# GT-SUITE Features and Applications for HEV/EV

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# Back Ground

- Control Engine/Motor/Transmission（Transmission, Clutch) for Design and Development of HEV/PHEV/EV especially
- Consideration of Control Strategy is needed Early Development Stage
- Objects of Controller is low fuel (electrical) consumption for HEV and long available displacement for EV
- Control State of Charge (SOC) for keeping Battery from deteriorating
- Understanding the potential of Vehicle System (Fuel Consumption etc.) if you develop new topology HEV

Inefficiency and high cost if you do trial and error by making prototype Necessary, Consider the controller method using Simulation for Vehicle System

# HEV Modeling in GT-SUITE

- Object-oriented general driveline architecture
- Versatility in modeling HEV/PHEV  configurations
- Two electric machine modeling levels
  - System Level
  - Electrical Circuit Level
- Multiple electric Motors/Generators, batteries
- Comprehensive control library for modeling complex HEV control strategies
- Completely integrated with Vehicle model
- Allows vehicle energy management studies
- GT-SUITE productivity features (Pre-Post GUI, DOE/Optimizer, NN(Neural Network), Distribute Computing, user models etc.)

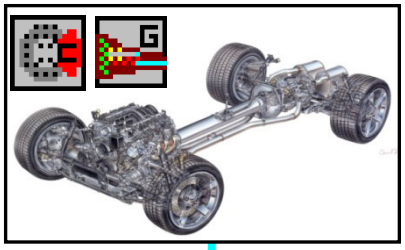
# GT-SUITE HEV/EV modeling elements

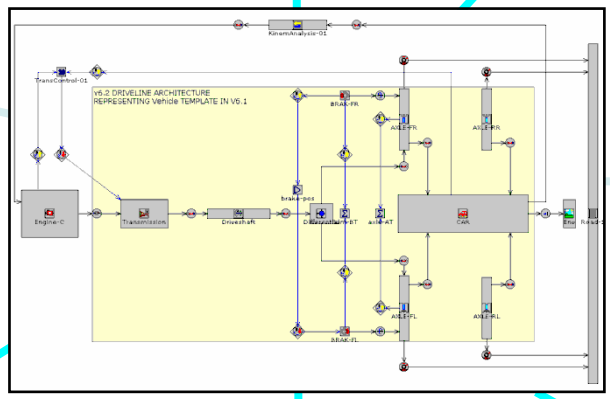
HEV COMPONENTS AND POWER ELECTRONICS

DRIVELINE COMPONENTS

ENGINE/ POWERTRAIN CONTROLS

DRIVELINE &TRANS.



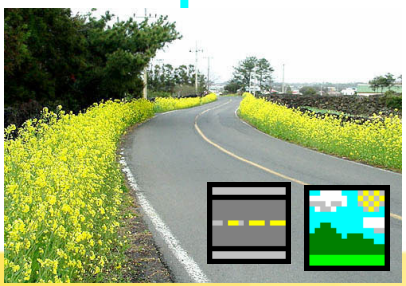


VEHICLE BODY

ENGINE

DRIVER

ROAD & ENVIRONMENT

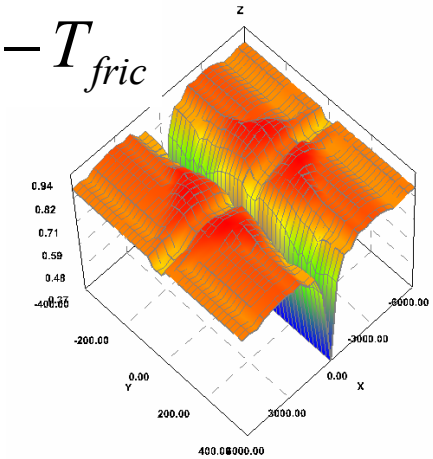


# GT-SUITE HEV/EV modeling elements

- Motor/Generator Model (System-Level)
  - MotorGeneratorMap(Map-Based)
    - Efficiency mapped as a function of speed and load
    - Efficiency is Motor Power/Battery Power to get from Experiment or Simulation (like JMAG)
    - Generate Electric Power at Negative Torque

$$T_{motor} = \frac{\eta_{motor} \cdot P_{bat}}{N_{shaft}}$$

$$J\omega'' = T_{motor} - T_{load} - T_{fric}$$




  - MotorGererator(Quasi-Electric)
    - Electro-mechanical model
    - Solves for current
    - Torque defined using a Torque coefficient $K_t$

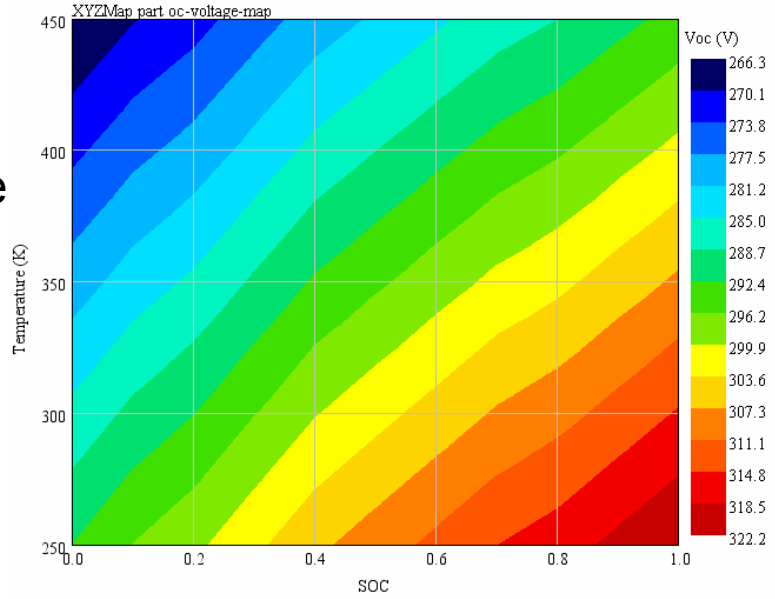
$$T_{motor} = K_t \cdot I_a$$

$$L_{eq} I_a'' = V_{app} - K_b w - I_a R_{eq}$$

$$J\omega'' = T_{motor} - T_{load} - T_{fric}$$

# GT-SUITE HEV/EV modeling elements

- Battery Model (system level)
  - Quasi-Electric Model
  - Open circuit voltage and internal resistance are maps of the battery SOC (State of Change) and average temperature
  - Thermal modeling
    - Built-in thermal model option,
    - Detailed thermal model can be made using the thermal library,
    - User thermal option available




$$L_{req} = IV_{op} - I^2 R_{\text{int}}$$

**•Current drawn from the battery**

$$SOC = 1 - \frac{\int Idt}{CAP_{total}}$$

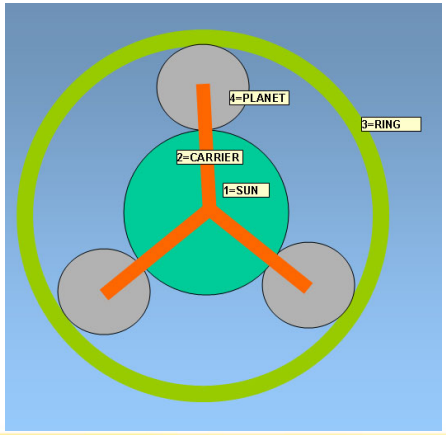
**•Battery State of Charge**

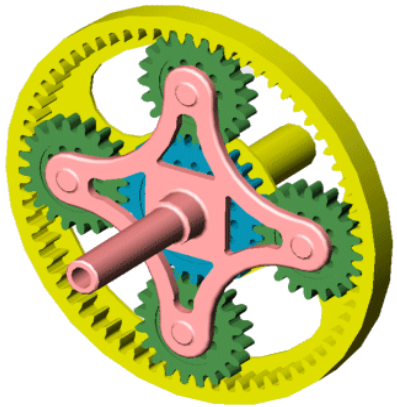
$$q = I - \left( V_{op} - V_t + T \frac{dV_{op}}{dT} \right)$$

**•Heat Generation Rate per cell**

# GT-SUITE HEV/EV modeling elements

- Driveline
  - Clutch (ClutchConn)
    - On/Off Clutch and middle pedal position (Slip Consideration)
  - PlanetaryGear (PlanetaryGearSet)
    - Planetary Gear for Toyota's way HEV (THS)
    - Input: Number of Sun/Ring Gear Teeth, Ring Gear Pitch Radius, Number of Planet Gears, Each of Moment, Sun/Planet and Ring/Planet Efficiency
    - Simulate Each Torque and Speeds Sun(EM2), Planet(Eng), Ring(EM1)



