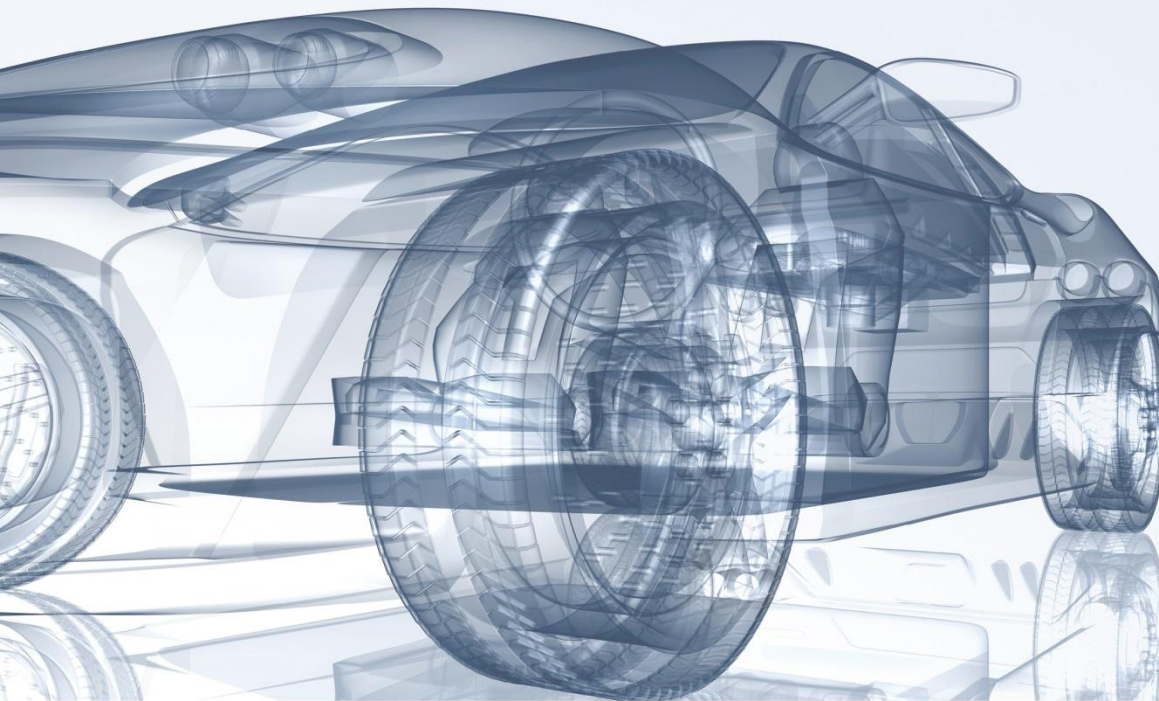


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# Development of Integrated Power Control Algorithm for a Series-Parallel Type PHEV

10 October 2017

Sungbae Jeon, Junbeom Wi, Yoonuk Kim, Jiho Yoo, Hyunsoo Kim

**Dynamic System Design Lab**



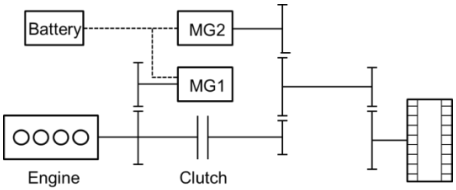
# Contents

- **Introduction**
- **Development of forward simulator for the target PHEV**
- **Development of backward simulator for the target PHEV**
- **Integrated battery energy-vehicle power control algorithm**
- **Conclusions**

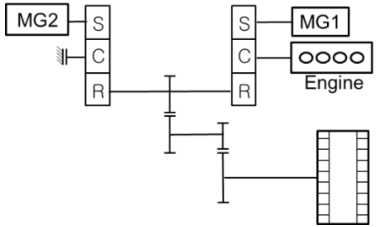
- **Introduction**
- Development of forward simulator for the target PHEV
- Development of backward simulator for the target PHEV
- Integrated battery energy-vehicle power control algorithm
- **Conclusions**

## What affects PHEV performance?

### Powertrain configuration

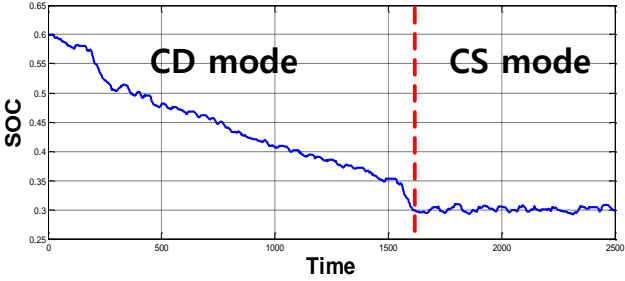


<Series-parallel type PHEV configuration>

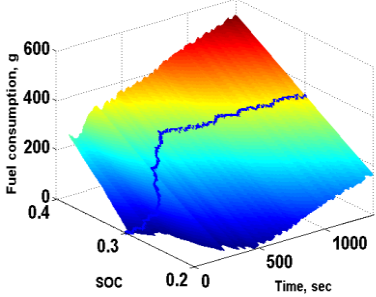


<Power-split type PHEV configuration>

### Control strategy



<Charge depleting-Charge sustaining(CD-CS) control>

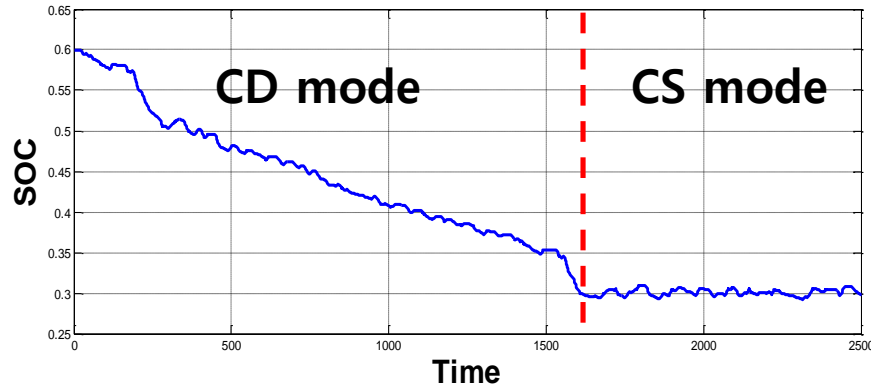


<Dynamic programming>

# Introduction

## Control strategy

- CD-CS control



- Optimal control

- ✓ Optimal results
- ✓ Long computation time

→ It is necessary to develop a novel control algorithm which can be applied in real time environment to improve the fuel economy of the PHEV.

