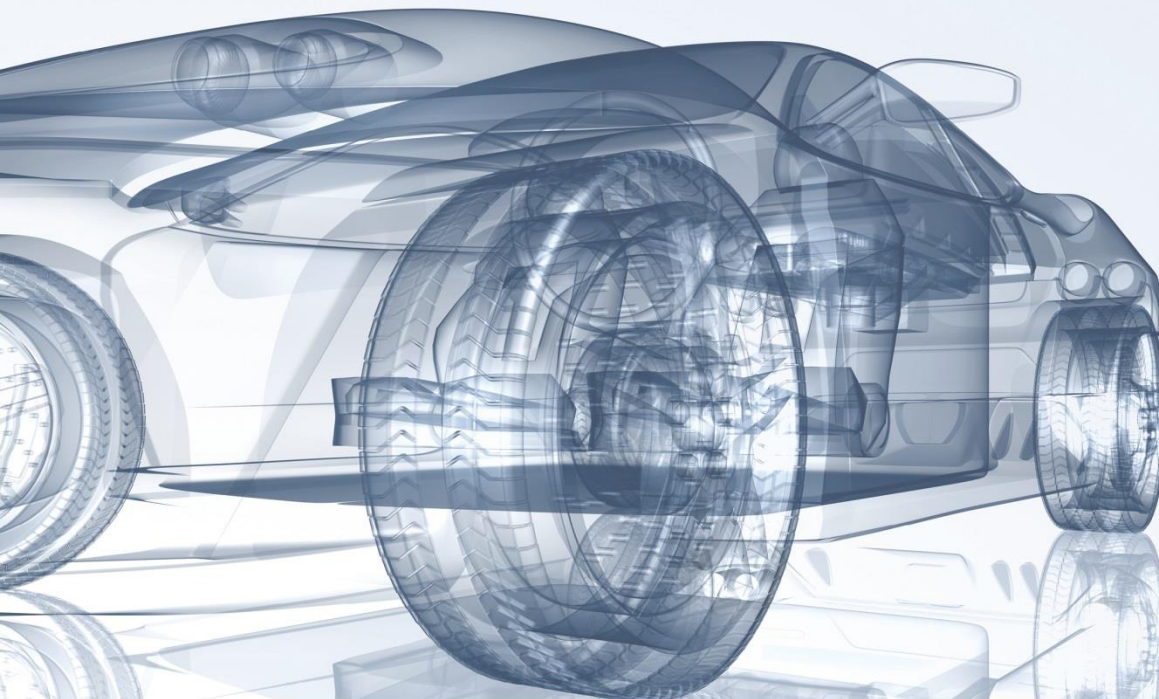


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Comparative Analysis of Power Characteristics for Volt PHEV Considering Drivetrain Losses

2017. 10. 10.

Hyunhwa Kim

Dynamic System Design Lab

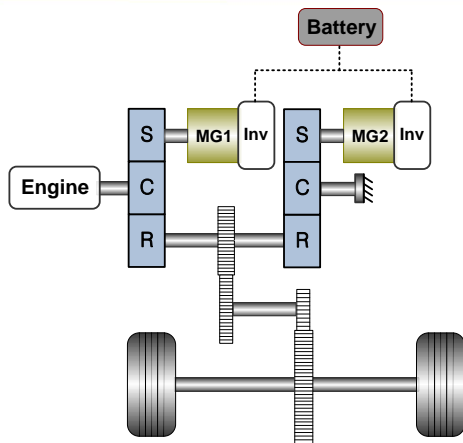


- **Introduction**
- **Network analysis and power characteristics**
- **Mode shift map by dynamic programming**
- **Comparative analysis of Volt 1 and Volt 2**
- **Conclusions**

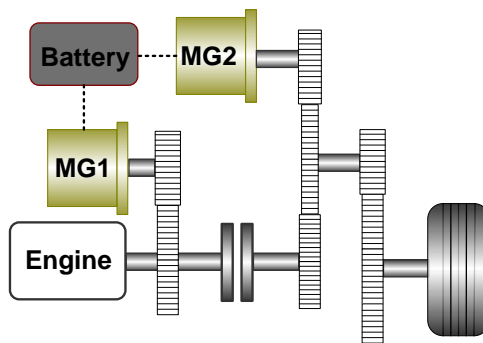
Introduction

Introduction

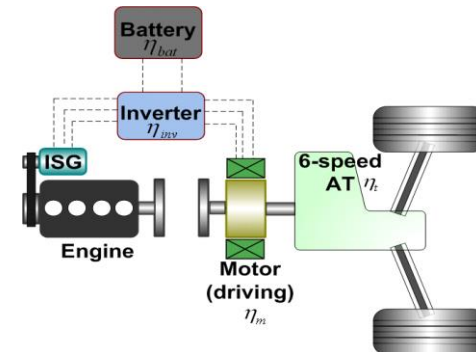
Background



< Toyota Prius >



< Honda i-MMD >



< Hyundai TMED >

Number of driving mode \uparrow

\rightarrow Fuel economy \uparrow \rightarrow Vehicle performance \uparrow : (+) effect

\rightarrow Number of components \uparrow \rightarrow Fuel economy \downarrow : (-) effect

- ✓ Positive effect by the additional modes and negative effect by the drivetrain element losses need to be evaluated for development of a new PHEV.

