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The 27th INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION
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Analysis and Simulation of a novel HEV using a Single Electric Machine

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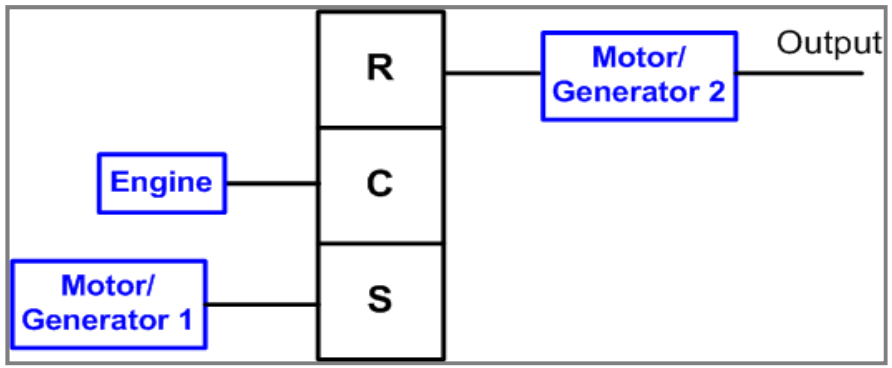
Motivation of developing a single EM HEV

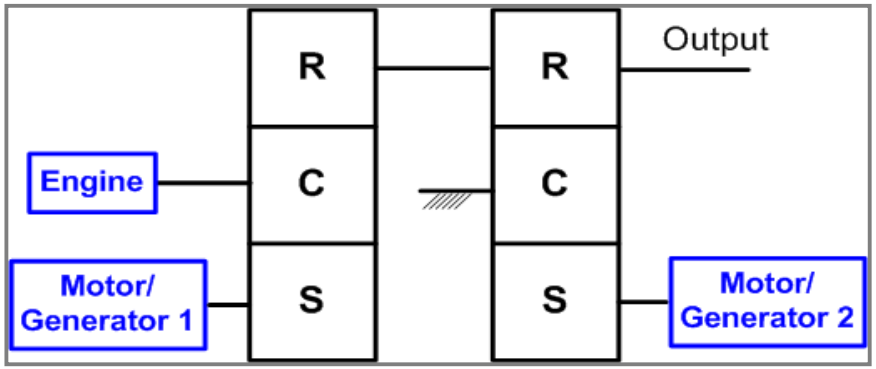
- **Overall objectives**
  - To improve fuel economy and reduce hazardous emissions.
- **Background**
  - For most of the popular HEVs, Toyota THS, Ford FHS, GM AHS, two EMs are used, with one as a motor, and the other as a generator.
- **Reasons for developing a single EM HEV**
  - An EM can be operated in any one of the four quadrants of the torque versus speed coordinate system. The EM works as a motor in the quadrant 1 and 3, and as a generator in 2 and 4.
  - The single EM HEV uses one less EM and its associated power electronics system, which imply advantages of compact, low power loss and low cost.

Motivation of developing a single EM HEV

- **Existing typical transmission architectures for two EM HEVs: from Toyota**

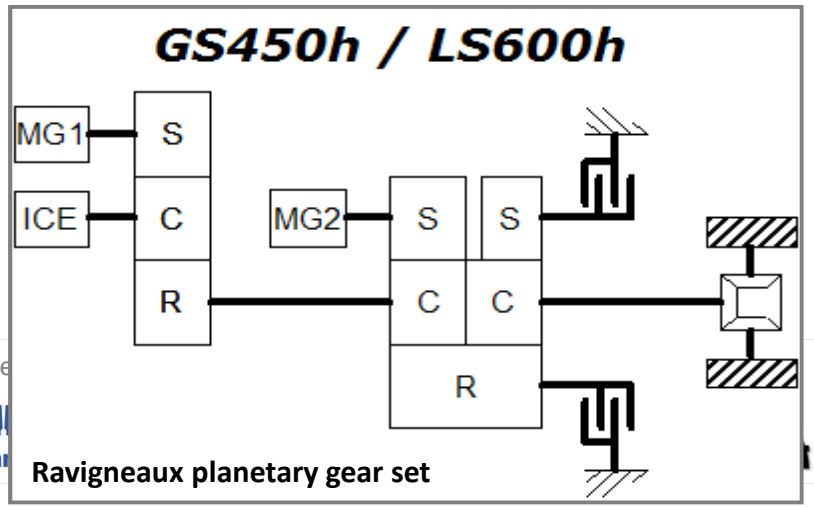


First-Generation (G1) Toyota Hybrid:
Toyota Hybrid System (THS)
Prius Hybrid



Second-Generation (G2) Toyota Hybrid:
Hybrid Synergy Drive (HSD)
RX400/Highlander Hybrid

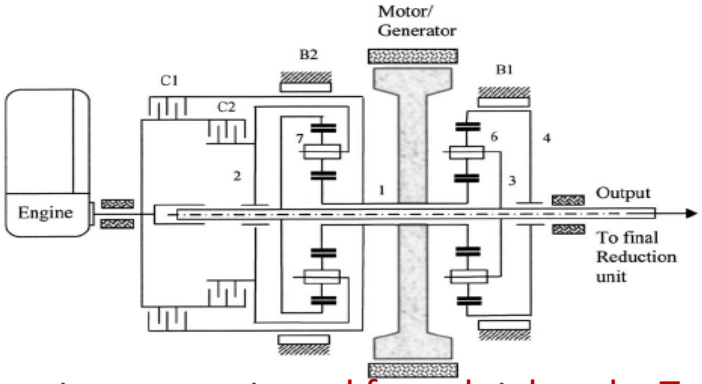
Third-Generation (G3) Toyota Hybrid:
Hybrid Synergy Drive (HSD)
Lexus Hybrid