# Introduction

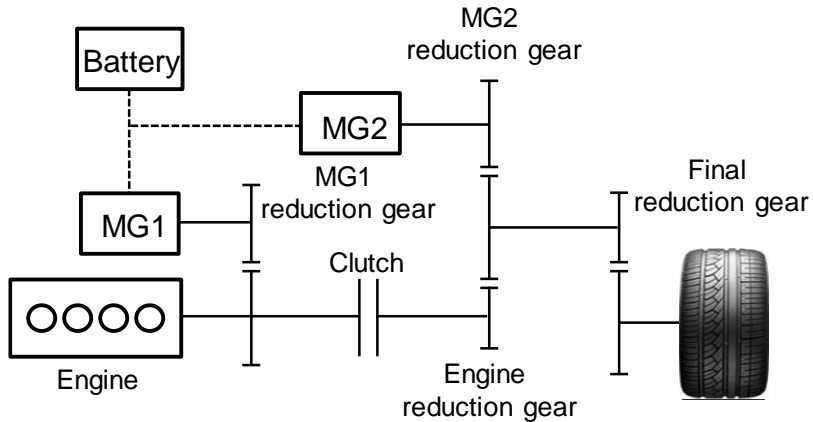
## Purpose of this study

- **Develop a forward simulator based on dynamic model of the target PHEV**
- **Develop the backward simulator for the target PHEV using dynamic programming**
- **Develop an integrated battery energy-vehicle power control algorithm**
- **Evaluate the integrated battery energy-vehicle power control algorithm**

- Introduction
- **Development of forward simulator for the target PHEV**
- Development of backward simulator for the target PHEV
- Integrated battery energy-vehicle power control algorithm
- Conclusions

# Development of forward simulator for the target PHEV

## Configuration and specification of the target PHEV



<Configuration of the target PHEV>

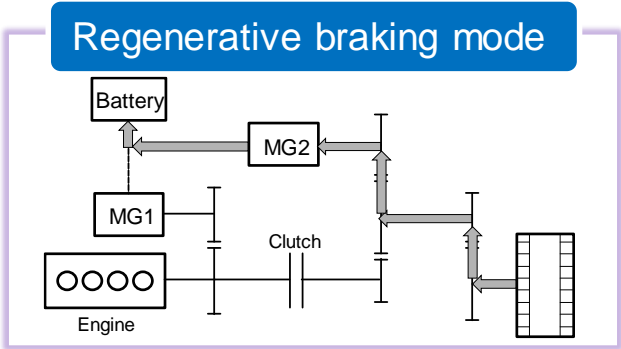
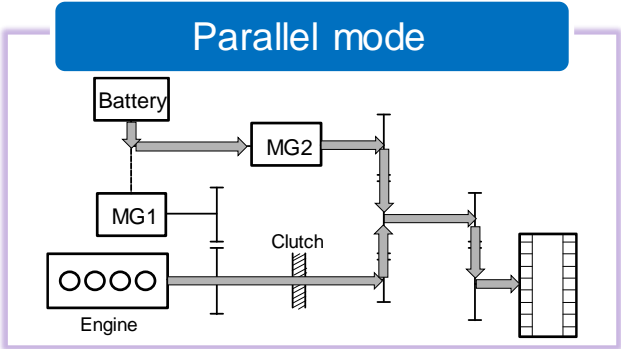
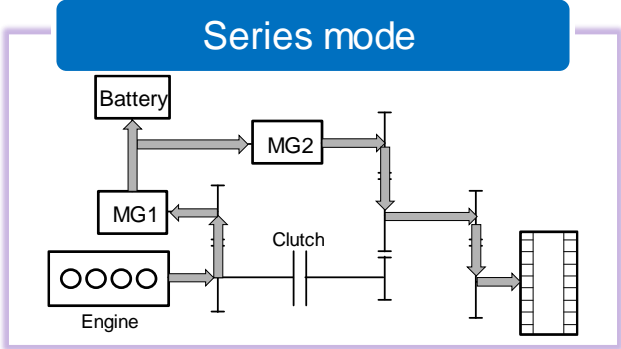
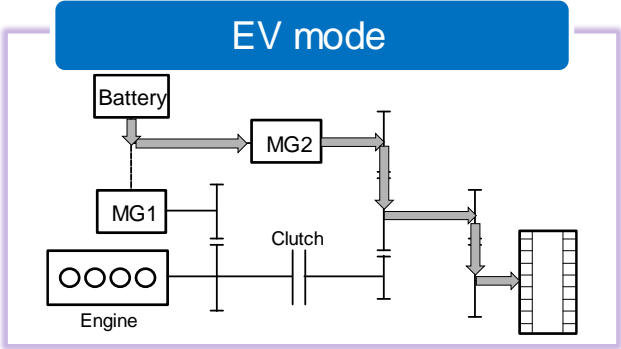
	Item	specification
Engine	Max. speed	6000rpm
	Max. torque	169Nm
	Max. power	102kW
MG2	Max. speed	12584rpm
	Max. torque	307Nm
	Max. power	124kW
MG1	Max. speed	10380rpm
	Max. torque	109Nm
	Max. power	118kW
Vehicle	MG2 reduction gear ratio	2.48
	MG1 reduction gear ratio	1.73
	Engine reduction gear ratio	0.738
	Final reduction gear ratio	3.5
	Vehicle mass	1800kg
	Tire radius	0.32m

