Energy Management Strategies for Vehicular Electric Power Systems, IEEE Transactions on vehicular technology

[6] A. Sciarretta, L. Guzzella, and M. Back, (2004). A real-time optimal control strategy for parallel hybrid vehicles with on-board estimation of control parameters, IFAC Symp.

[7] Cristian Musardo, Giorgio Rizzoni, Benedetto Staccia, (2005). *A-ECMS: An Adaptive Algorithm for Hybrid Electric Vehicle Energy Management,* IEEE Conference on Decision and Control.

[8] X. Wei, L. Guzzella, V. I. Utkin, G. Rizzoni, (2007*). Model-Based Fuel Optimal Control of Hybrid Electric Vehicle Using Variable Structure Control Systems*, Journal of Dynamic Systems, Measurement, and Control.

[9] S. Jeon, S. Jo, Y. Park, and J. Lee, (2002). Multi-mode driving control of a parallel hybrid electric vehicle using driving pattern recognition, ASME J. Dynamic Syst.

[10] S. DELPRAT, T.M. GUERRA, (2002). Control Strategies for Hybrid Vehicles: Optimal Control, *IEEE.*

[11] L. Buie, M. Fry, P. Fussey, and C. Mitts , (2004). An application of cost based power management control strategies to hybrid fuel cell vehicles, *SAE*, 2004-01-1299.

[12] V.H.Johnson, K.B.Wipke, and D.J. Rau, (2000). HEV control strategy for real-time optimization of fuel economy and emissions, *SAE*, 2000-01-154.

[13] Zhengmao Ye, (2003). Automotive Hybrid System Optimization using Dynamic Programming, *SAE*, 2003-01-0847.

Authors

Beomsoo Kim received bachelor's degree in School of Mechanical and Aerospace Engineering from Seoul National University, South Korea, in 2003. He is currently working towards Ph.D. degree in School of Mechanical and Aerospace Engineering at the Seoul National University. His research interests are modelling and control of dynamic driveline systems.

Yong-gi, Kim is a senior research engineer of HEV System Test Team at Hyundai Motor Company. He joined Hyundai Motor Company in 1997 and has been working on HEV system engineering since 2003.
He received his mechanical engineering degree at the Seoul National University in Seoul, Korea, in 1997.

Talchol Kim received a Ph.D. degree in mechanical engineering from The Sungkyunkwan University, Korea, in 2000.
Since 2000, he has worked as a senior research engineer of Hyundai-Motor company.
His main research interest in system of HEV, plug-in HEV and control strategy of HEV.

Yeong-il Park received bachelor's degree in Department of Mechanical Engineering from Seoul National University, South Korea, in 1979. The M.S. and the Ph.D. degree in Department of Mechanical Engineering from Seoul National University, in 1981 and 1991, respectively.
From 1995 to 1996, he was Visiting Scholar in Department of Mechanical Engineering, Michigan University. He was Visiting Professor in Department of Mechanical Engineering, The Pacific University from 2005 to 2006. His research interests are dynamic system of vehicle, hybrid vehicle control system and driveline system.

Suk Won Cha received bachelor's degree in Department of Naval Architecture and Ocean Engineering from Seoul National University, South Korea, in 1994. The M.S. and the Ph.D. degree in Department of Mechanical Engineering from Stanford University, in 1999 and 2004, respectively.
From 2003 to 2005, he was a Research Associate in Department of Mechanical Engineering, Stanford University. He is currently an Assistant Professor in School of Mechanical and Aerospace Engineering, Seoul National University. His research interests are fuel cell systems, design of hybrid vehicle systems and application of nanotechnology to energy conversion devices.