# GT-SUITE HEV/EV modeling elements

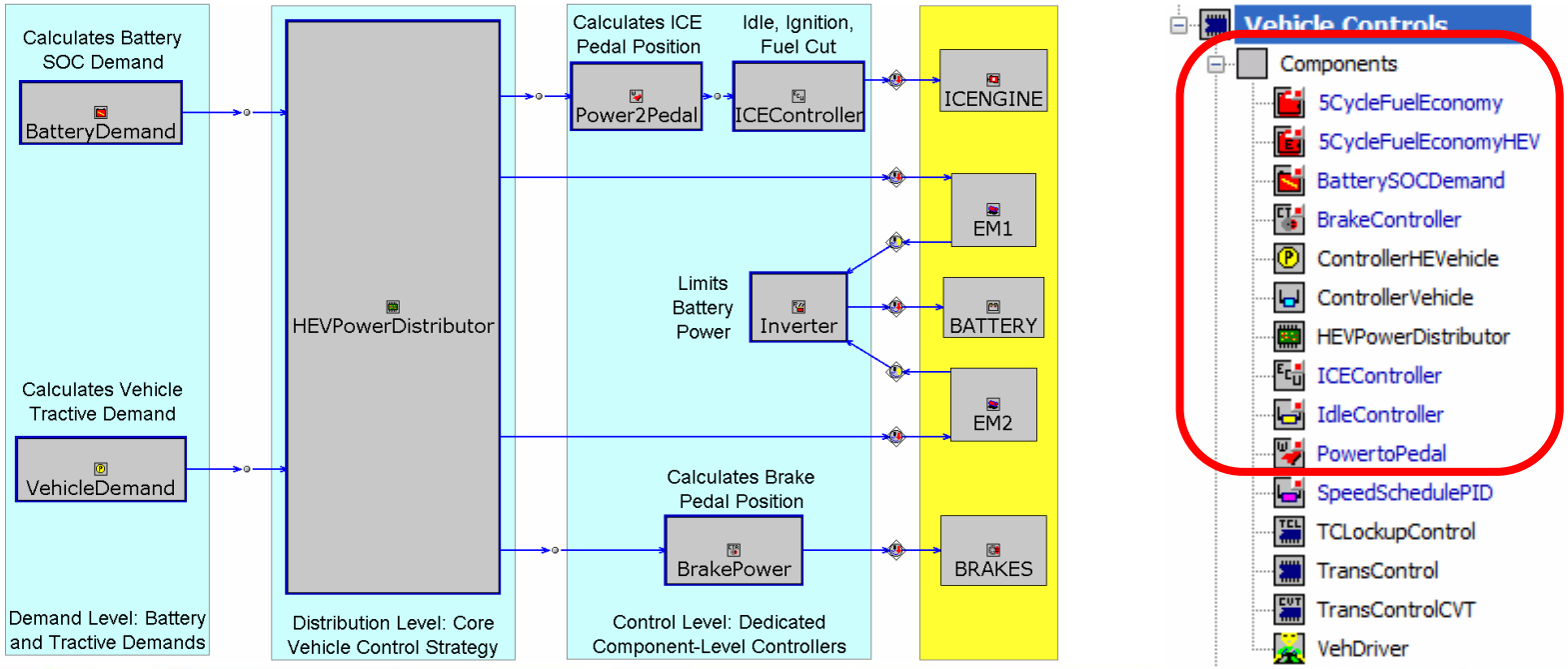
- Engine Model
  - Map-Based Model (EngineState)
    - Input: Eng.Speed/Load(Accel.)/BMEP, Eng.Speed/BMEP/BSFC
    - Very Fast Simulation (RTx1/10~)
    - Difficult for modeling Engine Control
    - Not Consider Air Flow
  - Mean Value Cylinder +NN(Neural Network) Model
    - Air Flow Dynamics (not Pressure Wave)
    - T/C Modeling
    - Fast Simulation (RTx1~1/5)
    - Need to Calculate DOE (Steady State) (3000case~)
    - For New additional Controls, Need to Calculate DOE again

# GT-SUITE HEV/EV modeling elements

- Engine Model(Cont.)
  - FRM (Fast Running Model)
    - Middle between Detail and Mean Value model
    - Available almost Controllers
    - Not necessary DOE Calculation
    - Fast Simulation (RTx3~1/2)
  - Detail Model (1D Air Flow Dynamics)
    - Predictive Air Flow and Pressure Wave
    - Available Engine Control modeling
    - Very Slow Simulation (RTx10~)

# GT-SUITE HEV/EV modeling elements

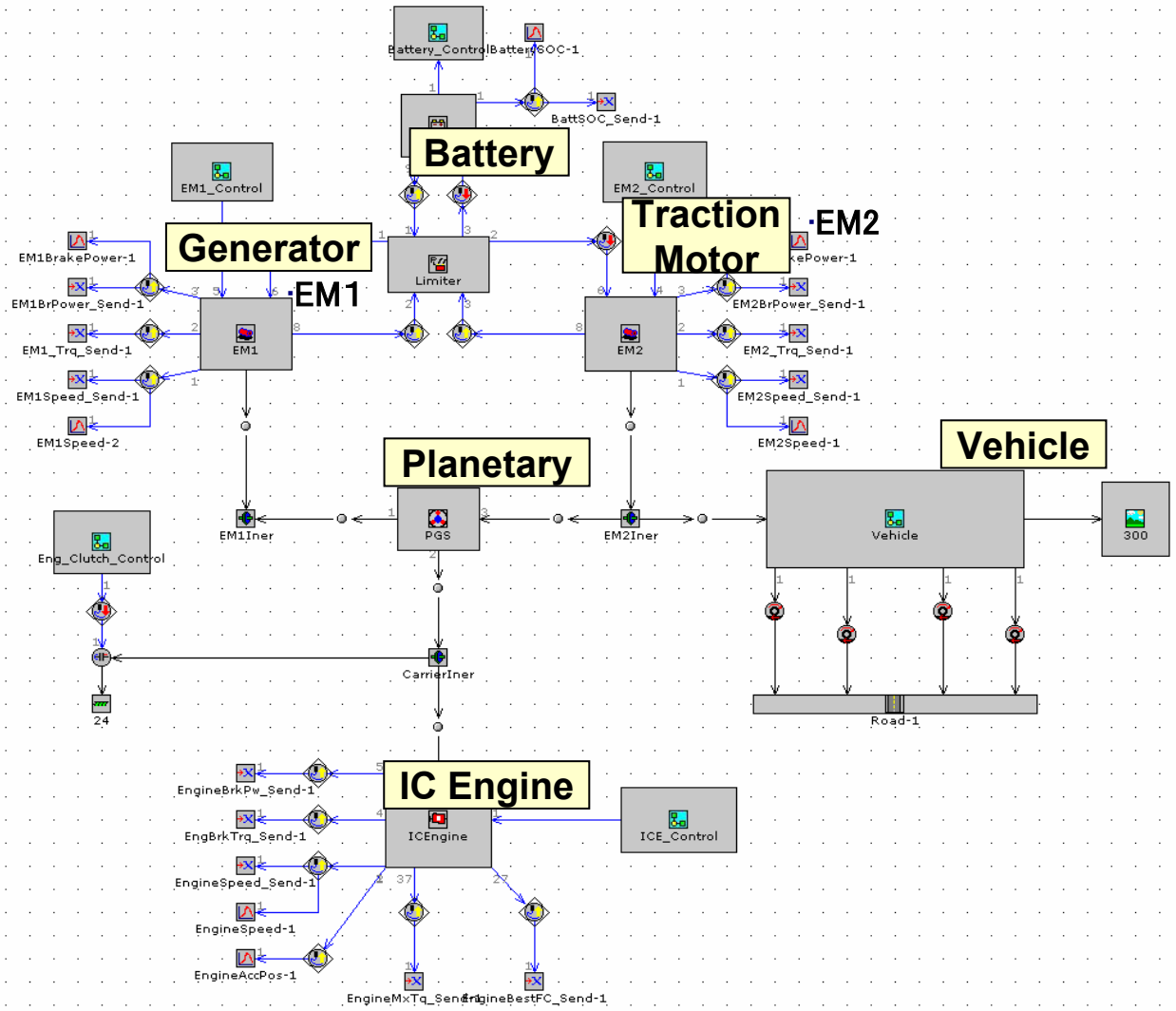
- Controls model for HEV
  - Demand: Calculate what the desired power from Target Vehicle Speed(ControllerHEVehicle, BatterySOCDemand)
  - Distribution: User Defined Code(HEVPowerDistributor)
  - Control: Dedicated Controllers for each source/sink