<Specification of the target PHEV>

# Development of forward simulator for the target PHEV



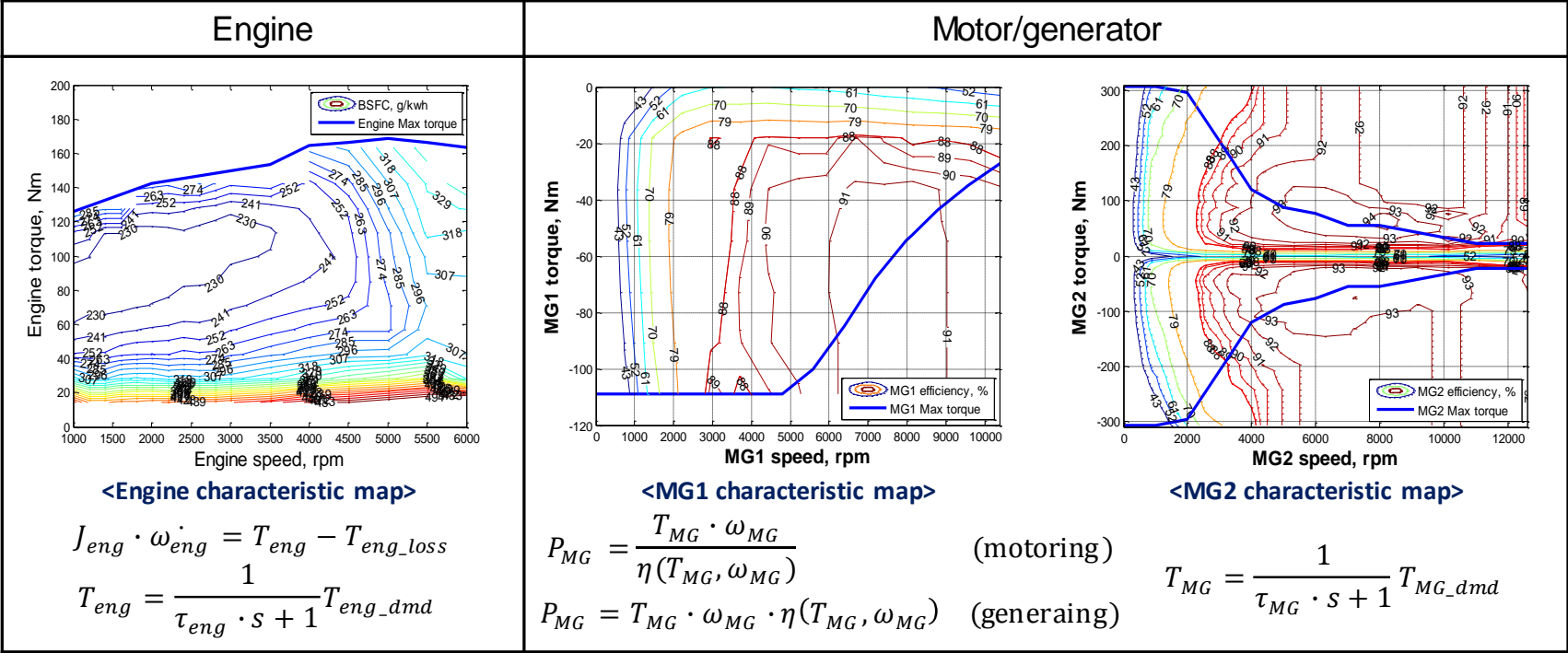
## Driving modes of the target PHEV



# Development of forward simulator for the target PHEV

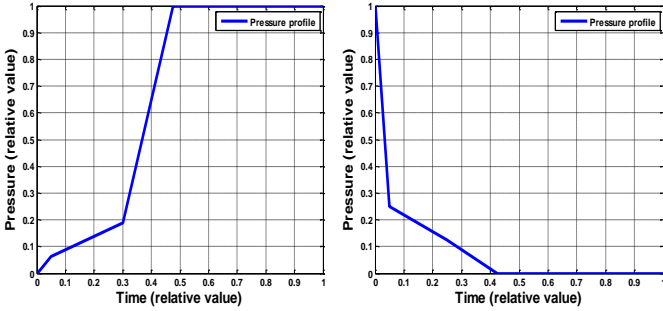


## Powertrain model



# Development of forward simulator for the target PHEV

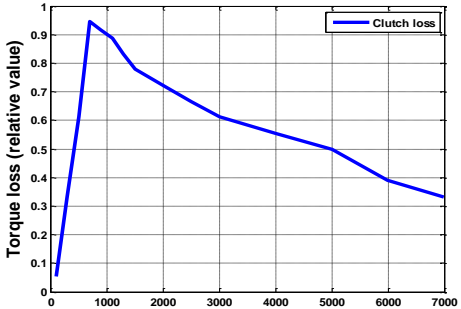
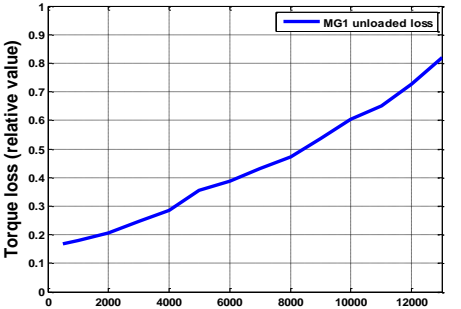
## Powertrain model