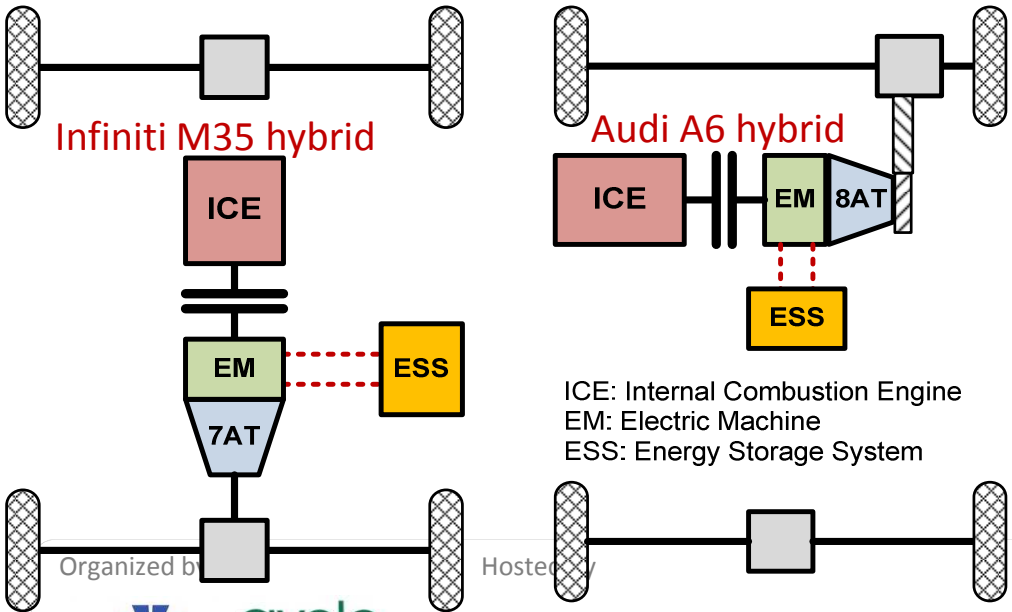
Ravigneaux planetary gear set

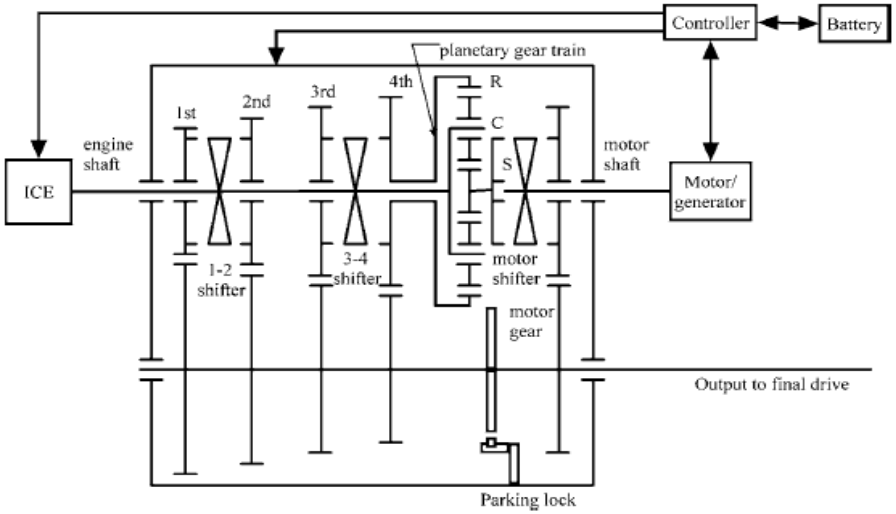
Electrically Variable Transmission (EVT)

Motivation of developing a single EM HEV



Two planetary gearsets and four clutches, by Tsai



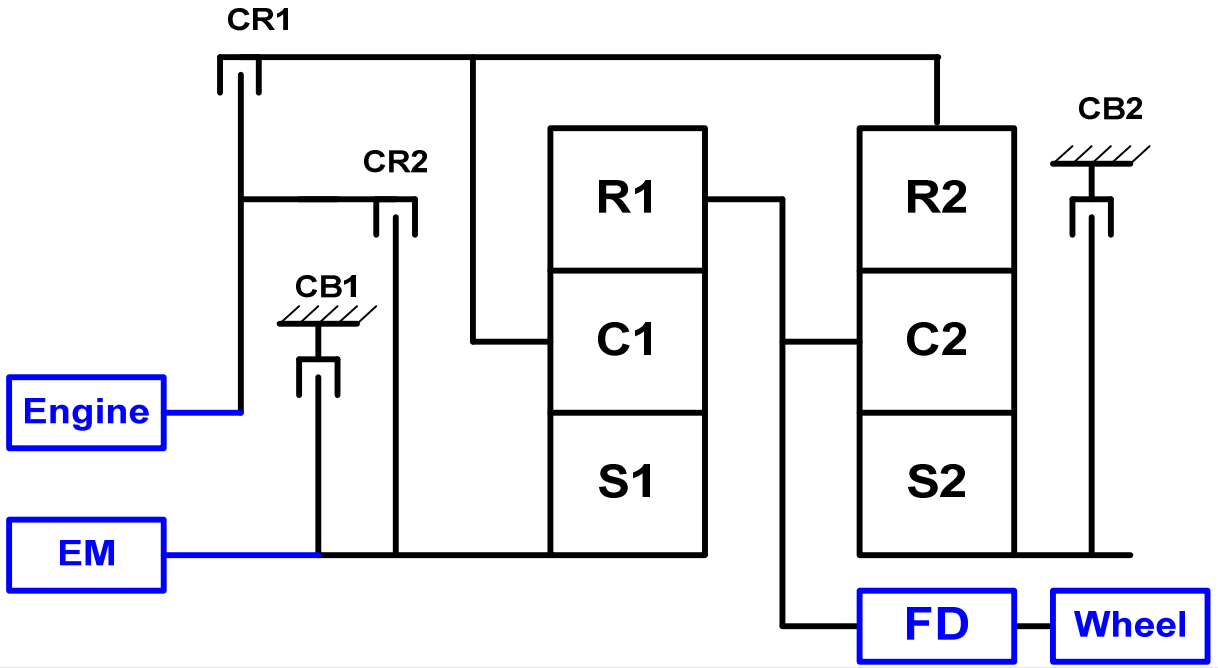


five shaft gear pairs and one planetary gearset, by Zhang and Lin

- **Existing typical transmission architectures for single EM HEVs**

Idea of a single EM HEV using a Multi-Mode Transmission

- **The MMT(multi-mode transmission) consists of input planetary gearset and output planetary gearset.**
- **Four clutches are employed, two rotating clutches (CR1, CR2) and two braking clutches (CB1, CB2).**