Introduction

Purpose of the study

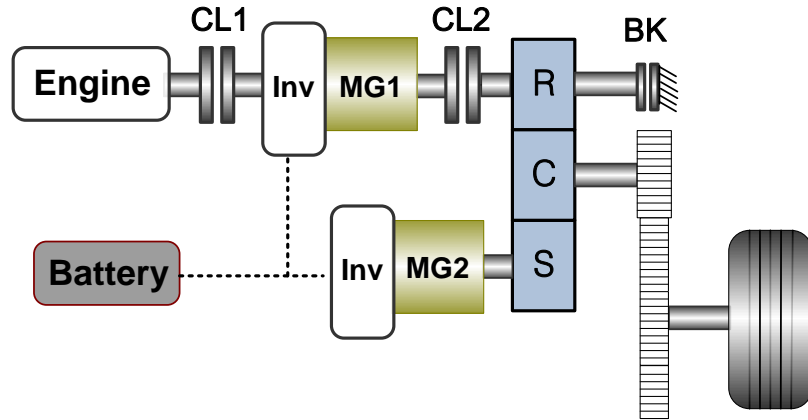


- Perform network analysis considering drivetrain losses
- Develop a backward simulator based on dynamic programming
- Analyze system efficiency, fuel economy and losses

■ Network analysis and power characteristics

Network analysis and power characteristics

Structure and specifications of the target PHEV – Volt 1



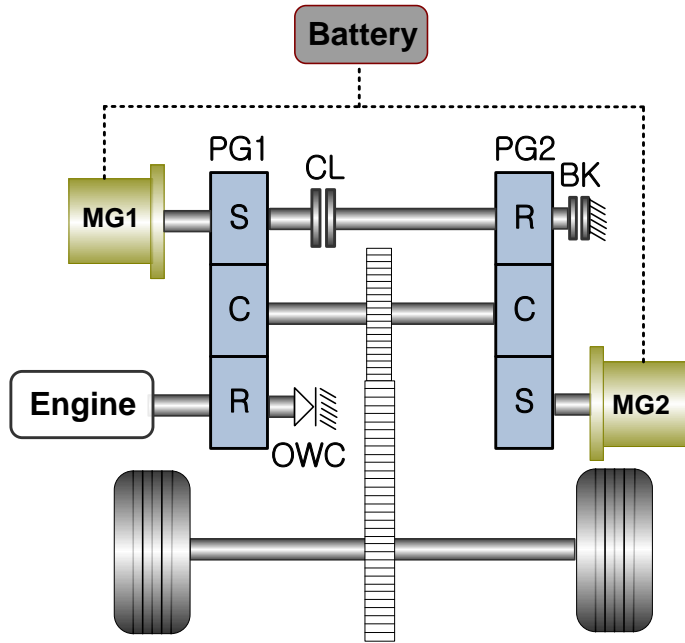
<Structure of Volt 1>

	CL1	CL2	BK
EV#1			○
EV#2		○	
Power split	○	○	
Series	○		○

○: engage

Network analysis and power characteristics

Structure and specifications of the target PHEV – Volt 2



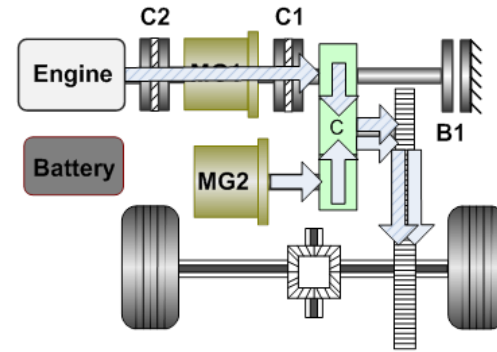
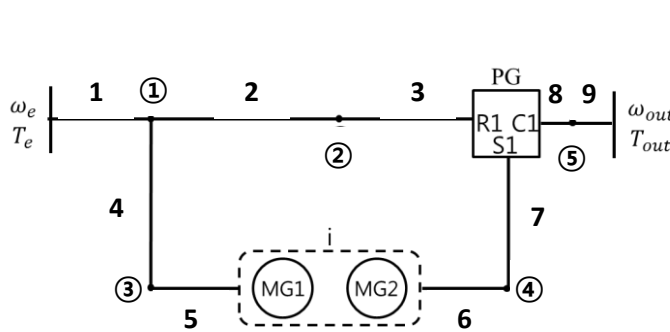
<Structure of Volt 2>

	CL	BK	OWC
One motor EV		○	
Two motor EV		○	○
Low extended range		○	
Fixes ratio extended range	○	○	
High extended range	○		

○: engage

Network analysis and power characteristics

Network analysis



< Network analysis model of power split mode >

$$[M_T] \cdot \vec{T} = \vec{\beta}_T$$

$$[M_\omega] \cdot \vec{\omega} = \vec{\beta}_\omega$$

- $[M_T], [M_\omega]$: relationships between the torque and speed of each node
- $\vec{T}, \vec{\omega}$: torque and speed matrices
- $\vec{\beta}_T, \vec{\beta}_\omega$: boundary vectors, or the input torque and speed

Network analysis and power characteristics

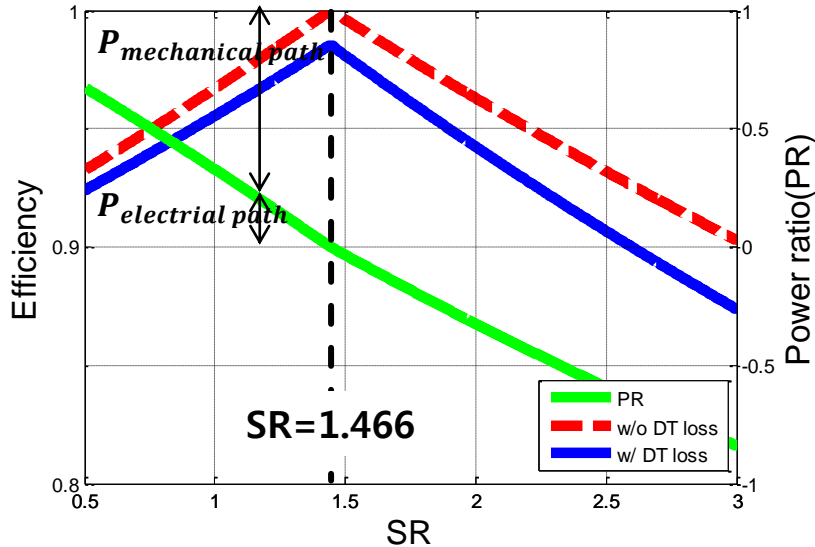
Assumptions for network analysis

- Fixed engine operation point
 - Volt 1 : 2000rpm, 90Nm
 - Volt 2 : 3000rpm, 90Nm
- Battery power : 0
- Only power electronics(PE) and planetary gears(PG) loss are considered
 - ✓ Efficiency of MG1 and MG2 : 90%