Clutch	Battery	Vehicle
<div data-bbox="115 434 782 748">  </div> <ul style="list-style-type: none"> <li>The clutch engagement is determined by the pressure</li> </ul>	<ul style="list-style-type: none"> <li>SOC(state of charge) is assumed by the current integration method</li> </ul> $SOC = SOC_{ini} - \frac{1}{C_{bat}} \int_{t_{ini}}^t \frac{P_{bat}}{V_{bat}} dt$ <ul style="list-style-type: none"> <li>The voltage is calculated using the open circuit voltage and internal resistance</li> </ul> $V_{bat} = V_{OC} - R_{bat} \cdot I_{bat}$ $I_{bat} = \frac{P_{bat}}{V_{bat}}$	<ul style="list-style-type: none"> <li>The vehicle longitudinal dynamics</li> </ul> $M \cdot \dot{v} = F_T - F_b - F_{road}$ <ul style="list-style-type: none"> <li>The coast-down test road load coefficients are used</li> </ul> $F_{road} = F_{coast-down} + F_{grade}$ $F_{coast-down} = f_0 + f_1 \cdot v + f_2 \cdot v^2$ $F_{grade} = M \cdot g \cdot \sin\theta$

# Development of forward simulator for the target PHEV



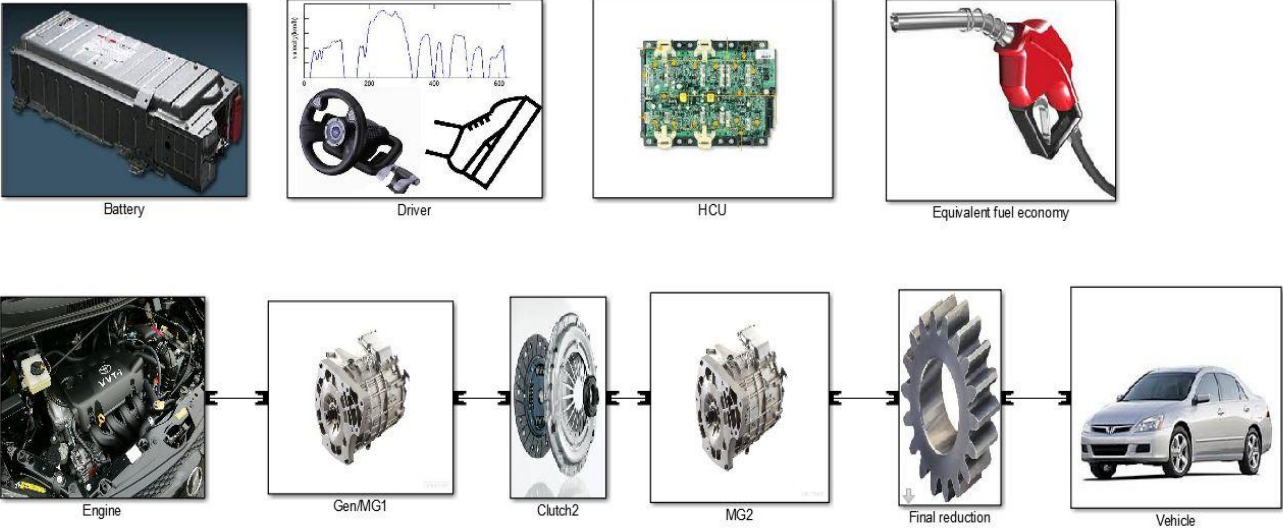
## Mechanical element loss model

Gear loss model	Clutch loss model	MG1 unloaded loss model
$T_{gear\_loss} = T_{in} \cdot (1 - \eta_{gear}) \cdot sign(P_{in})$ <ul style="list-style-type: none"> <li>The gear torque loss is assumed to be 1% of the transmitted torque</li> </ul>	 <p style="text-align: center;">&lt;Clutch loss map&gt;</p> $T_{clu\_loss} = 2 \cdot \pi \cdot N_f \int_{r_i}^{r_o} \alpha \frac{\mu r^3}{h} \omega_{rel} C_f dr$	 <p style="text-align: center;">&lt;MG1 loss map&gt;</p> <ul style="list-style-type: none"> <li>Since the MG1 rotates by the engine, and the MG1 unloaded loss occurs in the parallel mode</li> </ul>

# Development of forward simulator for the target PHEV



## Forward simulator



<Forward simulator of Series-Parallel type PHEV>

- Introduction
- Development of forward simulator for the target PHEV
- **Development of backward simulator for the target PHEV**
- Integrated battery energy-vehicle power control algorithm
- Conclusions

# Development of backward simulator for the target PHEV



## Dynamic programming

### Local optimization

- Series mode :

$$P_{bat} = f(T_{MG1}, \omega_{MG1}, T_{MG2}, \omega_{MG2}) = f(T_{eng}, \omega_{eng})$$

- Parallel mode :

$$P_{bat} = f(T_{MG2}, \omega_{MG2}) = f(T_{eng}, \omega_{eng})$$

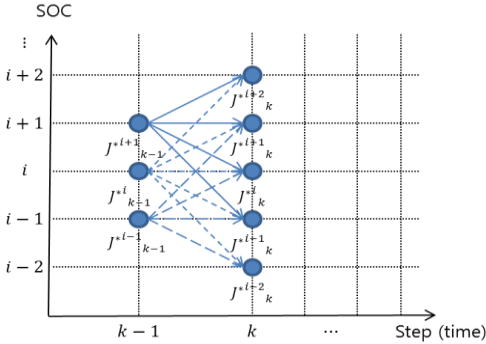
- Local optimization :