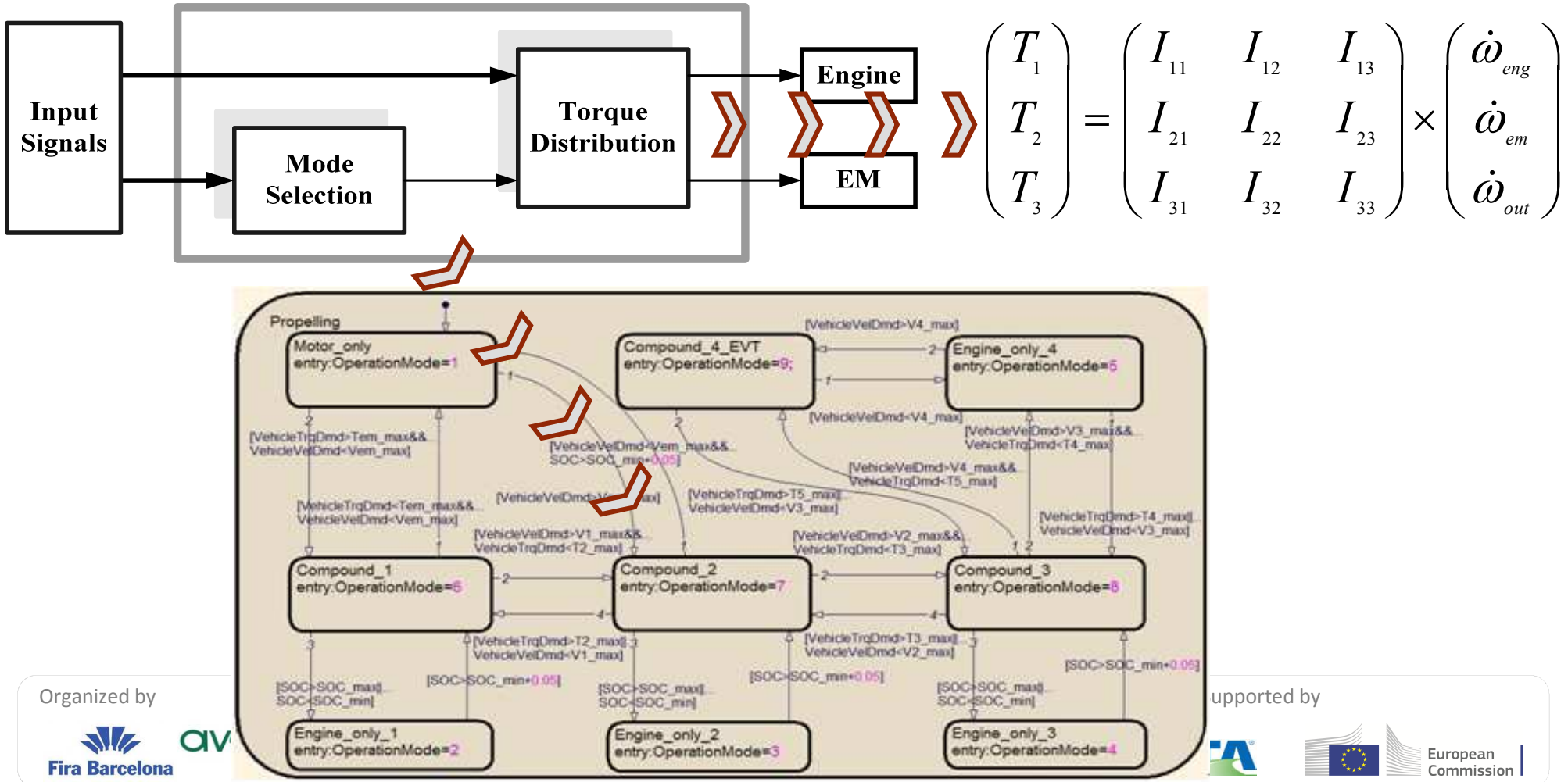
Idea of a single EM HEV using a Multi-Mode Transmission

- **Operation Modes of MMT based single EM HEV**

Power flow mode	Operation mode	Clutch operation				EM operation
		CB1	CB2	CR1	CR2	
Motor-only driving	Motor-only		◆			motor
Engine-only driving	Engine-only_1		◆		◆	spinning
	Engine-only_2		◆	◆		spinning
	Engine-only_3			◆	◆	spinning
	Engine-only_4	◆		◆		fixed
Compound driving	Compound_1		◆		◆	motor/generator
	Compound_2		◆	◆		motor/generator
	Compound_3			◆	◆	motor/generator
	Compound_4_EVT			◆		motor/generator
Braking	Mech_Braking					fixed
	Reg_Braking		◆			generator
	Compound_Braking_0		◆			generator
	Compound_Braking_1		◆		◆	generator
	Compound_Braking_2		◆	◆		generator
	Compound_Braking_3			◆	◆	generator
Charging while parking	Charging while parking				◆	generator