- ✓ Efficiency of planetary gears :
$$\begin{cases} 0.979 & \text{for Sun - Ring} \\ 1 - \frac{Z_r}{Z_r + Z_s} \cdot 0.021 & \text{for Sun - Carrier} \\ 1 - \frac{Z_s}{Z_r + Z_s} \cdot 0.021 & \text{for Carrier - Ring} \end{cases}$$

Network analysis and power characteristics

Results for Volt 1 power split mode (output split)

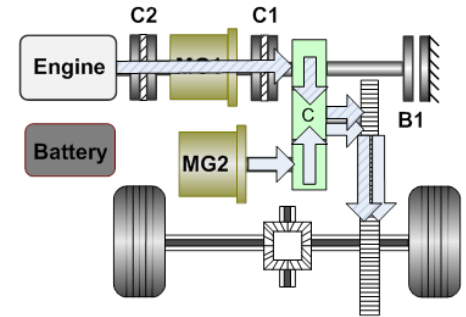


High ← Vehicle speed → Low

$$* SR = \frac{\omega_{engine}}{\omega_{output}}$$

$$* PR = \frac{Power_{electrical\ path}}{Power_{engine}}$$

< Power split mode network analysis model >

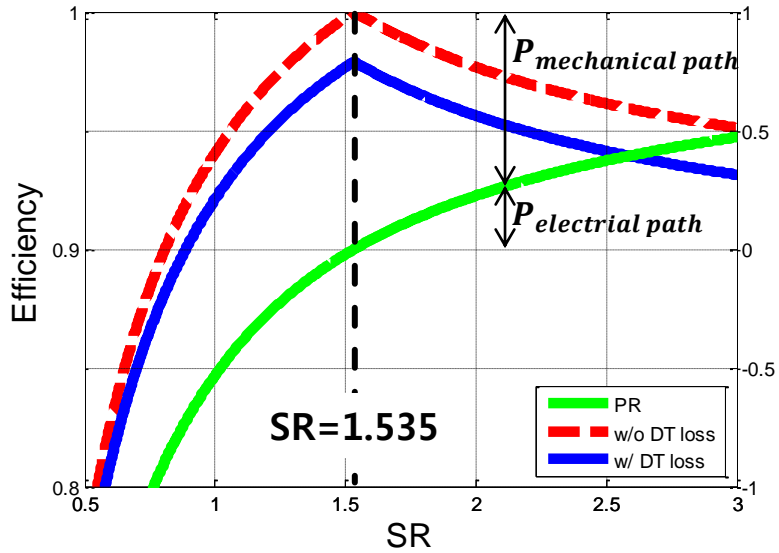


SR=1.466	w/o DT loss	w/ DT loss
System efficiency	100 %	98.6 %

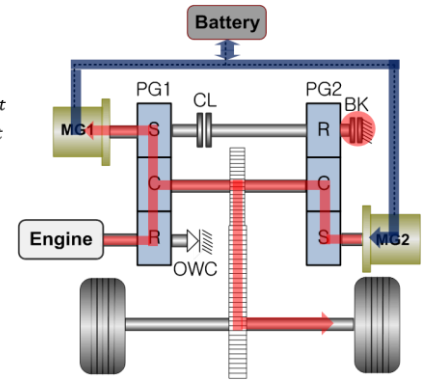
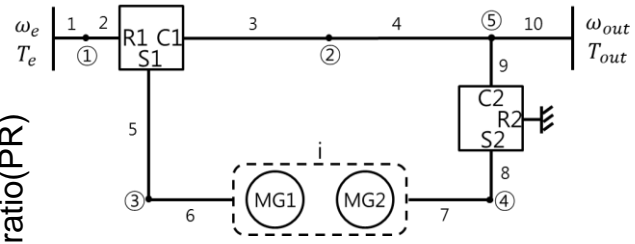
< System efficiency at the mechanical point >

Network analysis and power characteristics

Results for Volt 2 low extended range mode (input split)



Power ratio (PR)



< Low extended range mode network analysis model >

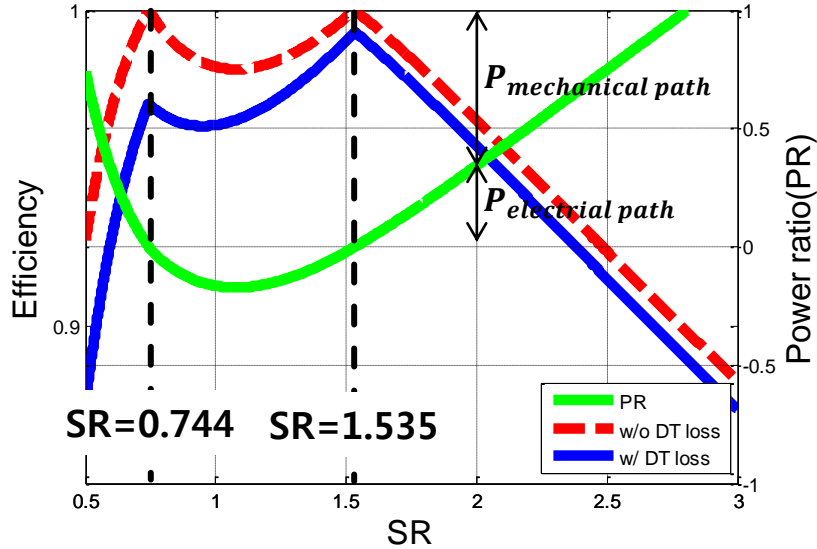
SR=1.535	w/o DT loss	w/ DT loss
System efficiency	100 %	97.9 %

< System efficiency at the mechanical point >

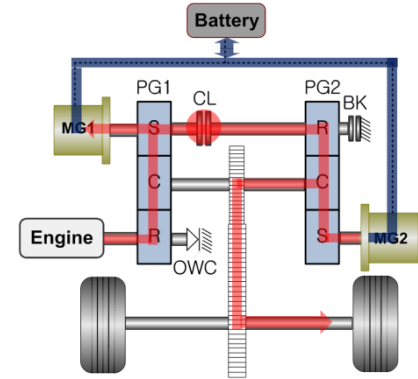
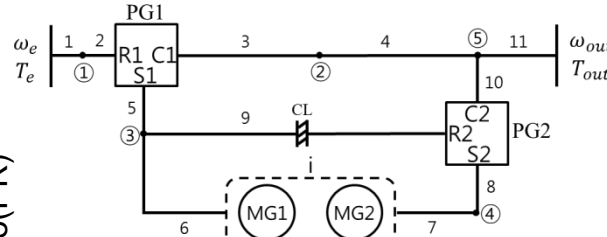
High ← Vehicle speed → Low