$$m_{fuel} = L(T_{eng}^*, \omega_{eng}^*) = g(P_{bat})$$

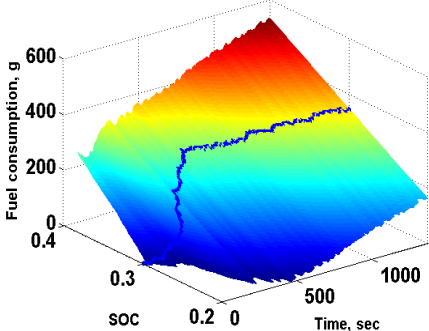
### Global optimization

Minimize  $J_k^*(x_k) = g_{k-1}(P_{bat}(k-1), Mode) + J_{k-1}^*(x_{k-1})$

Subject to  $\Delta SOC(k-1) = f(P_{bat}(k-1), Mode(k-1)), k = 2, 3, \dots, N$



<Optimal field>



<Optimal trajectory>

# Development of backward simulator for the target PHEV



## Backward simulator

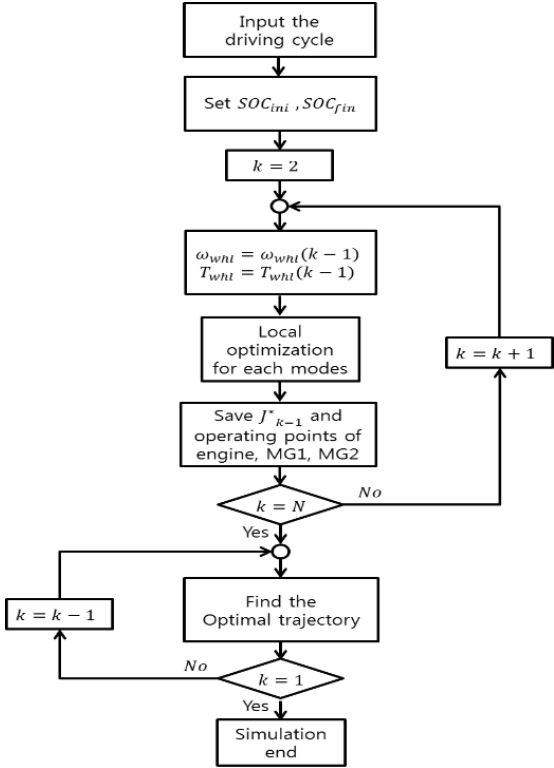
Set the driving cycle, initial and final SOC



Search the optimal SOC trajectory



Find the optimal mode  
for the demanded wheel torque and vehicle speed

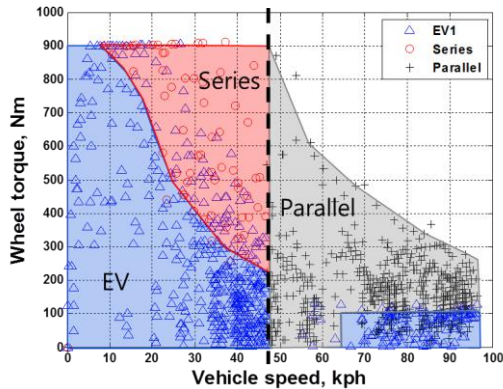


<Backward simulator flow chart>

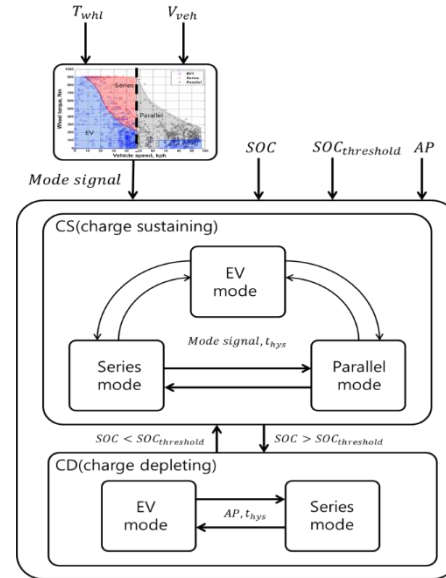
# Development of backward simulator for the target PHEV

## Mode shift map

- The mode shift map obtained by the backward simulation results was applied to the forward simulator



<Driving mode for UDDS and HWFET cycle>



<Mode change strategy>

- Introduction
- Development of forward simulator for the target PHEV
- Development of backward simulator for the target PHEV
- **Integrated battery energy-vehicle power control algorithm**
- Conclusions