# *Prius HEV Model*

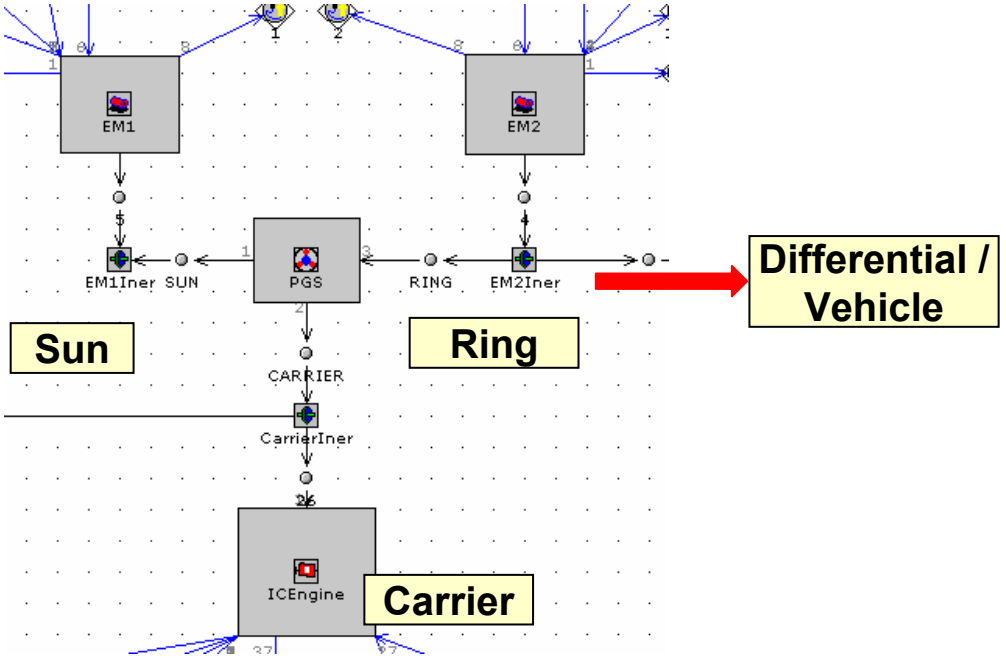
# *Gamma Technologies*

# Prius Model Overview



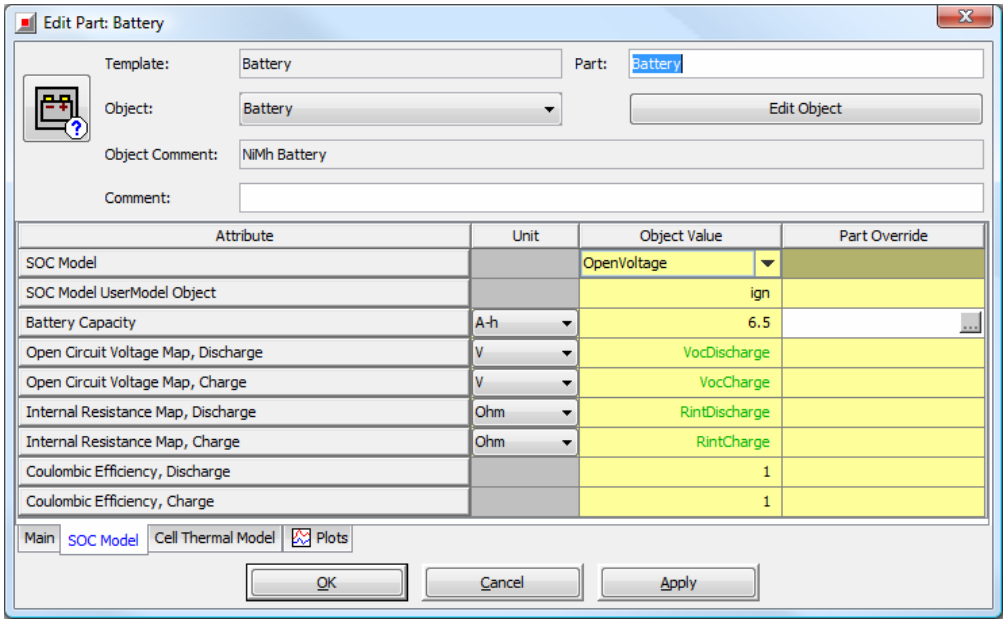
# Prius Model Overview and Components

- Planetary gear set
- 57 kW internal combustion engine (carrier)
- 50 kW traction motor / regenerative brake (ring -> vehicle drivetrain)
- 30 kW integrated starter / generator (sun)



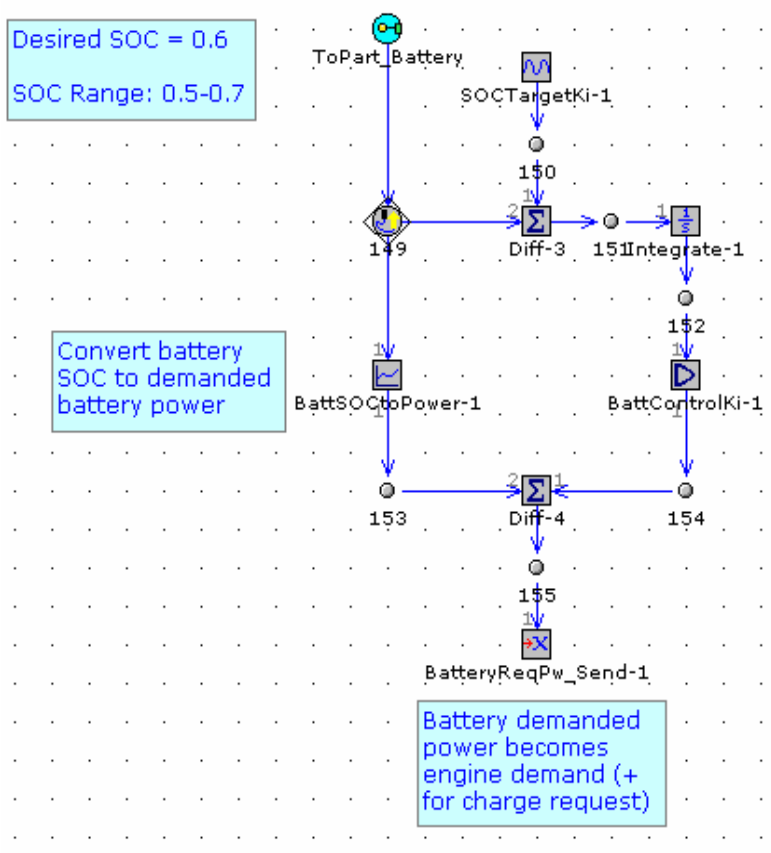
# Prius Model Components

- IC Engine modeled with map-based EngineState
- Electrical machines modeled with map-based MotorGeneratorMap
- Map-based battery model with hysteresis and cell thermal model (not applied currently)



# Prius Operating Strategy

- Battery target SOC = 0.6
- Thresholds also applied to operating modes for upper and lower limits; 0.5 and 0.7, respectively
- Battery requested power look-up table as a function of instantaneous SOC
- Additional integral gain demand added to lookup demand for additional SOC maintenance



# Prius Operating Strategy

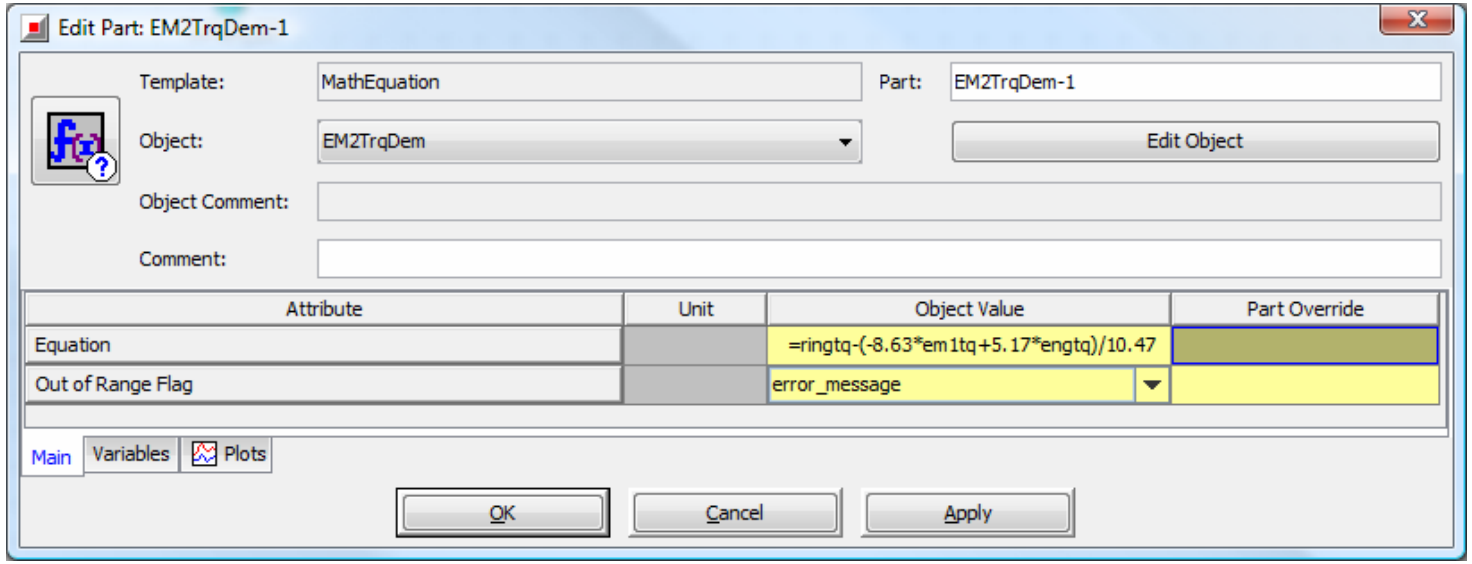
- Regenerative braking when battery SOC < 0.7
- Traction motor regenerative brakes up to torque limit then additional power sent to friction brakes
- Friction brake power converted to pedal position by maximum brake torque
- If high vehicle deceleration desired (a ≤ - 5 m/s^2), regenerative braking is disabled