Network analysis and power characteristics

Results for Volt 2 high extended range mode(compound split)



High ← Vehicle speed → Low



< High extended range mode network analysis model >

System efficiency	w/o DT loss	w/ DT loss
SR=0.744	100 %	97.0 %
SR=1.535	100 %	99.3 %

< System efficiency at the mechanical points >

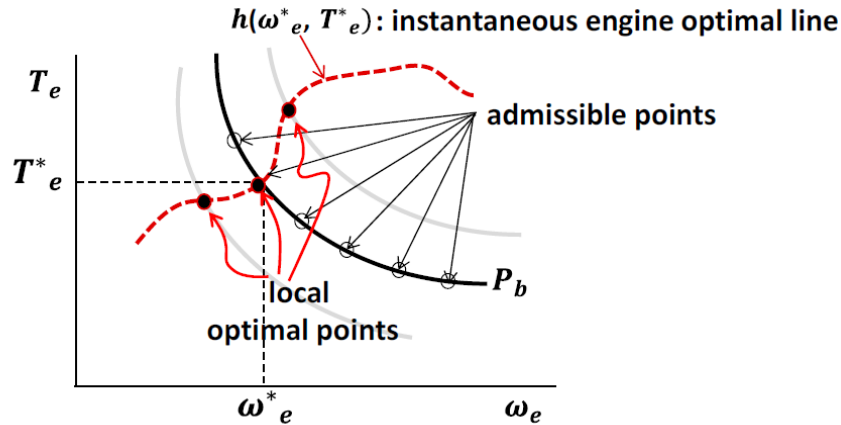
Mode shift map by dynamic programming

Mode shift map by dynamic programming

Dynamic programming considering drivetrain losses*

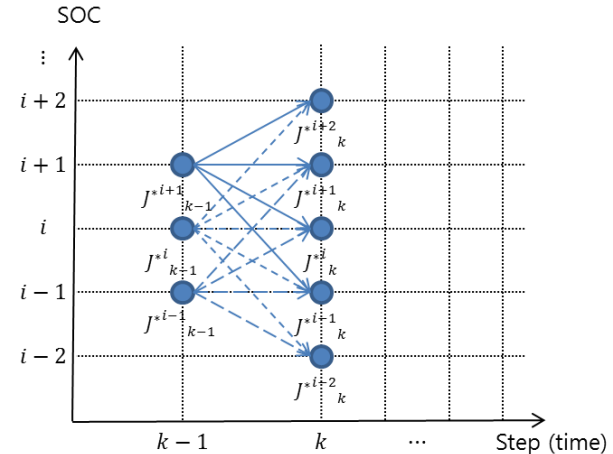
1) Local optimization

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



2) Global optimization

$$J_k^*(x_k) = g_{k-1}(P_{batt}(k-1)) + J_{k-1}^*(SOC(k-1))$$



* H.Son, K. Park, S. Hwang and H. Kim, *Design methodology of a power split type plug-in hybrid electric vehicle considering drivetrain losses*, Energies 2017, 10(4), 437, 2017

Mode shift map by dynamic programming

Dynamic programming considering drivetrain losses



Loss model*

1) Power electronics

- Motor loss : $T_{loss_MGs} = sign(P_{mech_{MG}}) \times (\eta_{MG}^k - 1) \times T_{MG} \times \omega_{MG}^k$

2) Drivetrain components

- Planetary gear :

$$T_{loss_PG} = 0.021(Sun - Ring), \frac{Z_r}{Z_r + Z_s} \cdot 0.021(Sun - Carrier), \frac{Z_s}{Z_r + Z_s} \cdot 0.021(Crrier - Ring)$$

- Gear loss : $T_{gear_loss} = T_{in} \cdot (1 - \eta_{gear}) \cdot sign(P_{in})$
- Churning loss : $T_{loss_churning} = f(geometry, lubricant, dynamics)$
- Brake, Clutch
- One-way clutch

* H.Son and H. Kim, *Development of near optimal rule-based control for plug-in hybrid electric vehicle taking into account drivetrain losses*, Energies 2016, 9, 420, 2016

Mode shift map by dynamic programming

Dynamic programming considering drivetrain losses



Specifications of Volt 1

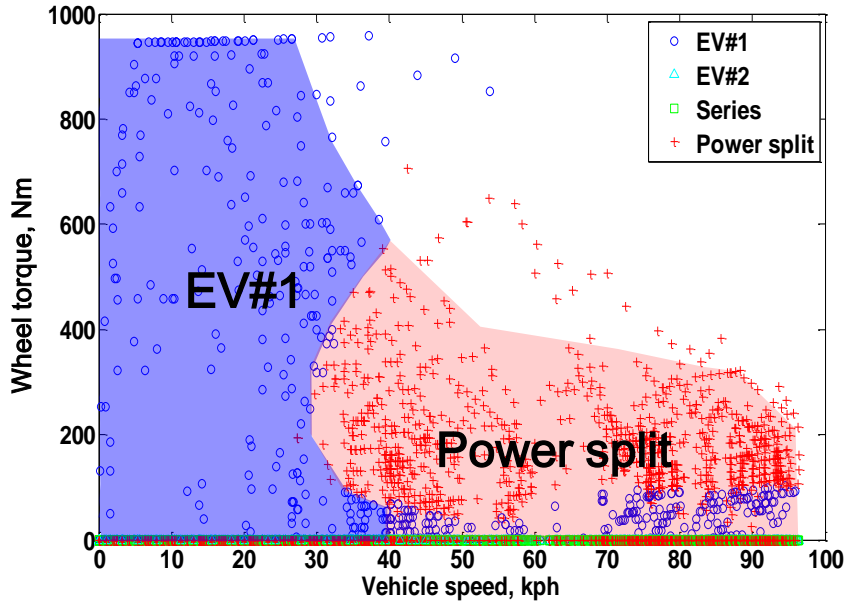
	Item	Specification
Engine	Max output	63kW/127Nm
MG2	Max power	111kW
	Max torque	370Nm
MG1	Max power	55kW
	Max torque	186Nm
Battery	Capacity	16.5kWh
Vehicle	Final reduction gear ratio	2.16
	Planetary gear ratio	3.38
	Mass	1721kg