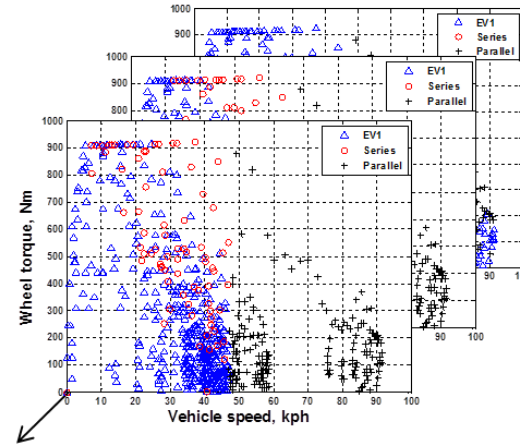
## The target SOC rate

$$\dot{SOC}_{target} = \frac{SOC - SOC_{final}}{\Delta t_{destination}}$$

$\dot{SOC}_{target}$  →

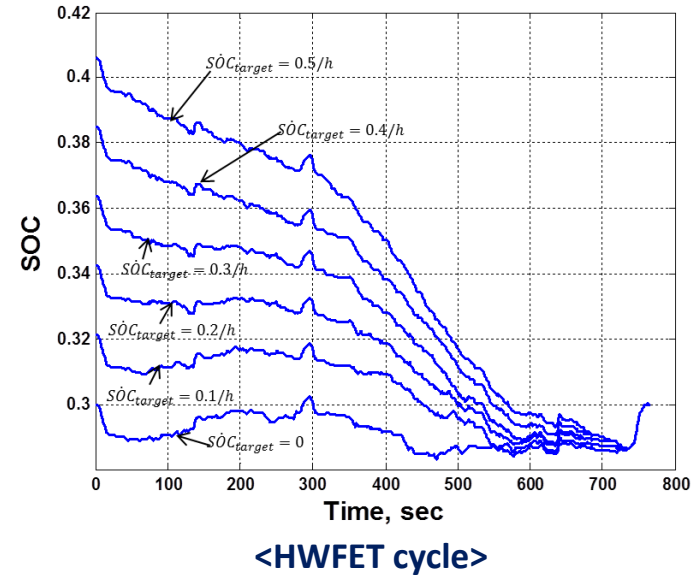
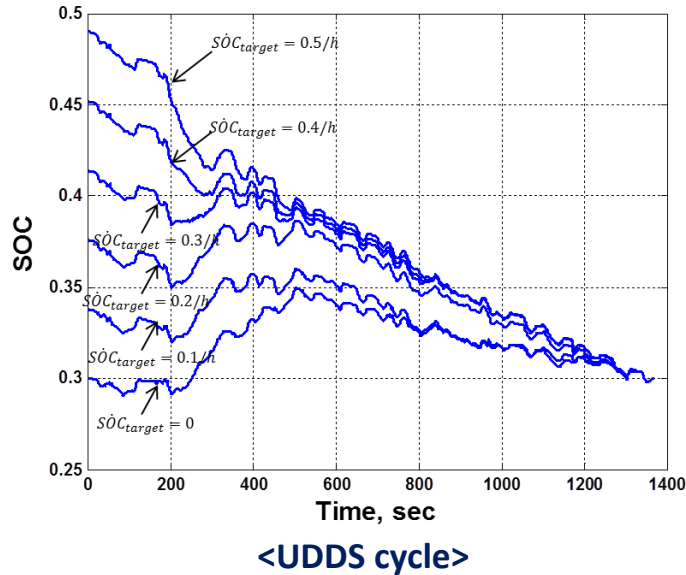
$T_{whl}$  →

$V_{veh}$  →



- If the remaining time to destination can be obtained by the navigation, the SOC rate can be calculated.

## Backward simulation results for various target SOC rate

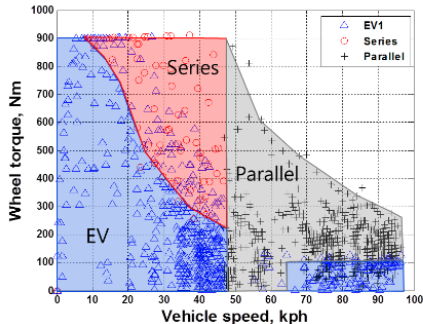


- The backward simulations were performed for the target SOC rate range 0/h to 0.5/h for UDDS cycle(city cycle) and HWFET cycle(highway cycle).

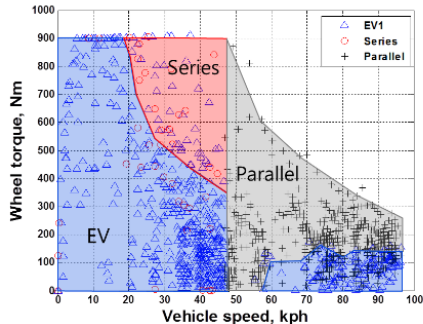
# Integrated battery energy-vehicle power control algorithm



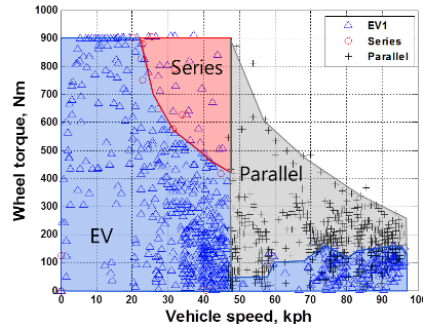
## Mode shift map for various target SOC rate



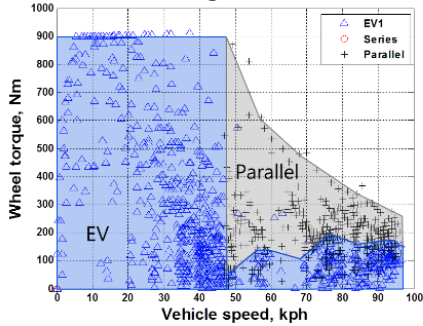
$\langle \dot{SOC}_{target} = 0/h \rangle$



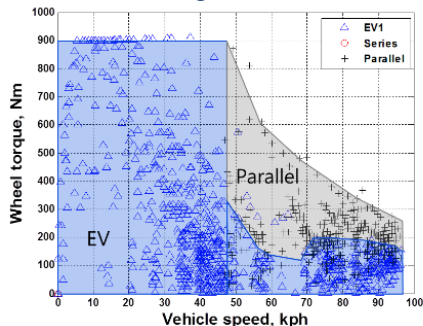
$\langle \dot{SOC}_{target} = 0.1/h \rangle$



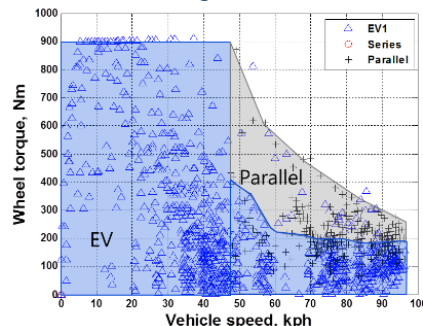
$\langle \dot{SOC}_{target} = 0.2/h \rangle$