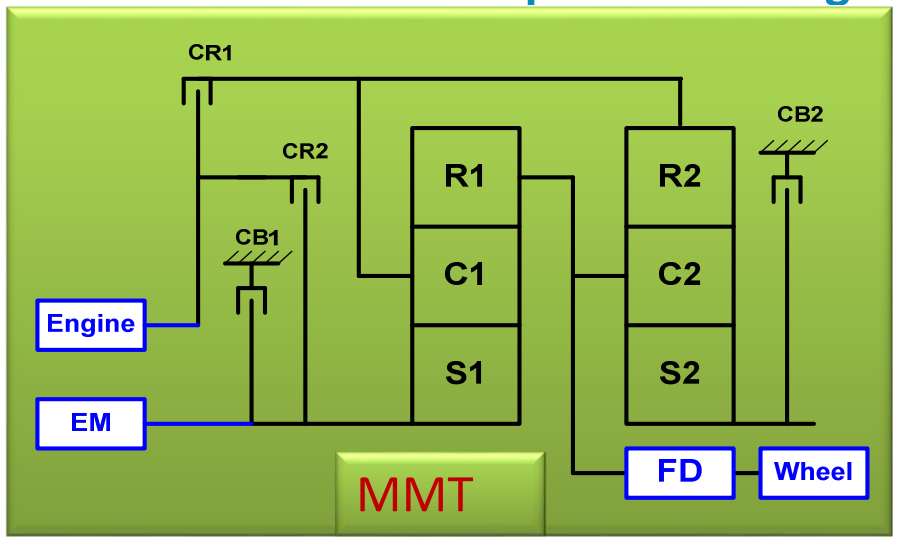
Energy management strategy of the single EM HEV

- **Structure of energy management system**



Simulation Results and Analysis

- **Performance comparison through simulation in NEDC**



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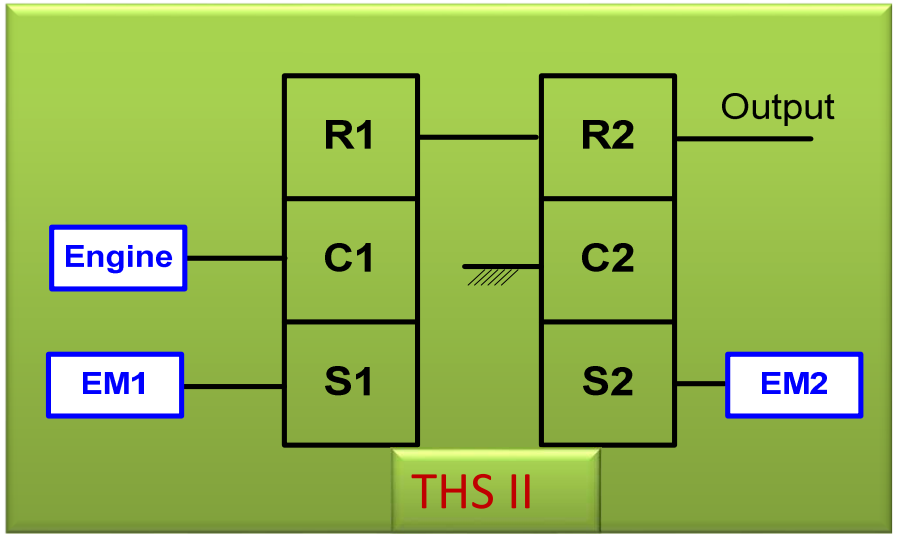
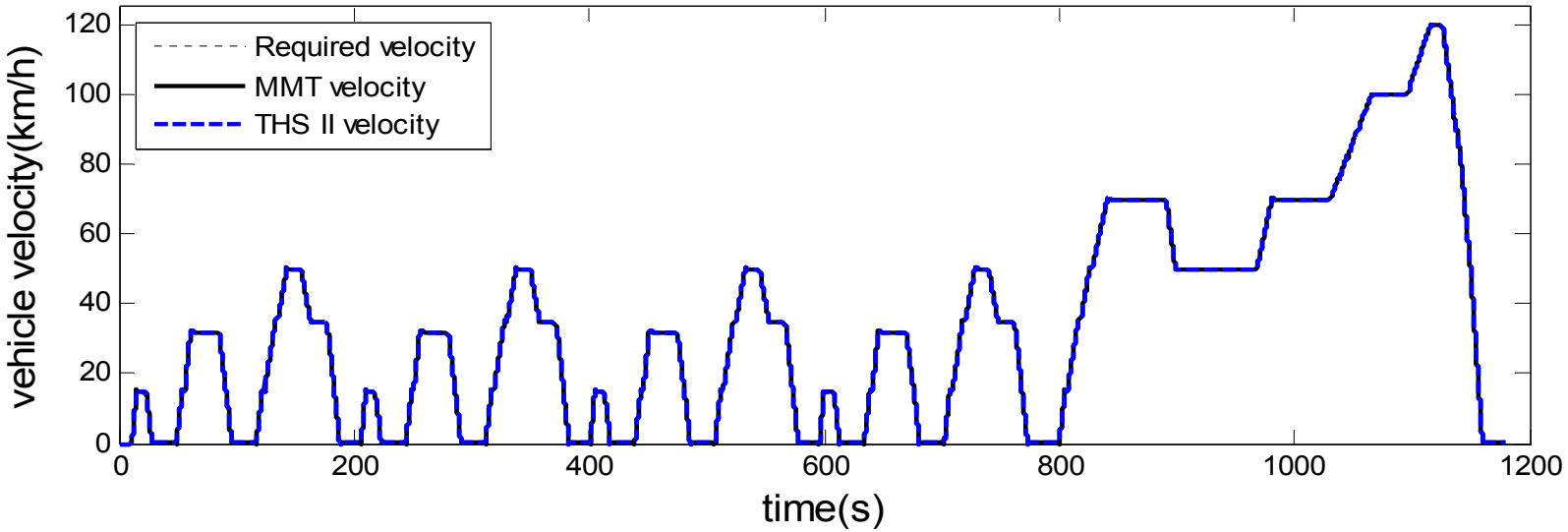