Specifications of Volt 2

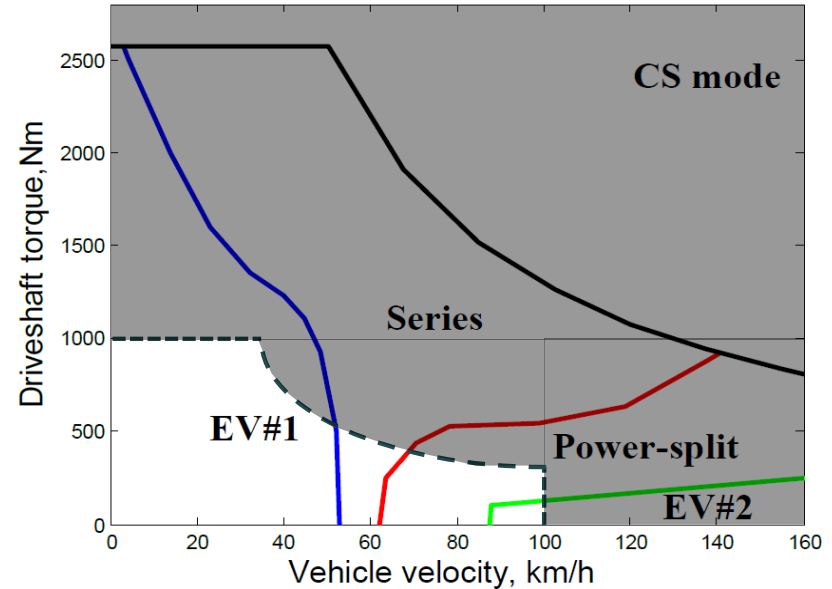
	Item	Specification
Engine	Max output	75kW/140Nm
MG2	Max power	87kW
	Max torque	280Nm
MG1	Max power	48kW
	Max torque	118Nm
Battery	Capacity	18.4kWh
Vehicle	Final reduction gear ratio	2.64
	Planetary gear ratio	2.87/3.077
	Mass	1672kg

Mode shift map by dynamic programming

Mode shift map of Volt 1



(a) Mode shift map by dynamic programming

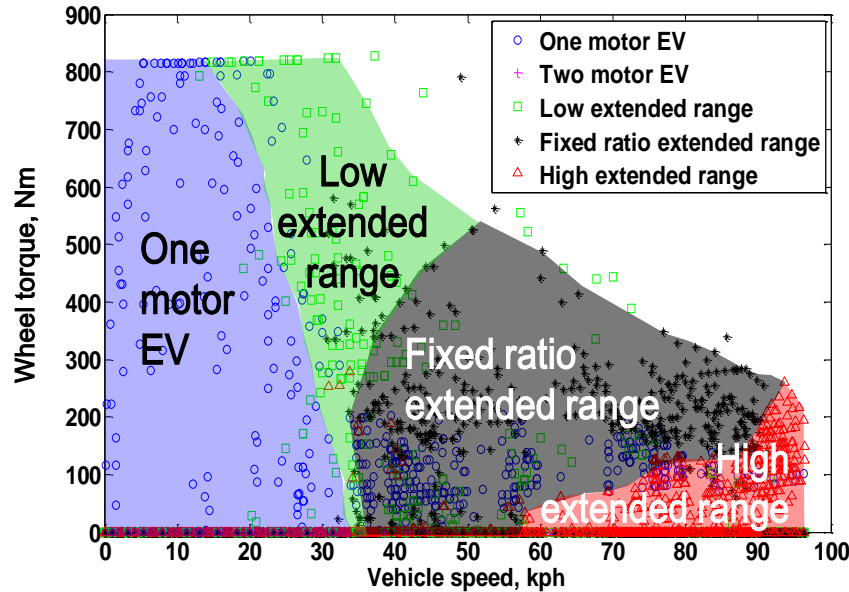


(b) Mode shift map using mode control algorithm*

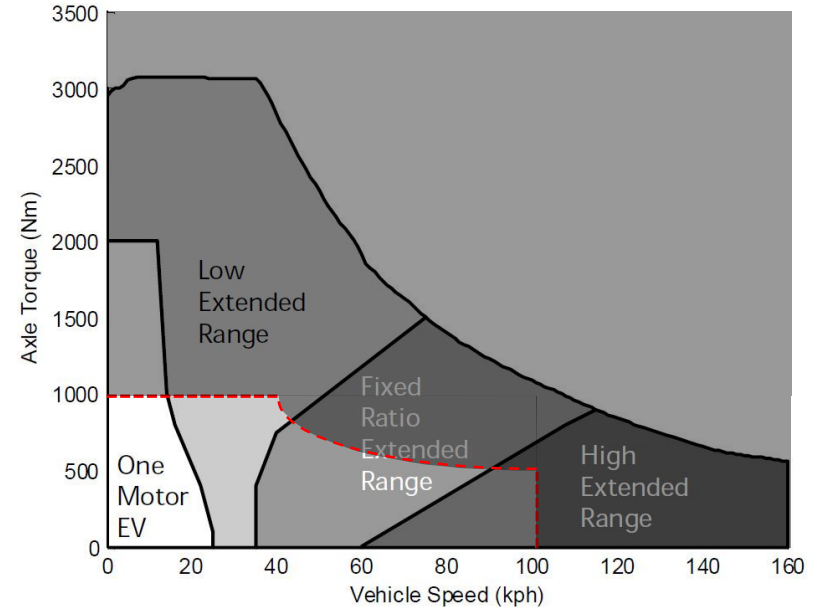
* C. Ma et. al, *Comparative study on power characteristics and control strategies for plug-in hybrid electric vehicle*, IJAT, Vol. 13 (3), 2012, 505-516