# Prius Operating Strategy

- Total requested power (vehicle + battery) is sent as request to IC engine
- Lookup table for most efficient engine operating speed as function of requested power
- EM1 (generator) speed target determined through known ring gear speed and optimum engine speed
- Torque is applied by EM1 to accelerate or decelerate the engine to run at optimum speed, using the planetary gear set as a CVT between the vehicle and engine
- When request to start engine, EM1 applies torque to bring IC engine to operating speed

# Prius Operating Strategy

- EM2 (traction motor) power is determined by necessary ring gear torque to follow driving cycle, IC engine torque, EM1 torque, and constant geometric properties of the planetary gear set
- If IC engine off, vehicle operates in EV-only mode and EM2 provides all tractive power



# Prius Operating Strategy

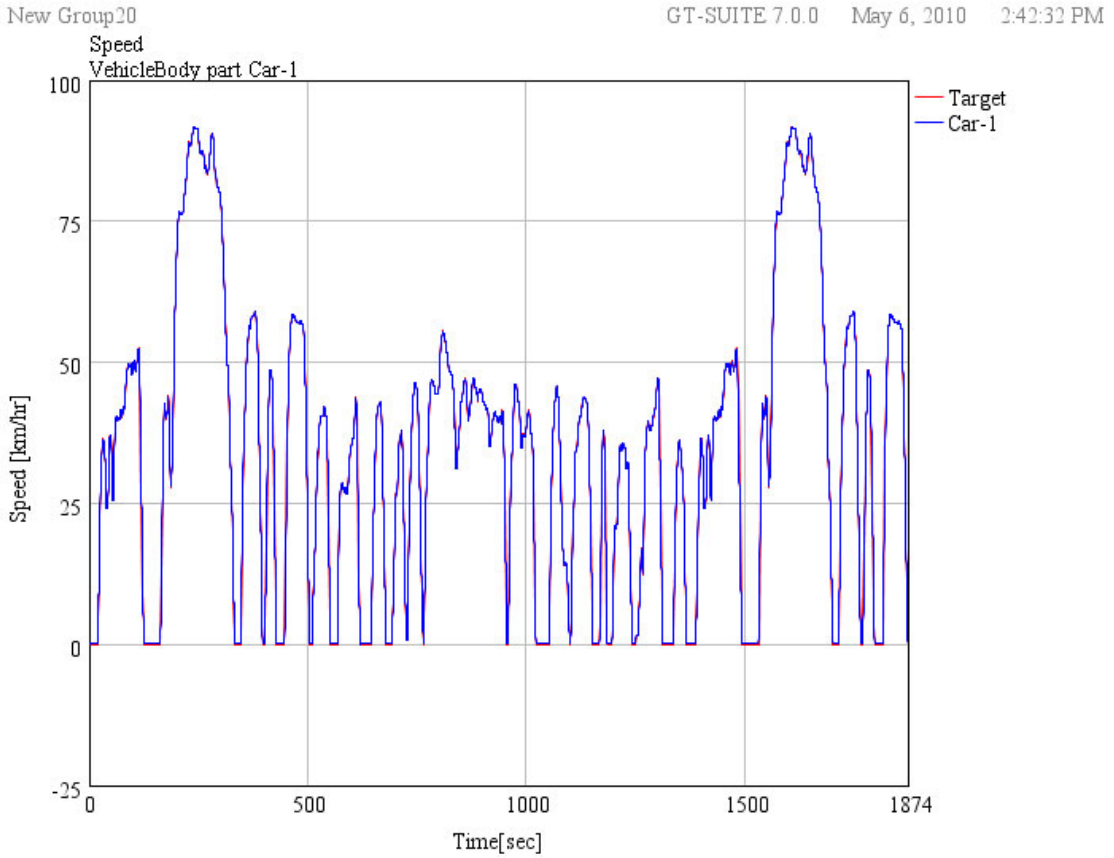
- Engine on/off strategy determined by demanded power and limits of generator
- Vehicle will operate in EV-only mode until 90% of maximum traction motor power is requested, generator speed < -6500 RPM, or SOC reaches 0.5
- Any of above criteria must be met for 0.1 s
- Engine must stay on/off for a minimum duration of 2 s

# Simulation Results

- Vehicle speed targeting very accurate, within 1 kph of target speed for FTP cycle
- Initial battery SOC: 0.6, Final battery SOC: 0.602
- FTP fuel economy: 52.3 mpg
- CPU Time: 5 min