Parameter	Value
gross mass (kg)	1295
rolling radius (m)	0.2898
rolling resistance coefficient	0.011
air resistance coefficient	0.31
frontal area (m^2)	2.1
final drive ratio	3.905
engine maximum power (kW)	57
engine maximum speed (rpm)	4500

comparison	Fuel consumption (L/100km)
THS II	3.90
MMT	3.81
Results	Comparable

Simulation Results and Analysis

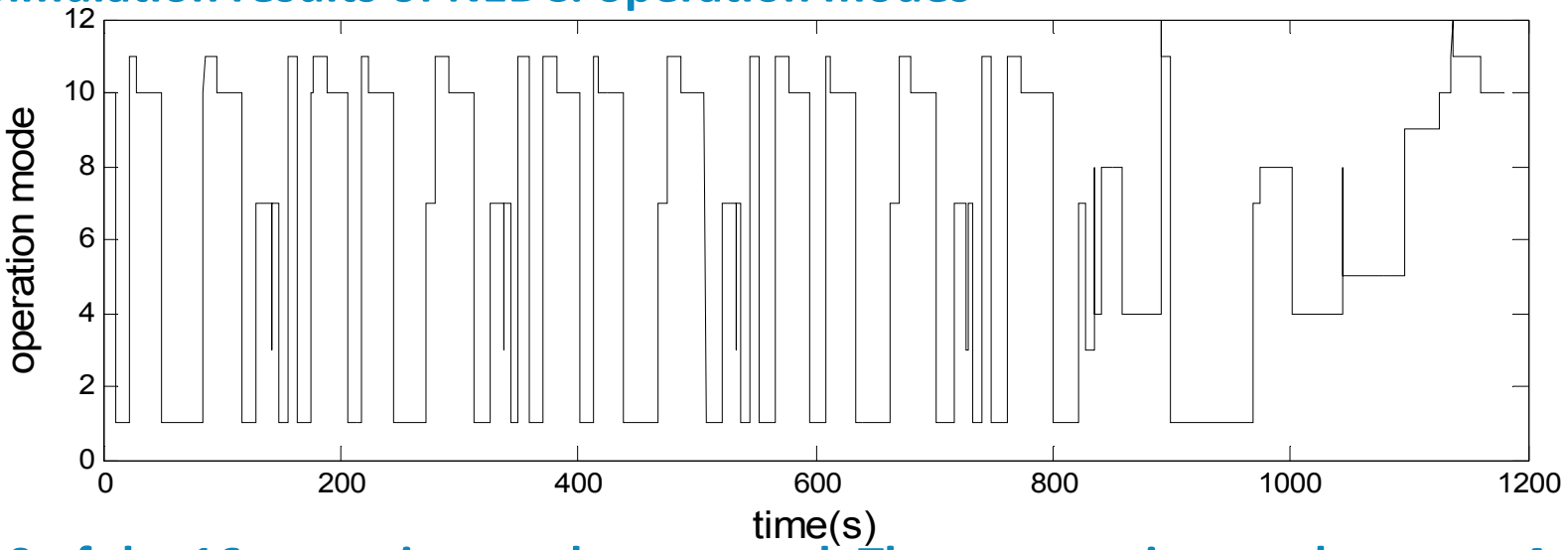
- **Simulation results of NEDC: vehicle velocity**



- **Both the MMT vehicle and the THS II like vehicle track the NEDC profile very well.**
- **Both vehicles gain identical kinetic energy through the NEDC process.**

Simulation Results and Analysis

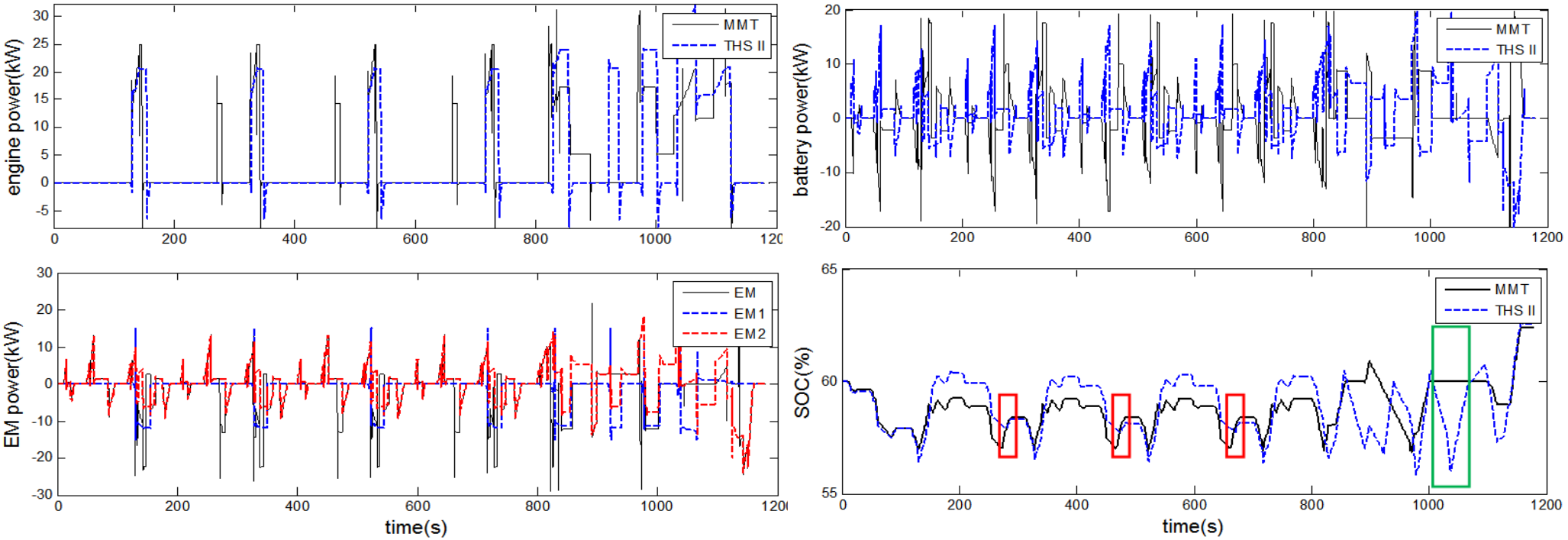
- **Simulation results of NEDC: operation modes**