Mode shift map by dynamic programming

Mode shift map of Volt 2



(a) Mode shift map by dynamic programming



(b) Mode shift map in the literature*

* B. M. Conlon et.al, *The next generation "Voltec" extended range EV propulsion system*, SAE paper No. 2015-01-1152, 2015

■ Comparative analysis of Volt 1 and Volt 2

Comparative analysis of Volt 1 and Volt 2

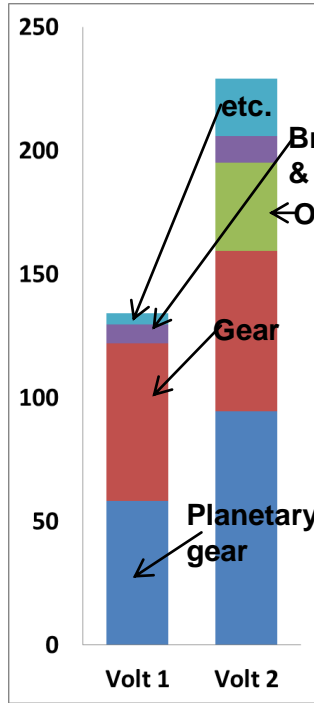
Results of dynamic programming – UDDS(city cycle)



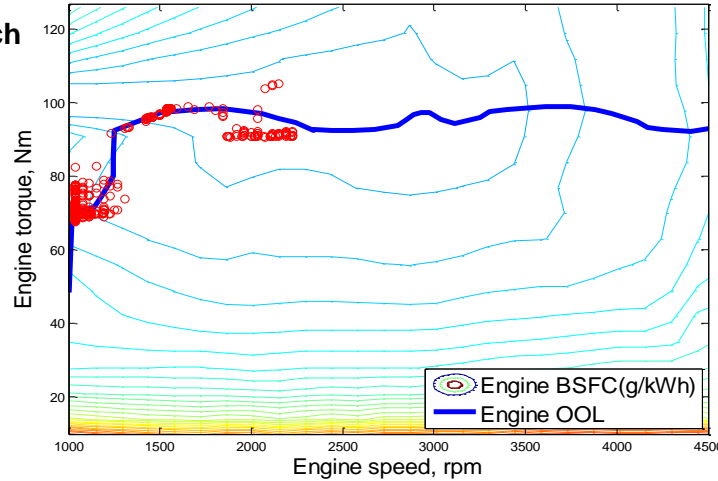
UDDS		Volt 1	Volt 2
Fuel economy [km/L]	without DT loss	26.20	31.86
	with DT loss	25.37(3.2%↓)	29.65(6.9%↓)
Powertrain efficiency[%]		82.4	82.6
Engine efficiency[%]		34.0	36.0
① Engine energy[k]		5023.1	4549.9
② Consumed fuel energy[k]		14786.9	12652.5
③ Battery energy[k]		1966.7	1940.5
④ Wheel demanded energy[k]		5629.8	5361.4
⑤ Total loss[k]((⑥)+(⑦))		1359.2(100%)	1127.2(100%)
⑥ PE loss[k]		1225.1(90.1%)	898.1(79.7%)
⑦ DT loss[k]		134.1(9.9%)	229.1(20.3%)

Comparative analysis of Volt 1 and Volt 2

Results of dynamic programming – UDDS(city cycle)