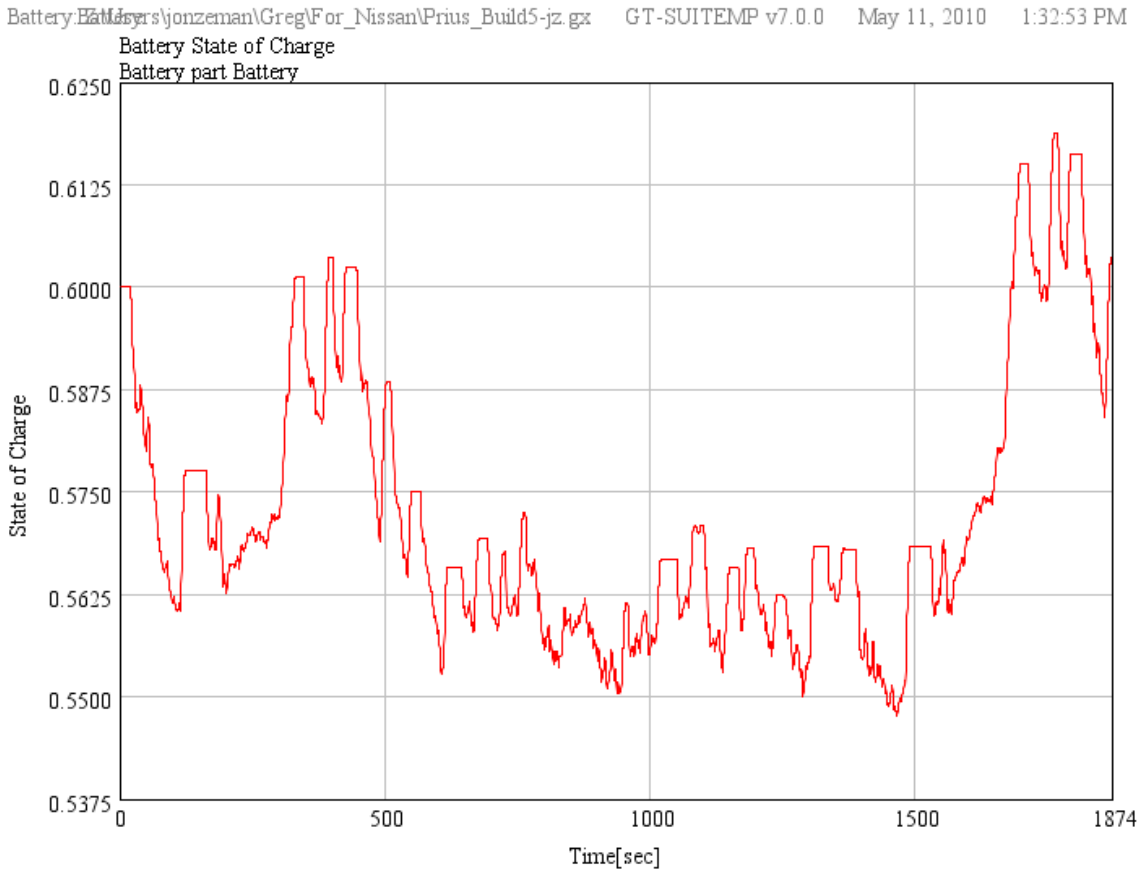
# Simulation Results

- Vehicle Speed



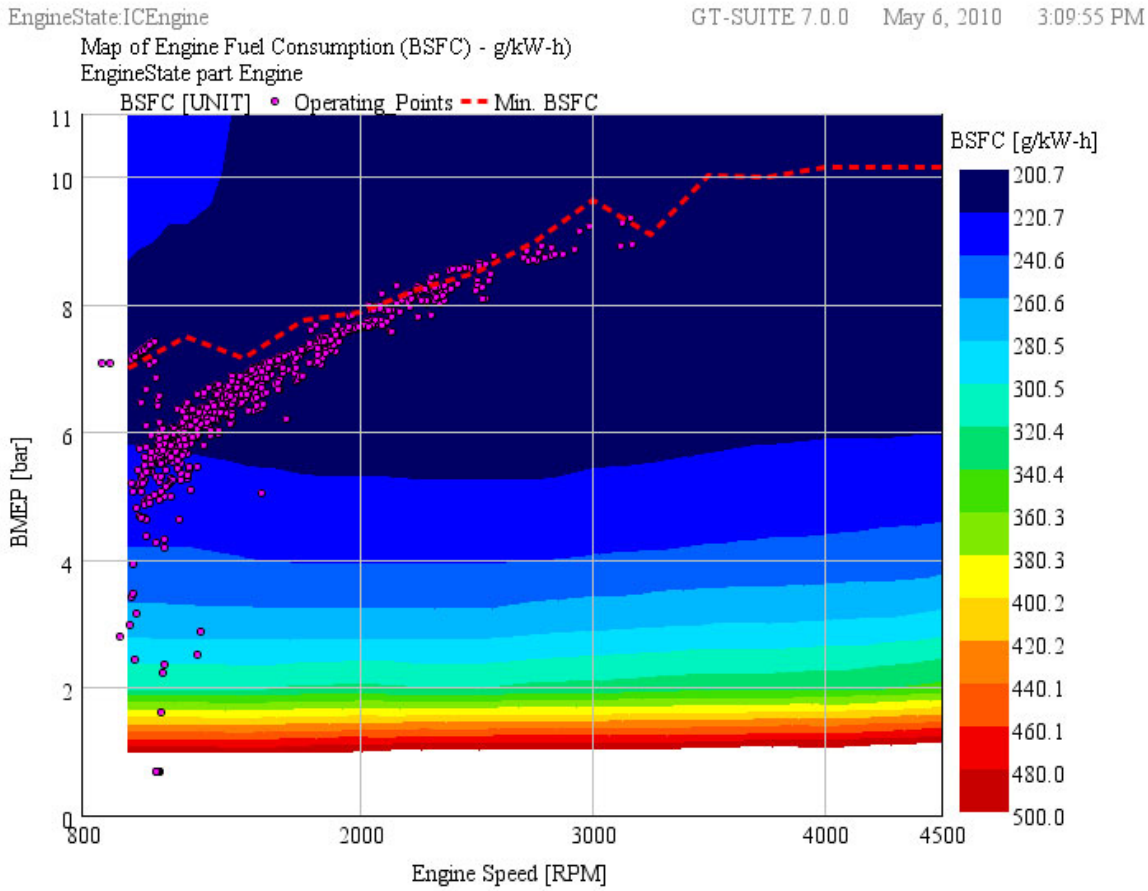
# Simulation Results

- Battery SOC



# Simulation Results

## Operating Locus on BSFC Map



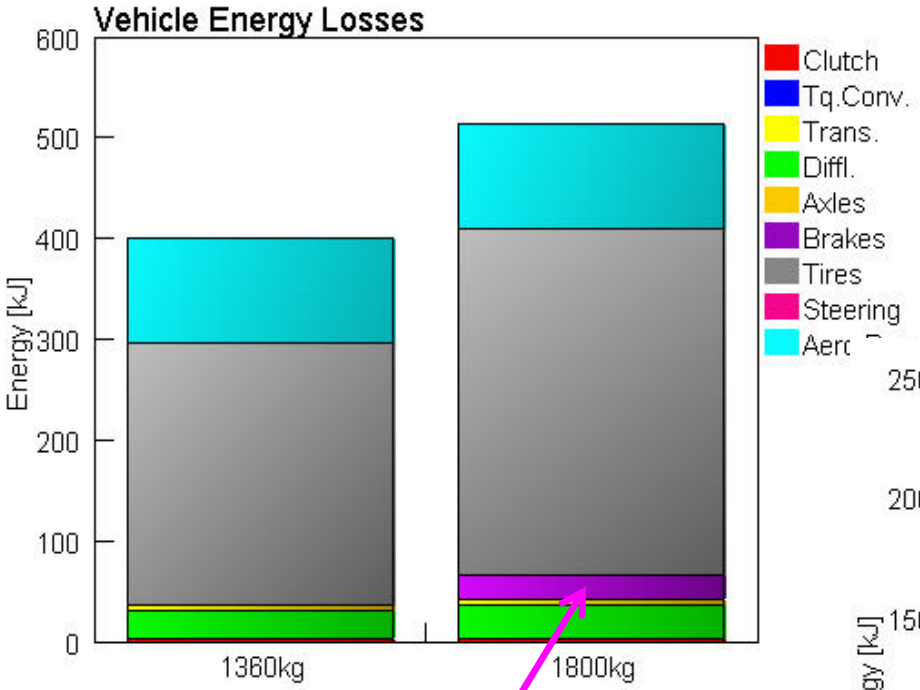
# Simulation Results

- Comparison with FEV model and published results, NEDC driving cycle
- Battery SOC target shifted to 0.5
- Initial battery SOC: 0.5, Final battery SOC: 0.549
- Fuel Economy: 47.7 mpg
- CPU Time: 2 min

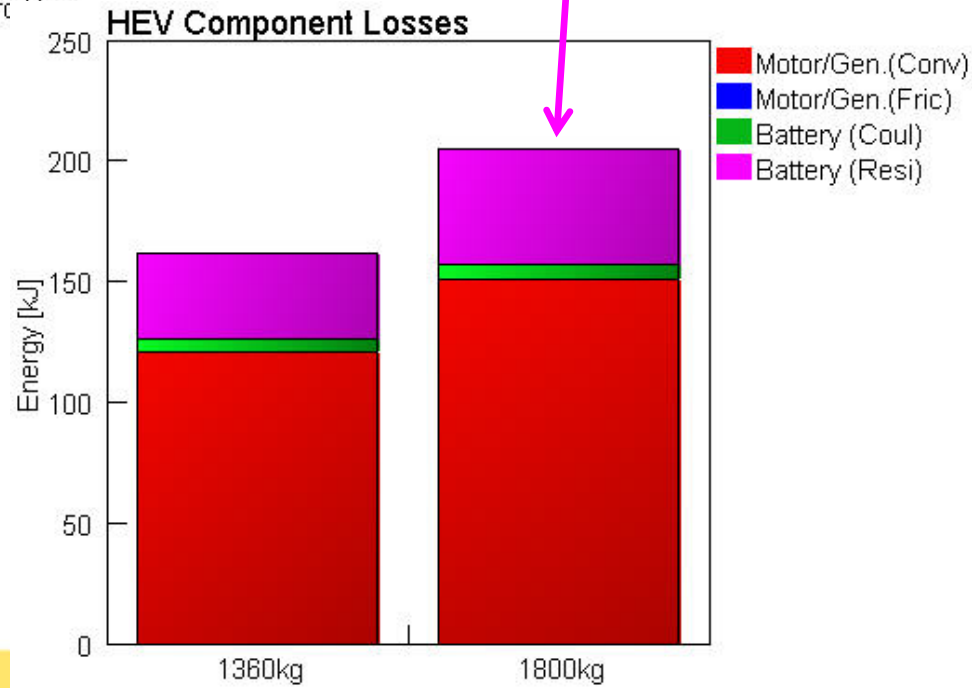
# •Energy Redistribution and Loss Output