$\langle \dot{SOC}_{target} = 0.3/h \rangle$



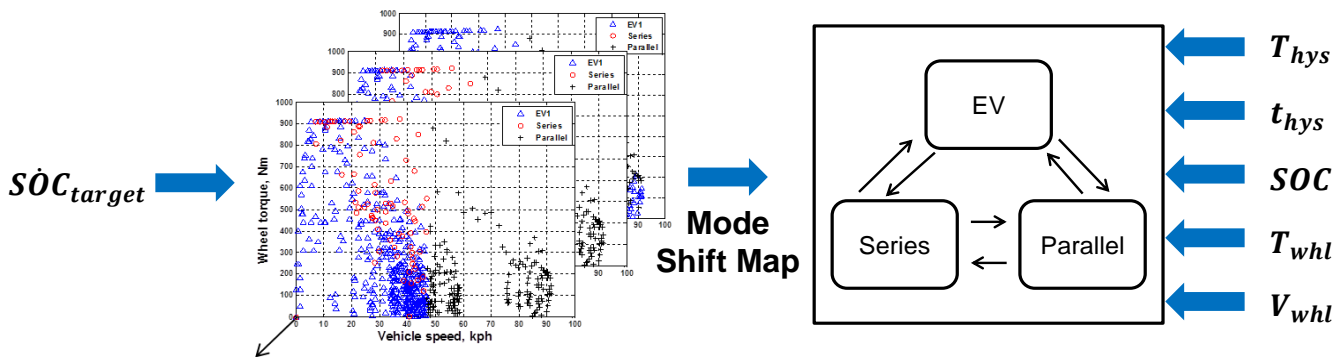
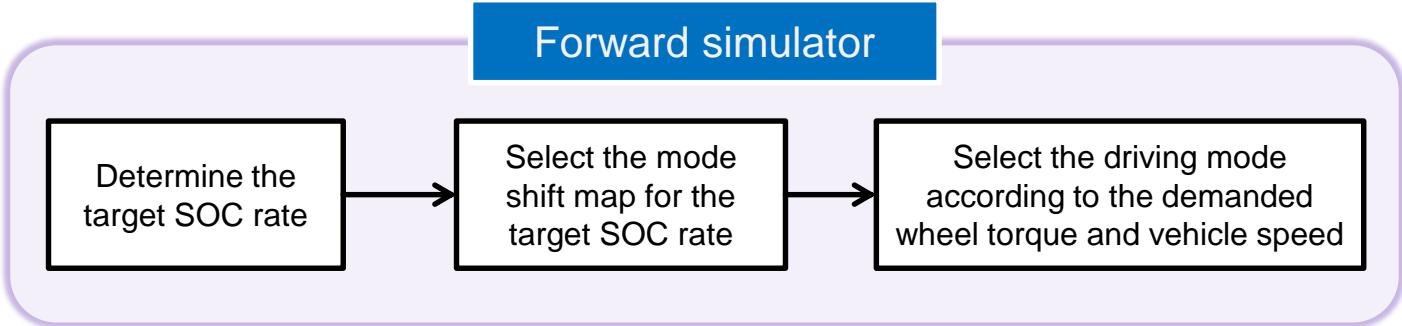
$\langle \dot{SOC}_{target} = 0.4/h \rangle$



$\langle \dot{SOC}_{target} = 0.5/h \rangle$

# Integrated battery energy-vehicle power control algorithm

## Development of integrated control



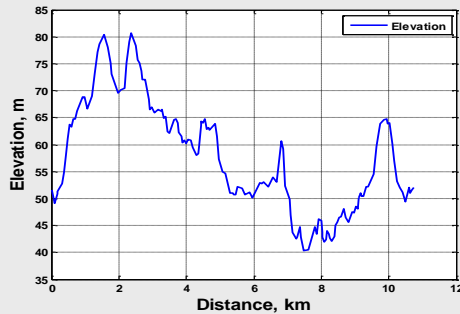
# Integrated battery energy-vehicle power control algorithm