- **10 of the 16 operation modes are used. These operation modes cover 4 of the 5 power flow modes.**
- **The charging while parking power flow mode is not activated as the battery SOC can be balanced during vehicle running.**

Simulation Results and Analysis

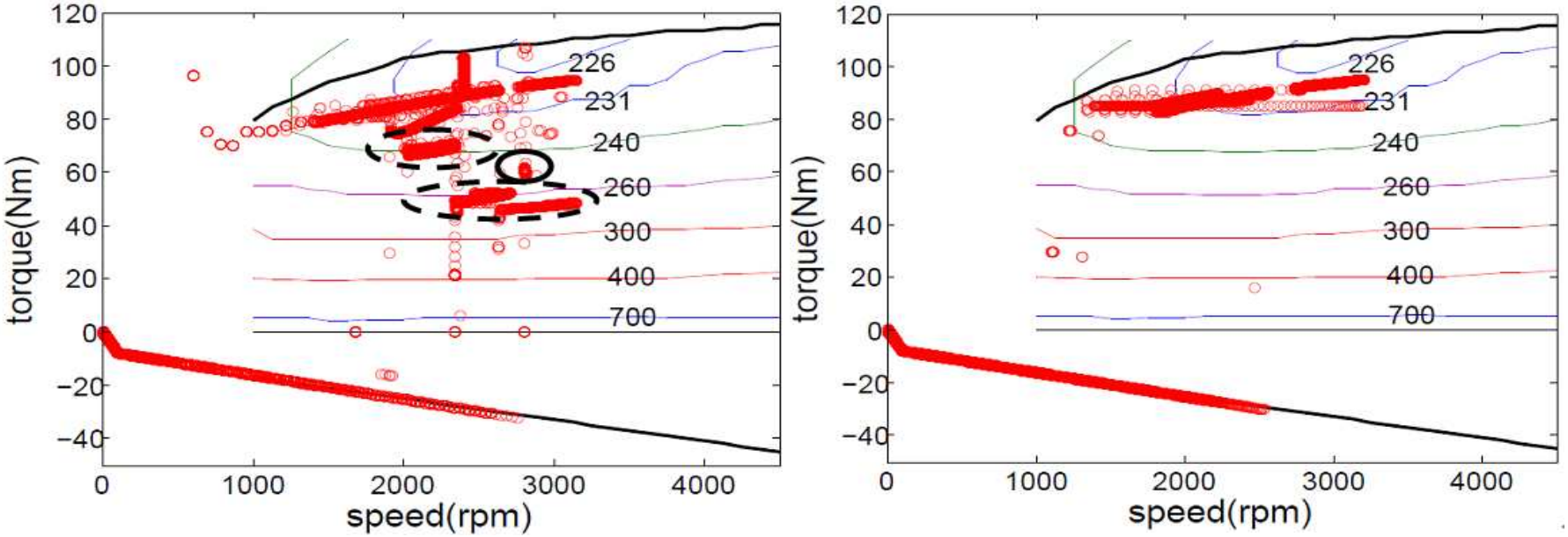
- **Simulation results of NEDC: Engine, EM, Battery power, and Battery SOC**



- **More positive and negative engine power in THS II.**
- **More frequent usage of EMs and batteries in THS II.**
- **Initial and ending SOC are identical, MMT SOC is more stable.**

Simulation Results and Analysis

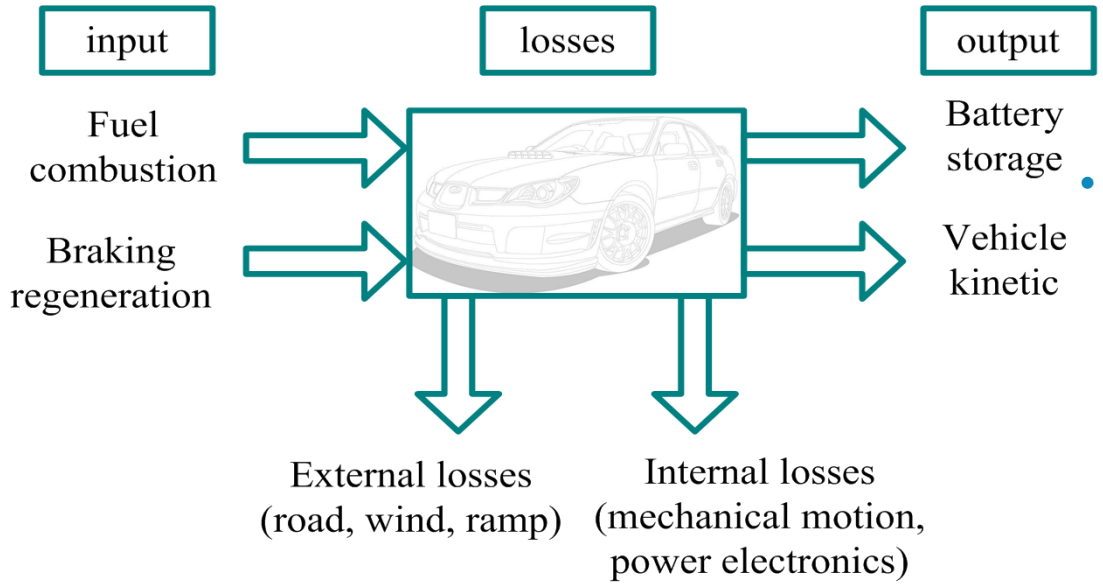
- **Engine operating points**



- **Most operating points of MMT engine spread in the high efficiency region defined by the engine speed :1500rpm ~ 4000rpm, the engine torque: 70Nm ~ 100Nm.**
- **The operating points of THS II engine concentrate on high efficiency area.**