## Example: Prius model, 187sec of FTP cycle

- *Energy Losses:Vehicle, HEV components*



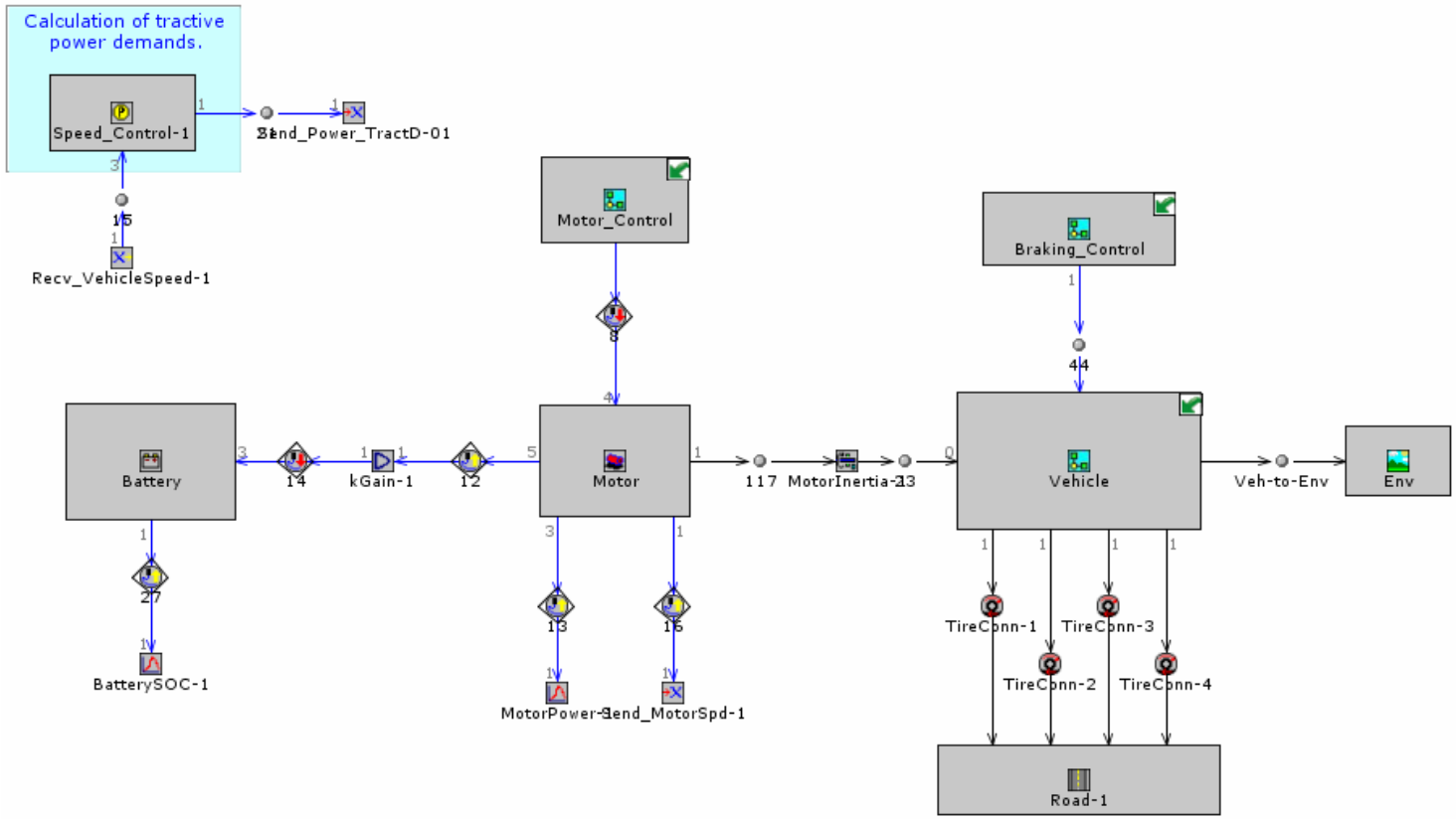

·Higher Electrical Energy Losses



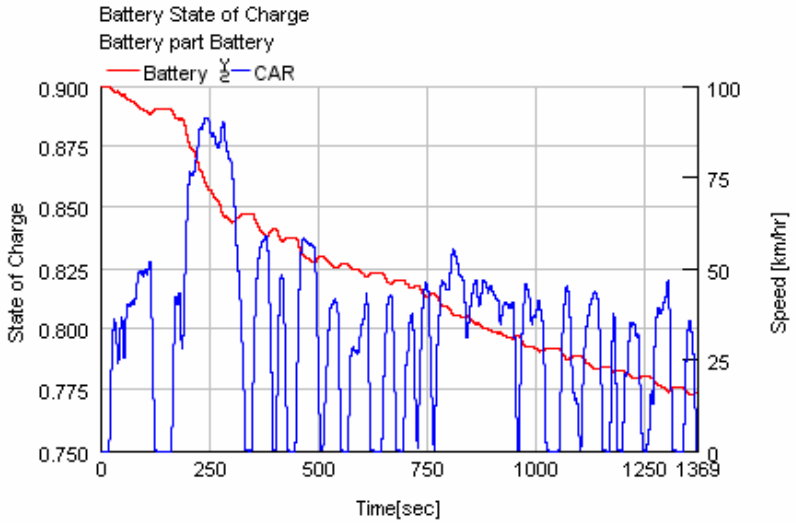

·Higher Braking Energy Loss

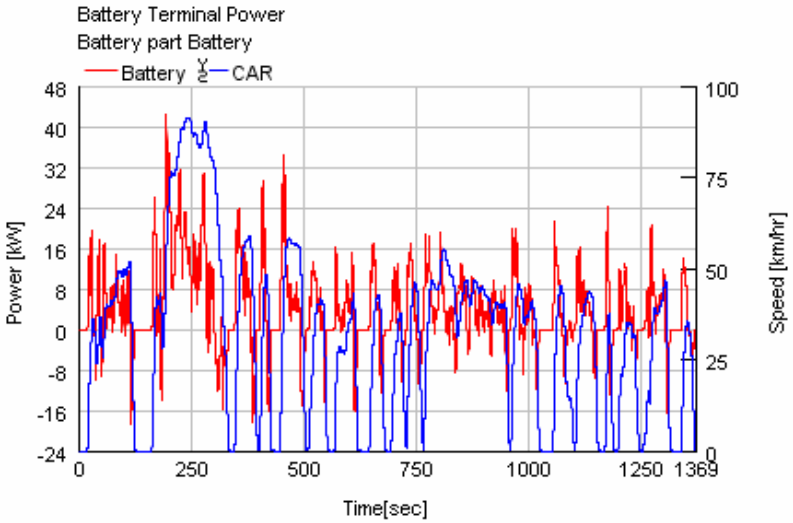
# GT-SUITE EV Model Example

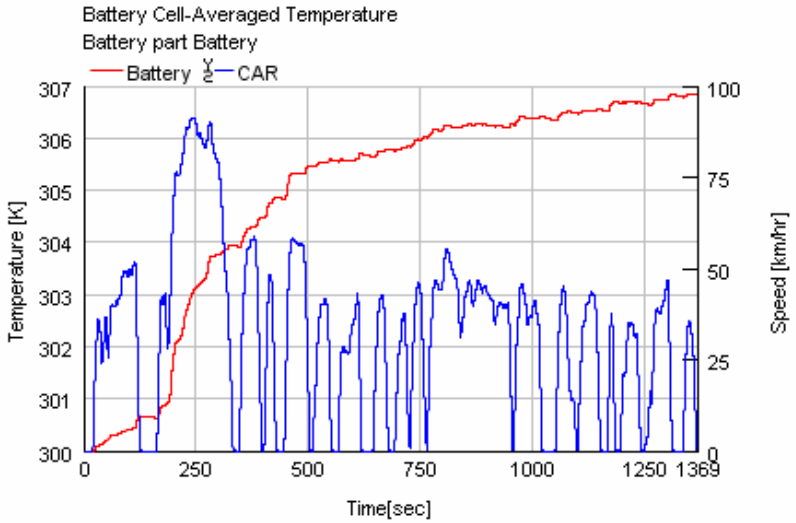
- Connect Battery, Motor/Generator and Vehicle in Series for EV (Delete EngineStete and Planetary Gear from HEV)

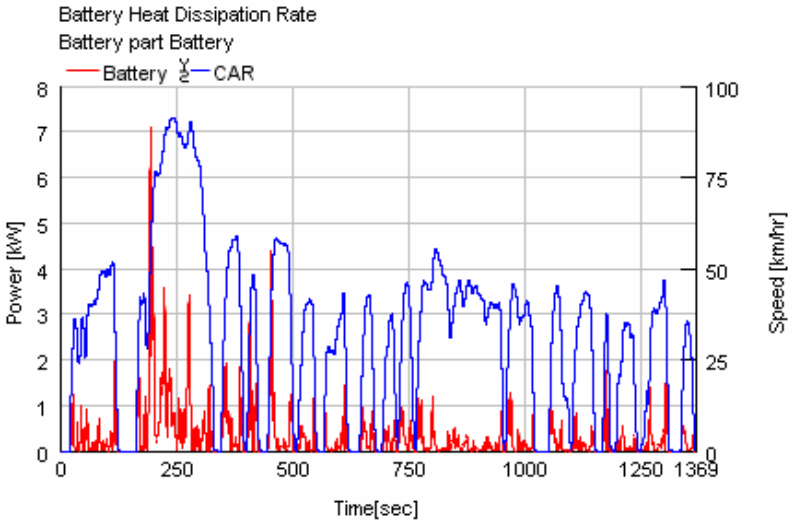


# GT-SUITE EV Model Example



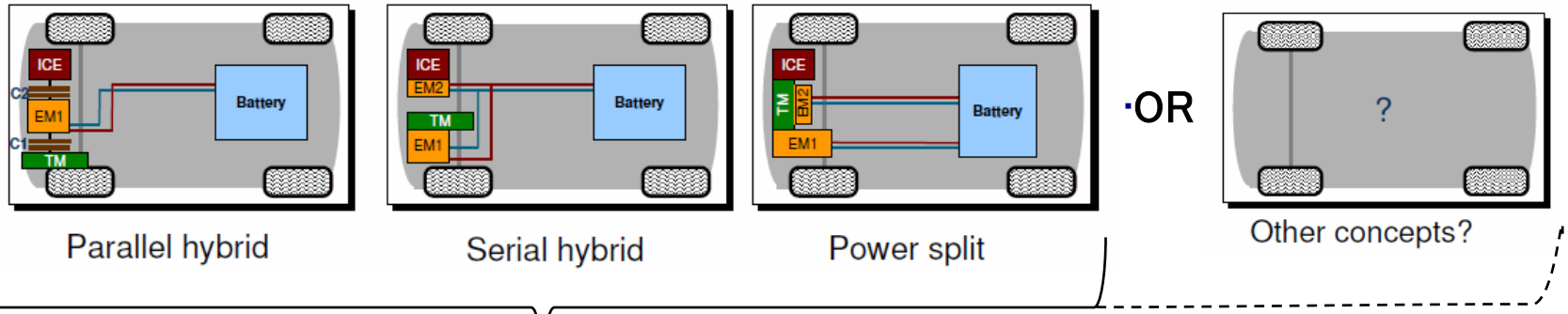



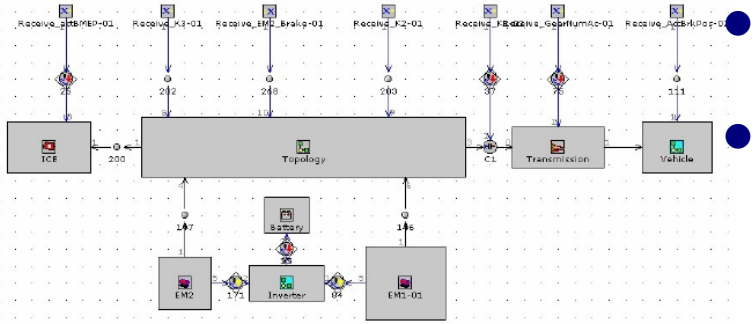
# GT-SUITE HEV Application (Volkswagen)