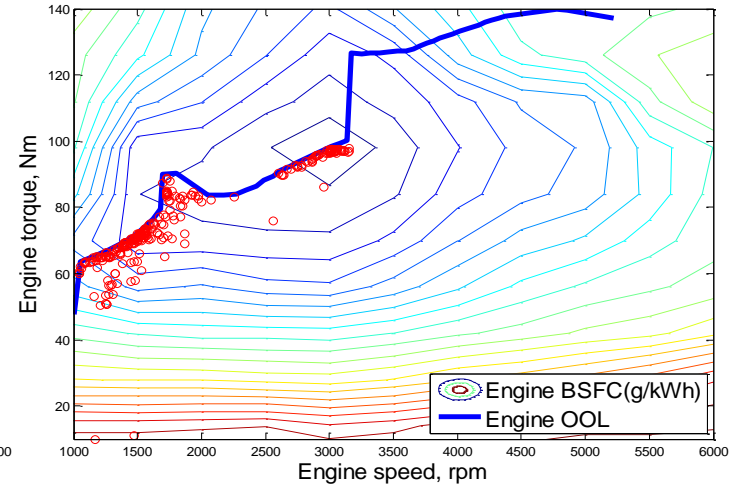


< Drivetrain losses >



(a) Volt 1

< Engine operation points >



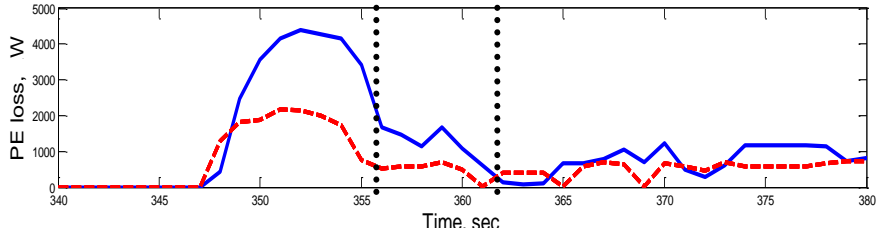
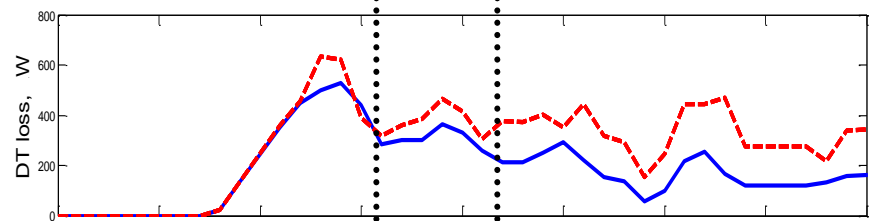
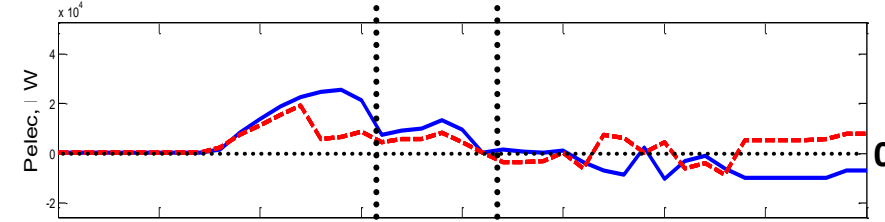
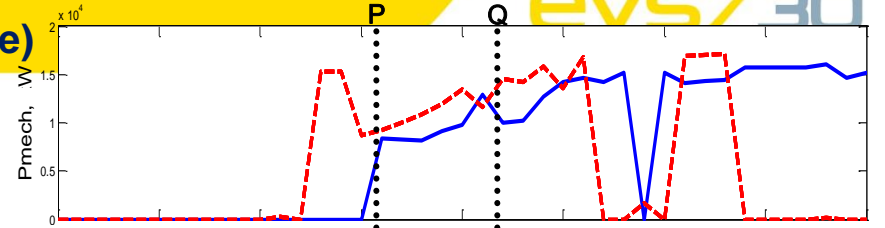
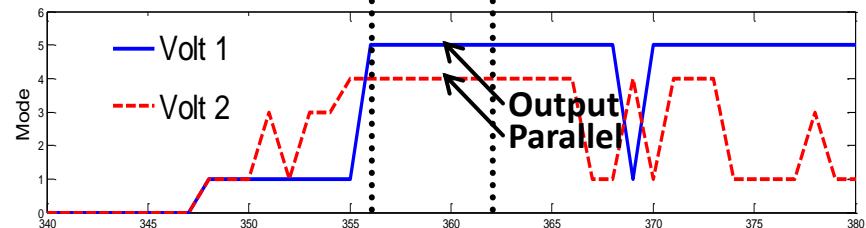
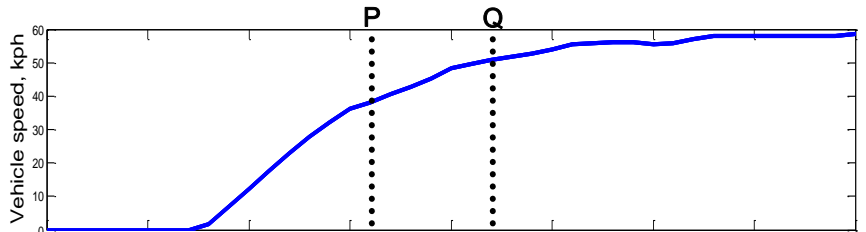
(b) Volt 2

Comparative analysis of Volt 1 and Volt 2

Results of dynamic programming – UDDS(city cycle)



Volt 1	Time [sec]	Volt 2	Time [sec]
EV #1(1)	318	EV#1(1)	349
EV #2(2)	0	EV#2(2)	0
Series(4)	0	Input split(3)	145
Output split(5)	441	Parallel(4)	225
Regen(6)	352	Compound split(5)	54
		Regen(6)	338



Comparative analysis of Volt 1 and Volt 2

Results of dynamic programming – HWFET(highway cycle)



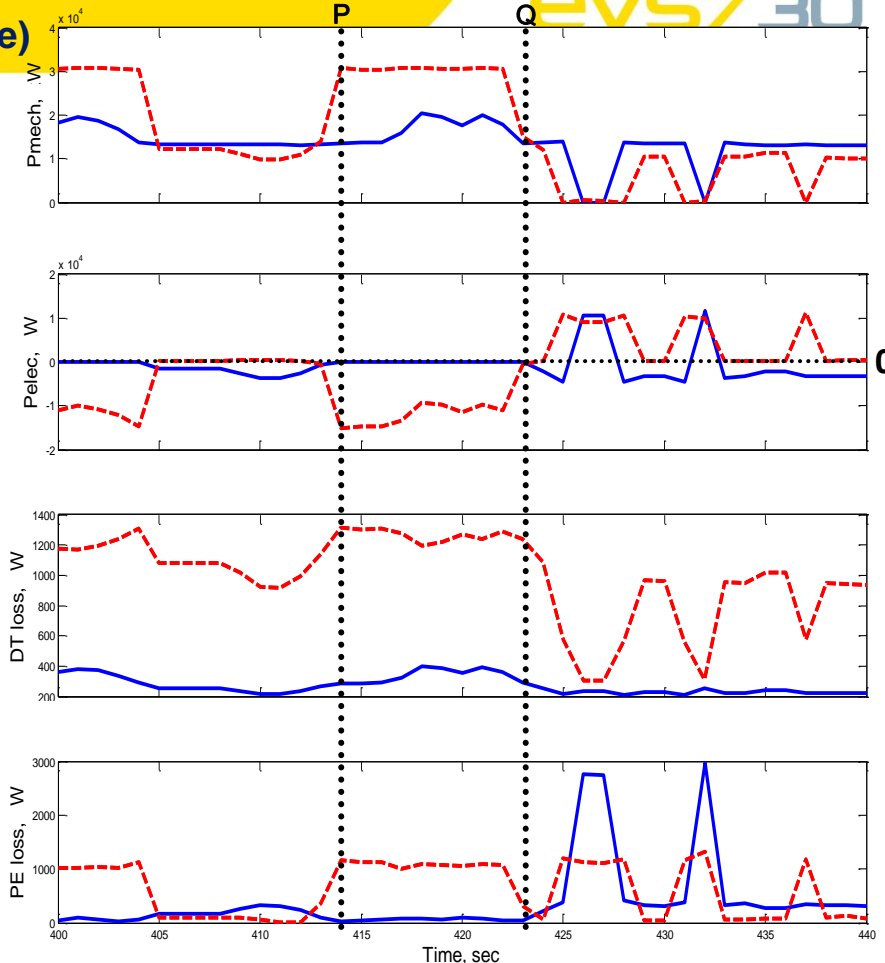
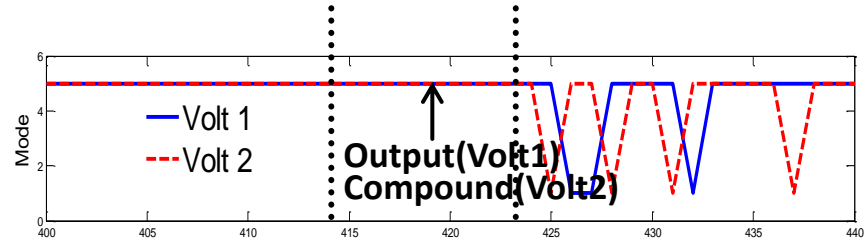
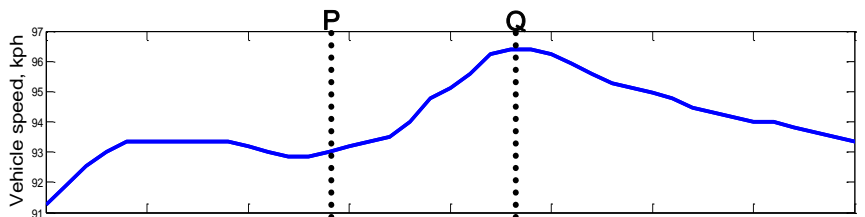
HWFET		Volt 1	Volt 2
Fuel economy [km/L]	without DT loss	25.32	27.76
	with DT loss	24.80(2.1%↓)	25.98(6.4%↓)
Powertrain efficiency[%]		90.4	86.6
Engine efficiency[%]		33.3	36.5
① Engine energy[kJ]		6951.3	7275.8
② Consumed fuel energy[kJ]		20899.1	19949.9
③ Battery energy[kJ]		618.6	559.5
④ Wheel demanded energy[kJ]		6799.2	6696.9
⑤ Total loss[kJ](⑥+⑦)		770.2(100%)	1132.9(100%)
⑥ PE loss[kJ]		614.2(79.7%)	715.6(63.2%)
⑦ DT loss[kJ]		155.9(20.3%)	417.3(36.8%)