Simulation Results and Analysis

- **The energy flow for NEDC simulation**

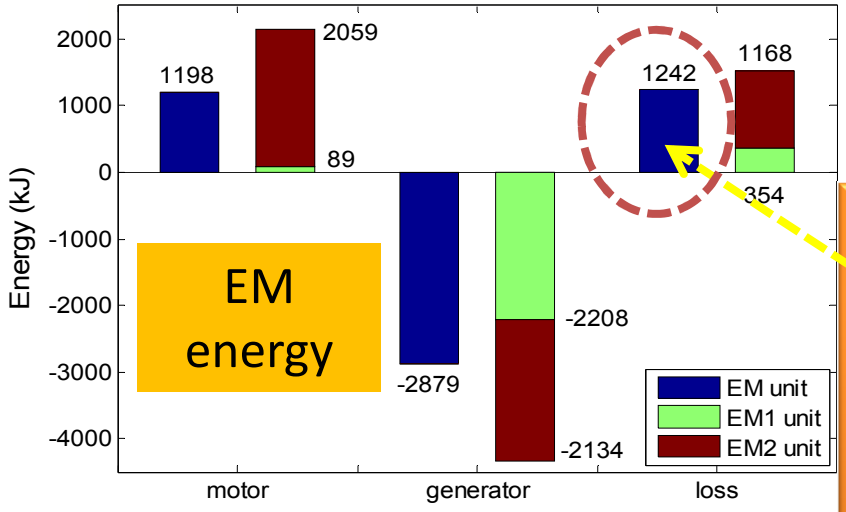


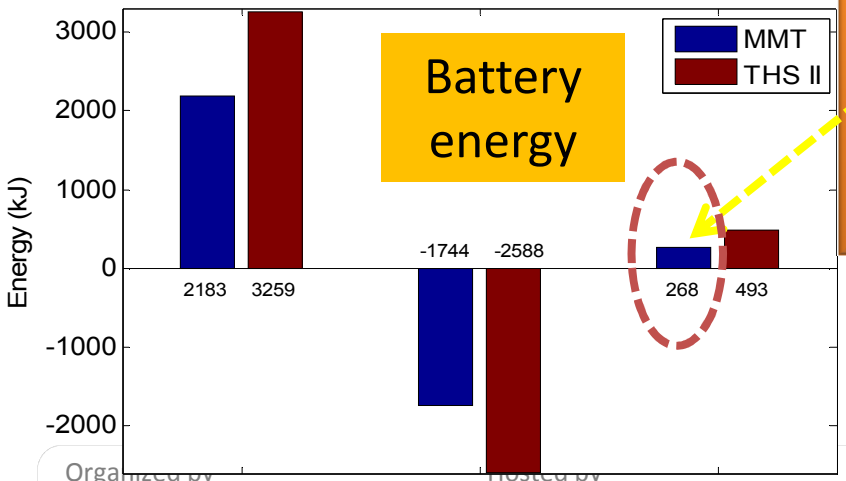
- No plug-in electricity input and auxiliary component consumption for simplification

- **Why the MMT vehicle can accomplish the NEDC by using *less engine energy* with a lower average engine efficiency?**
- **Possible explanation: *more regenerative regeneration, less internal losses*. The internal losses come from the electric machines, battery and their power electronics.**

Simulation Results and Analysis

- **Statistic data and detailed explanation**





$E_{EM\_loss\_MMT} = 1242\text{kJ}$

$E_{EM\_loss\_THS} = 1522\text{kJ}$

Causes:

(1) ***less internal loss*** in EM and Battery of MMT vehicle;

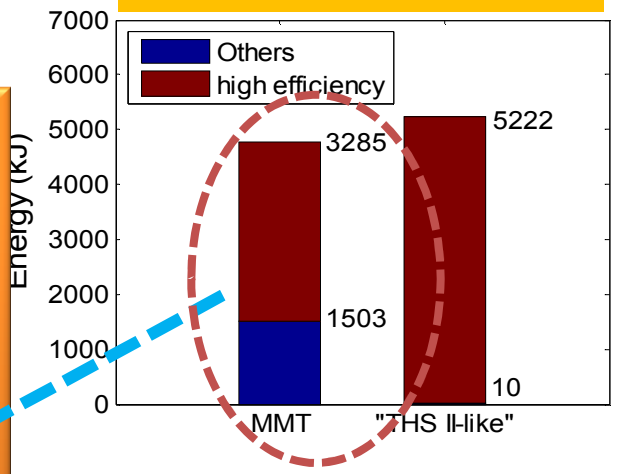
(2) ***more regenerative regeneration*** in MMT vehicle.

Result: ***less engine energy*** is consumed by MMT vehicle.