- GT-SUITE Conference in 2009
- **“All-in-one Simulation and DoE Methodology for the Evaluation and Optimization of HEV Configurations”**

Fast Concept Evaluation




All-in-One Model

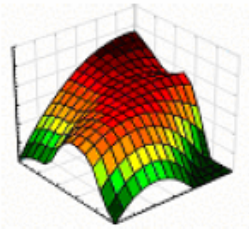


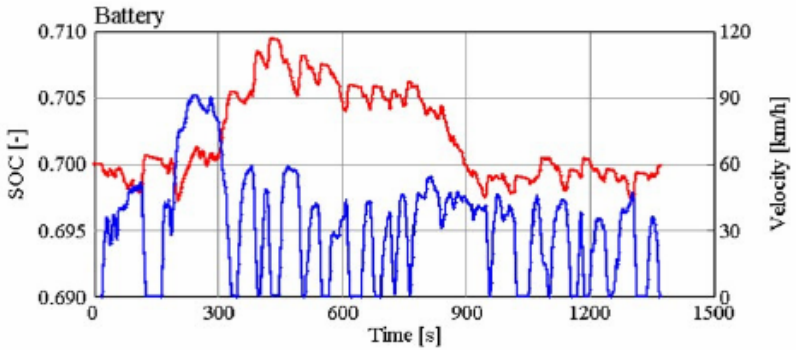

- Possible to use Same File for Several Configurations
- Easy to use DOE tool (Parameter Optimization) and Compare with Configurations

# GT-SUITE HEV Application (Volkswagen)

**Target magnitudes**

- **Fuel consumption → Minimum**
- **State of charge → Initial value**






**Compact Class vehicle**
**Cycle: FTP 72**
**General condition:**
**End SOC = Start SOC**

- This concept study enabled to define the most desirable HEV configurations for reduced fuel consumption
- Necessary step before doing thermal management and component design studies

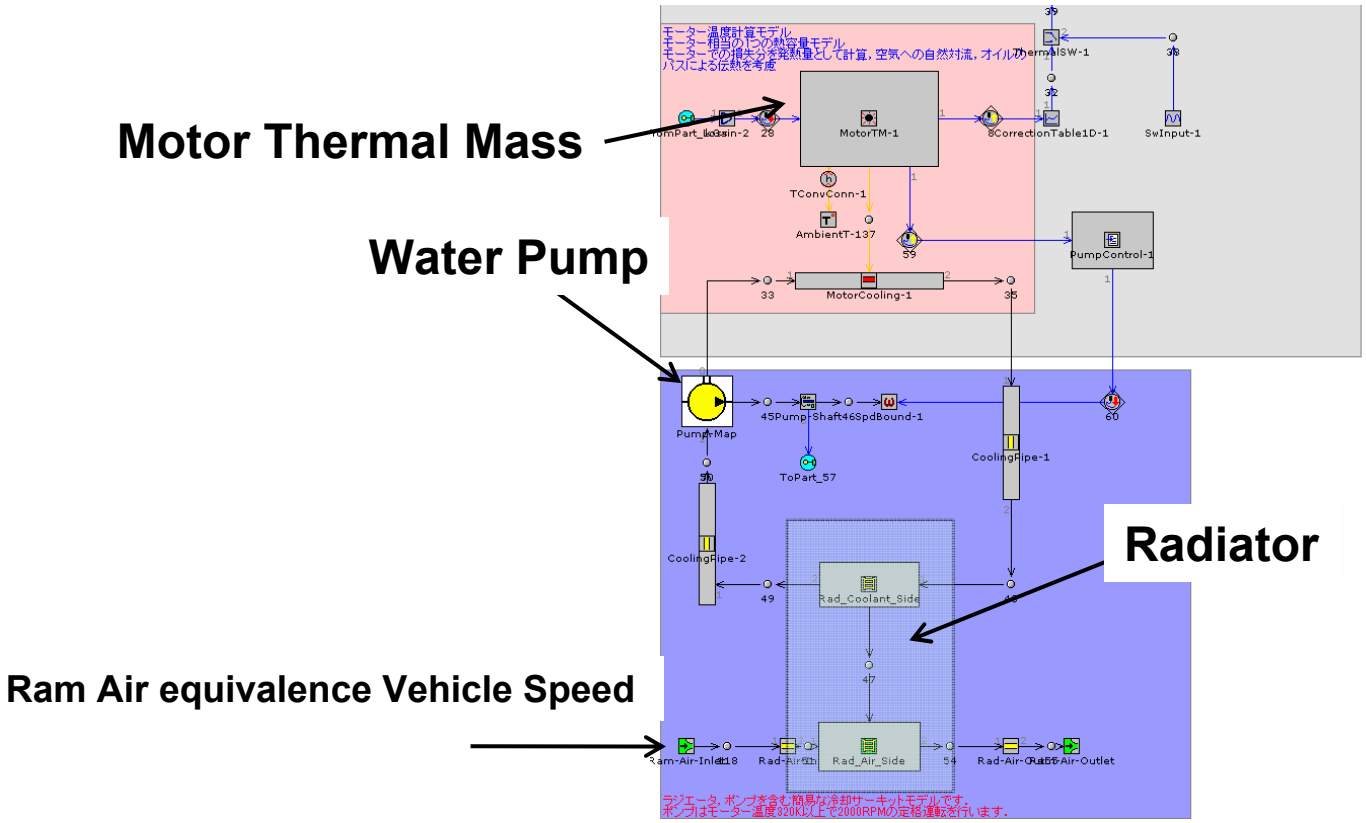
# HEV/EV Modeling w/ Thermal Management

- Integrated GT-SUITE Thermal Management Model (Engine Cooling and Lubrication) in HEV/EV

- Two Model for Motor/Generator
  - Input Loss Power of Motor/Generator to One “ThermalMass”
  - Input Loss Power of Motor/Generator to Multiple “ThermalMass “ as Caper Core, Iron Core, and Rotor in the Motor/Generator

# HEV/EV Modeling w/ Thermal Management

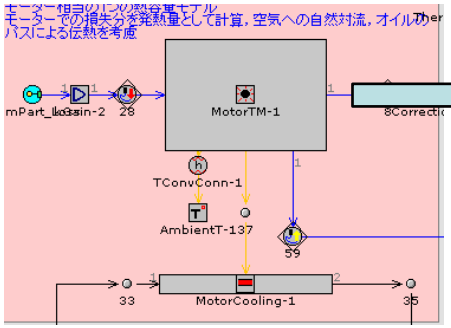
- Lumped Motor Thermal Model
  - Modeled as one thermal mass and calculated one temperature
  - Cooling Circuit Model includes Electric Pump and Radiator etc.

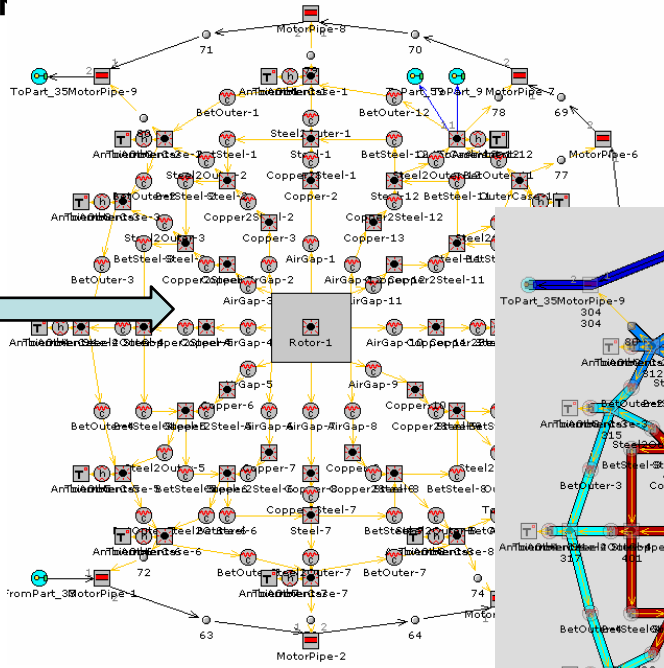


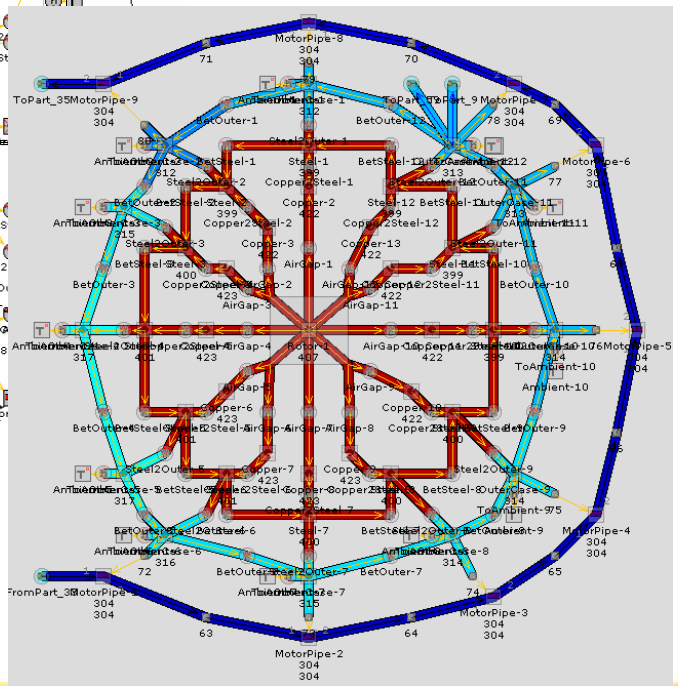
# HEV/EV Modeling w/ Thermal Management

- Divide One Mass into Multiple Thermal Masses to Calculate Temperature Distribution of Motor
- Divided Each Coil, Capper Core, Iron Core, Rotor and Casing