Comparative analysis of Volt 1 and Volt 2



Results of dynamic programming-HWFET(highway cycle)

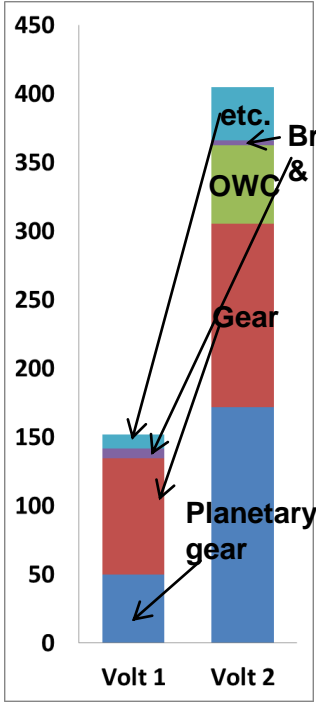
Volt 1	Time [sec]	Volt 2	Time [sec]
EV #1(1)	158	EV#1(1)	157
EV #2(2)	0	EV#2(2)	0
Series(4)	0	Input split(3)	27
Output split(5)	516	Parallel(4)	173
Regen(6)	86	Compound split(5)	320
		Regen(6)	83



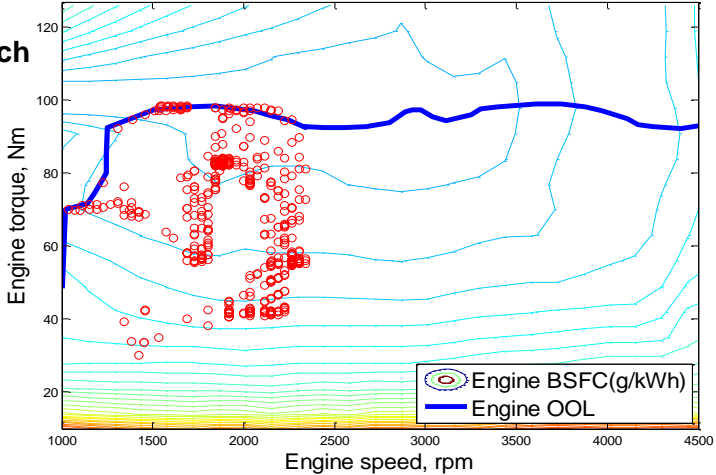
Comparative analysis of Volt 1 and Volt 2



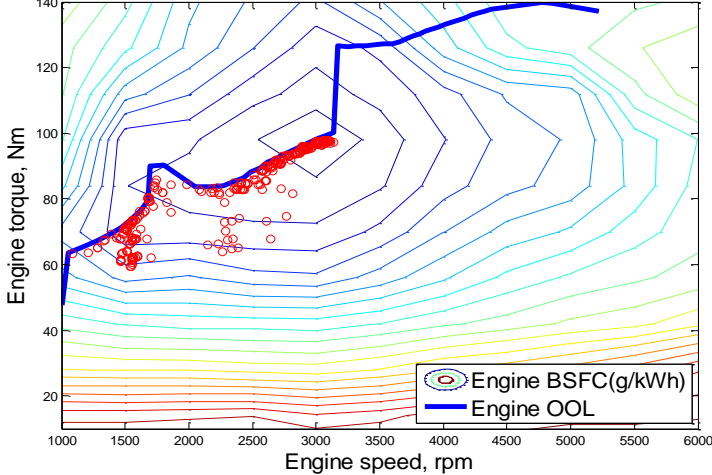
Results of dynamic programming – HWFET(highway cycle)



< Drivetrain losses >



(a) Volt 1



(b) Volt 2

< Engine operation points >

Conclusions

- Network analysis was performed for the power split modes for Volt 1 and Volt 2
 - System efficiency has the highest value at the mechanical point.
 - System efficiency decreases due to power electronics and drivetrain loss.
 - The amount of efficiency drop by drivetrain loss becomes larger depending on the speed ratio when the power circulation occurs.

- Using the dynamic programming, comparative study was performed for Volt 1 and Volt 2.
 - Mode shift map by dynamic programming shows a similar tendency with that from the literature.
 - Gear loss accounts for the largest part of the drivetrain losses followed by planetary gear and brake and clutch(Volt 1), OWC(Volt 2).
 - In spite of the increased drivetrain losses, powertrain and engine efficiency of Volt 2 are improved in the CS mode with application of two power split (input and compound) modes and parallel mode.

THANK YOU