$E_{batt\_loss\_MMT} = 268\text{kJ}$

$E_{batt\_loss\_THS} = 493\text{kJ}$

Engine energy



Regenerative energy

- MMT vehicle: 916.8kJ
- THS II vehicle: 815.8kJ

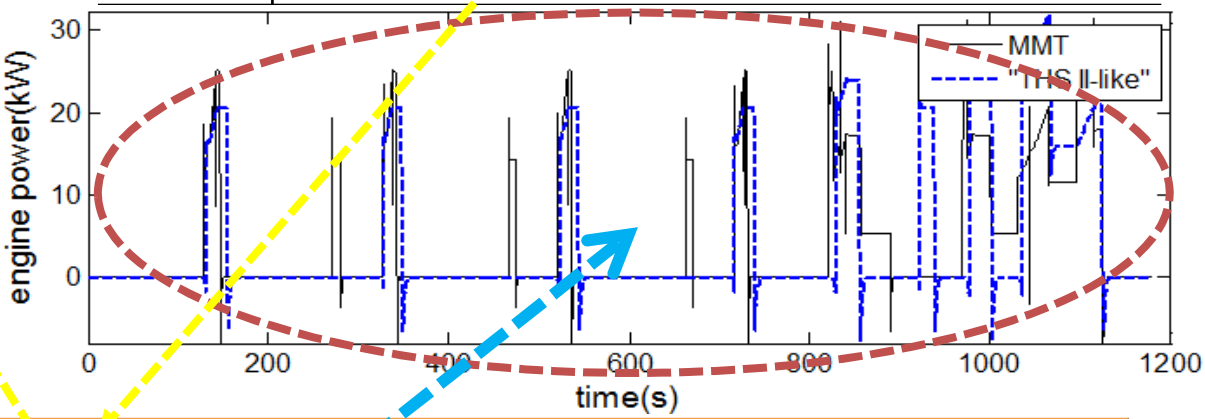
Simulation Results and Analysis

Accumulative operating time of the EMs

Electric Machine	Status	Operating Time (s)	Percentage of NEDC Time (%)
EM	Motor	410.90	34.82
	Generator	320.34	27.15
	Spin	84.26	7.14
	Rest	364.5(rest more)	30.89
EM1	Motor	65.24	5.53
	Generator	207.22	17.56
	Spin	677.14	57.38
	Rest	230.40	19.53
EM2	Motor	544.28	46.13
	Generator	353.72	29.98
	Spin	51.60	4.37
	Rest	230.40	19.53

Accumulative operating time of the batteries

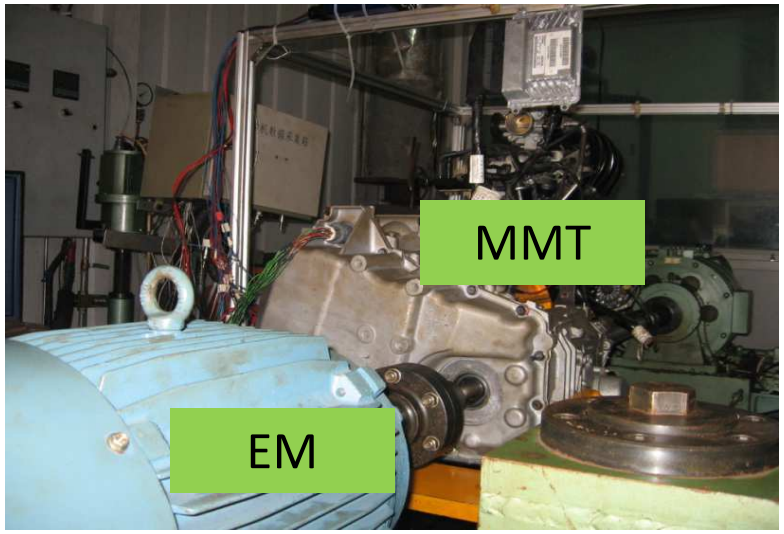
Vehicle	Battery status	Operating Time (s)	Percentage of NEDC Time (%)
MMT	Charging	313.64	26.58
	Discharging	424.16	35.95
	Rest	442.2(rest more)	37.47
"THS II-like"	Charging	561.40	47.58
	Discharging	337.30	28.58
	Rest	281.30	23.84

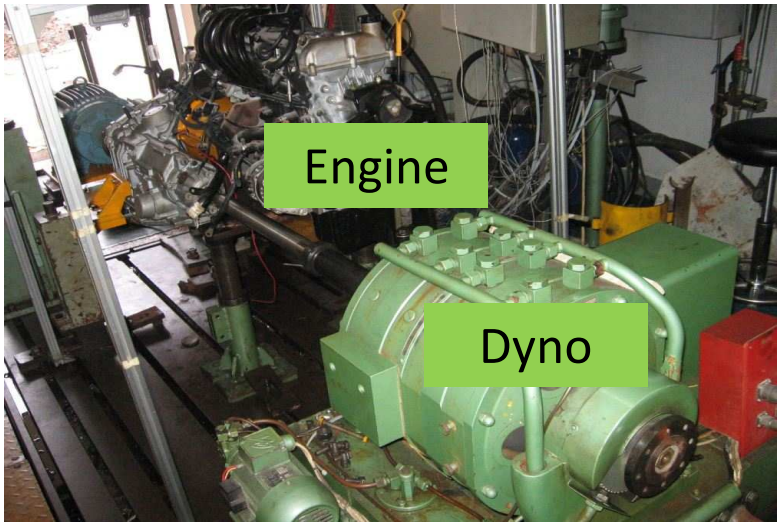


- The EM and Battery of MMT ***rest more*** and has ***less internal loss*** than THS II vehicle.
- ***Less engine energy*** (area in 'engine power' figure) is consumed in the MMT vehicle.

Prototyping and bench test

- **Prototyping of MMT and bench test for the MMT vehicle**

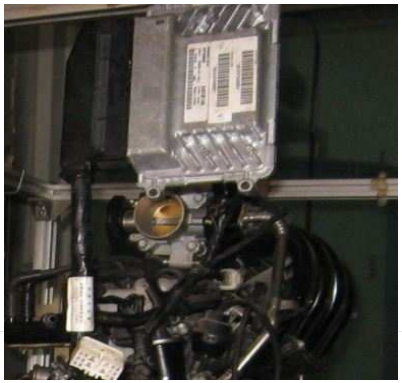





VCU

TCU


MCU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Summary

- **A novel MMT for a HEV using a single EM is developed, the HEV:**
  - uses one less EM and its associated power electronics, which imply advantages of compact, low power loss and low cost.
  - makes use of many components of the conventional ATs. Thus, the reliability and cost effectiveness are likely to be superior.

- **The comparable simulation results with THS II vehicle indicate the potential of the proposed MMT vehicle in fuel economy.**

- **The prototyping of proposed MMT and bench test for the MMT vehicle validated the basic operation modes and viability of this single EM HEV scheme.**

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