## Comparison of the integrated control with CD-CS control for real route

SKKU#1 route



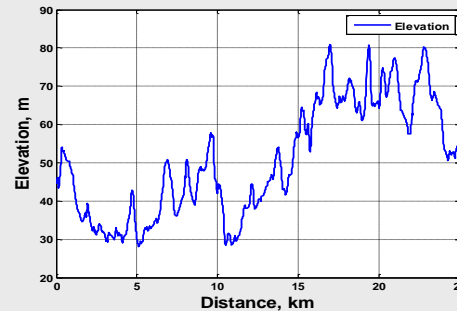
10.73km



SKKU#2 route



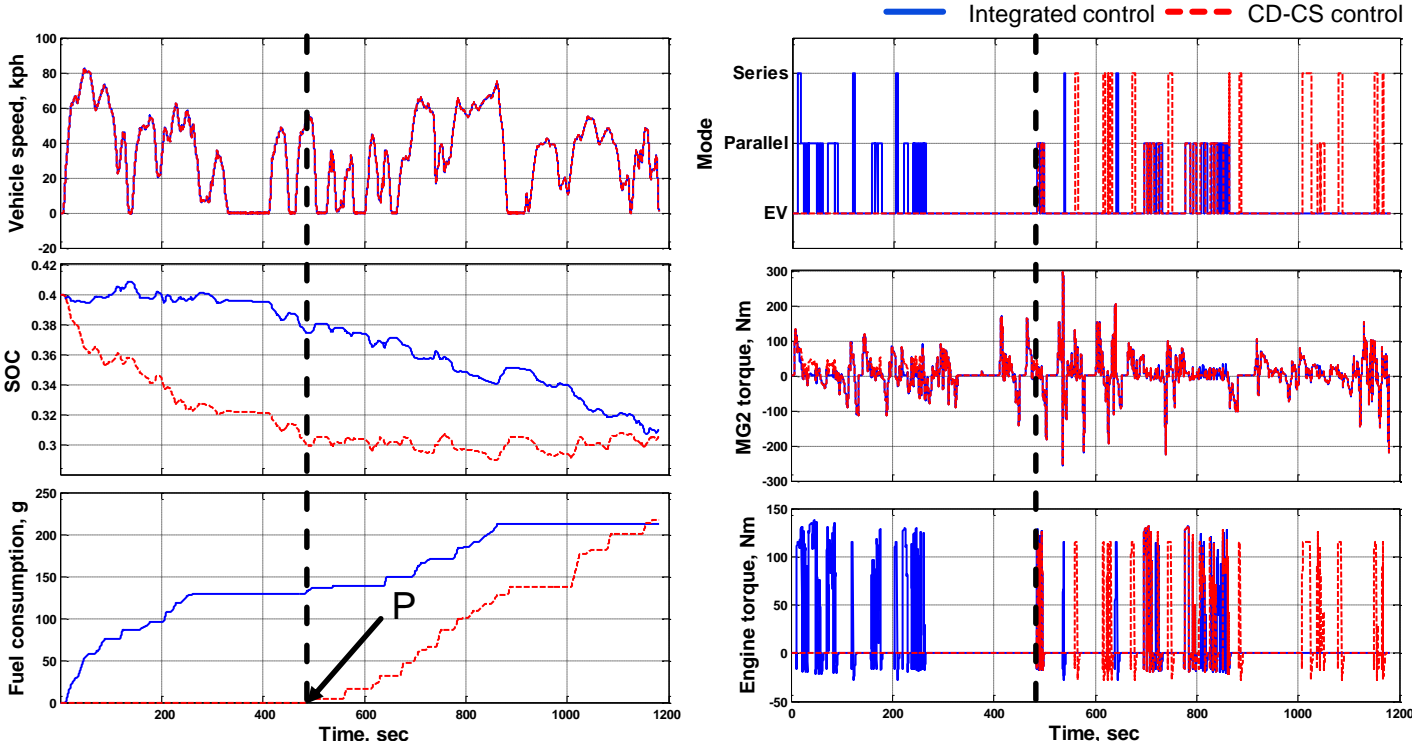
25.00km



# Integrated battery energy-vehicle power control algorithm



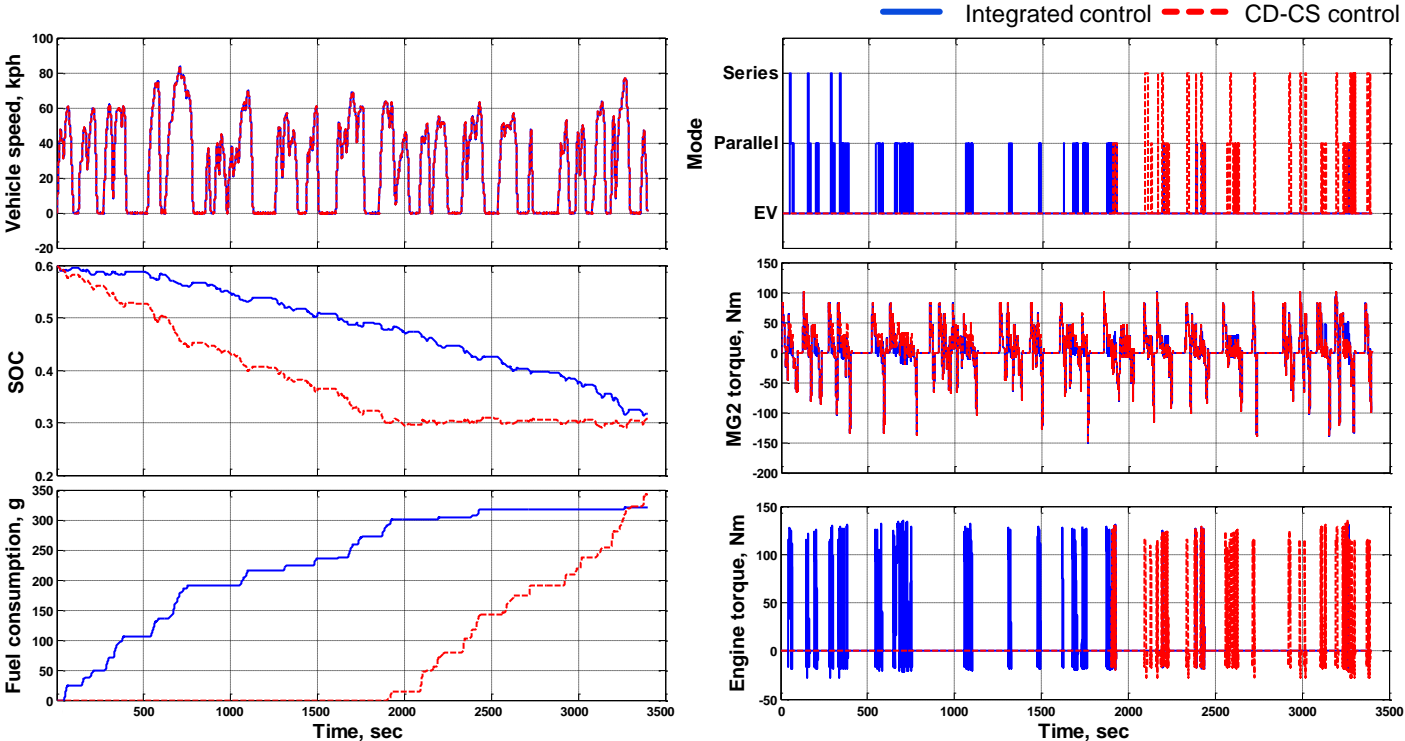
## Simulation results when vehicle driving SKKU#1



# Integrated battery energy-vehicle power control algorithm



## Simulation results when vehicle driving SKKU#2



# Integrated battery energy-vehicle power control algorithm

## Comparison of the integrated control with CD-CS control for real route

Cycle		Fuel consumption (g)	Final SOC (%)	Equivalent fuel economy (km/l)	Improvement rate (%)
SKKU#1 route	CD-CS	217.2	30.48	21.98	-
	Integrated	212.5	30.96	22.73	+3.4
SKKU#2 route	CD-CS	341.9	30.69	23.54	-
	Integrated	321.6	31.80	24.70	+4.7

- **Introduction**
- **Development of forward simulator for the target PHEV**
- **Development of backward simulator for the target PHEV**
- **Integrated battery energy-vehicle power control algorithm**
- **Conclusions**

- **The integrated battery energy-vehicle power control algorithm was proposed for a series-parallel type PHEV using the powertrain model and dynamic programming.**
- **The performance of the integrated control algorithm was evaluated by comparing with the existing CD-CS control. The fuel economy of a proposed control algorithm was improved fuel economy by 3.4%, 4.7% for SKKU#1 and SKKU#2 route.**
- **It is expected that the integrated control algorithm can be applied in real time environment since it only requires the present SOC and the remaining time to the destination**



**THANK YOU**