**Motor Thermal Mass**

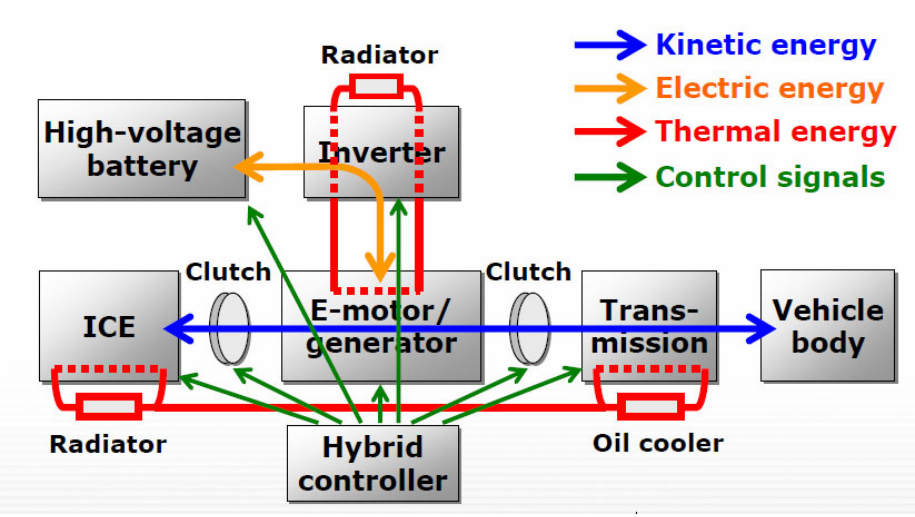


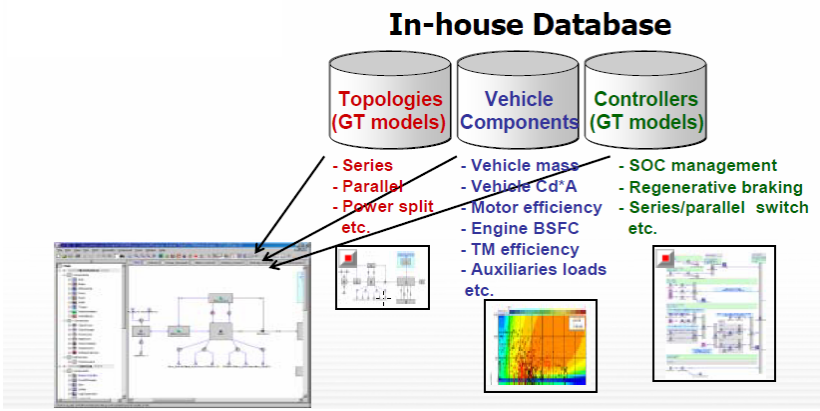



# GT-SUITE HEV Application w/ Thermal Management (Nissan)

- GT-SUITE Conference in Europe in 2011
- **"Integrated Powertrain Simulation for Energy Management of Hybrid Electric Vehicles"**
  - Fuel Consumption
  - Cooling of high-voltage system



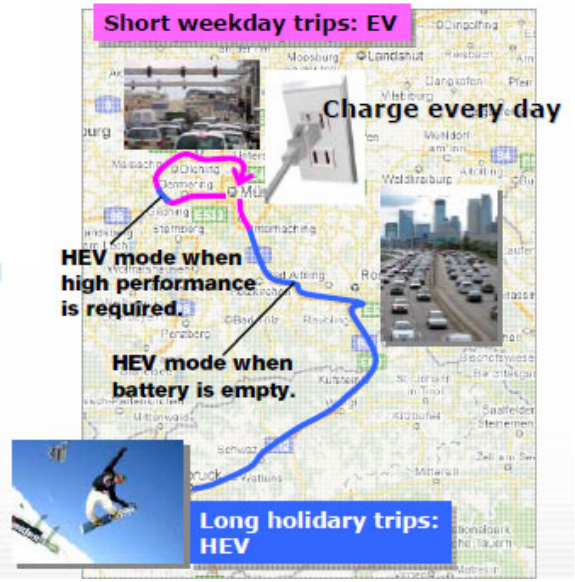

- All the basic models were prepared on GT-SUITE
- Easy to build a vehicle model by combining models



# GT-SUITE HEV Application w/ Thermal Management (Nissan)

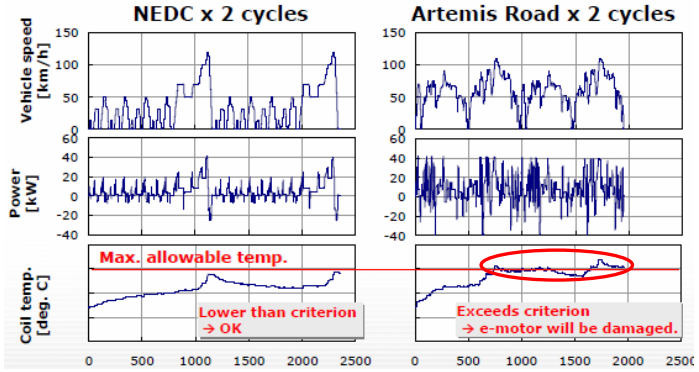
## Plug-in Hybrid Concept

- 2 drive modes
  - ✓ EV for short trips
  - ✓ HEV for long trips

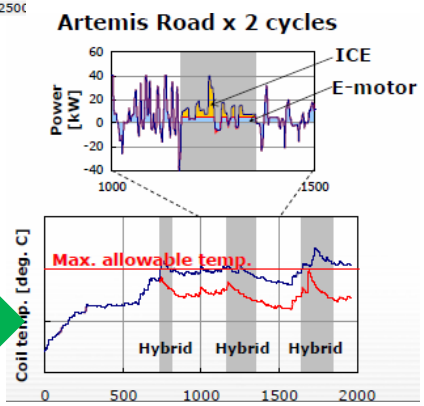



- 2/3 of annual mileage is covered by EV mode

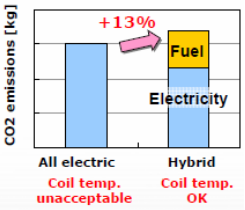
- EV mode




Coil Temp. Exceeded Criterion -> HEV mode

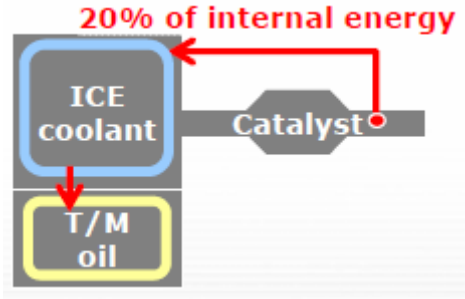


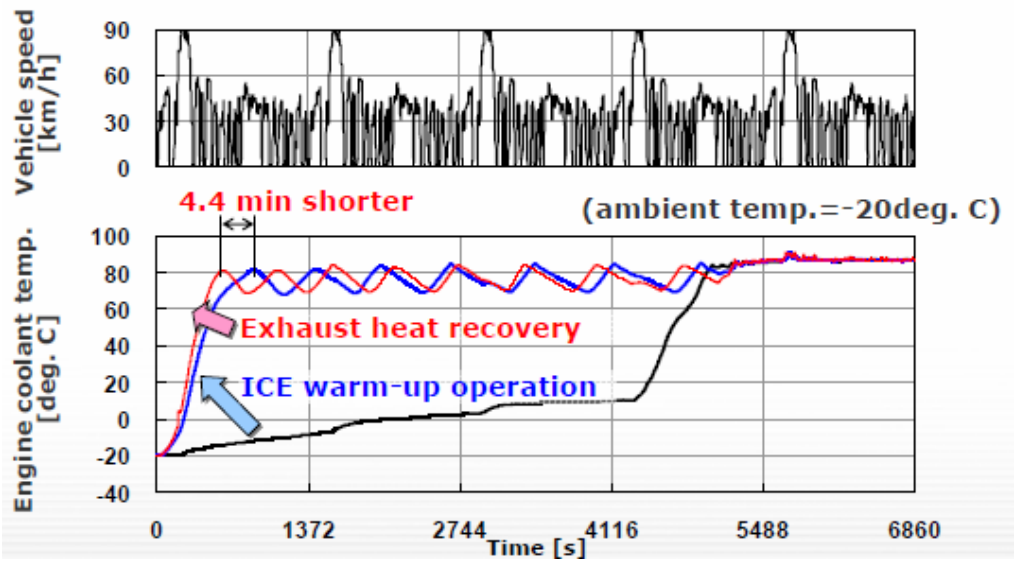

But CO2 emissions increase



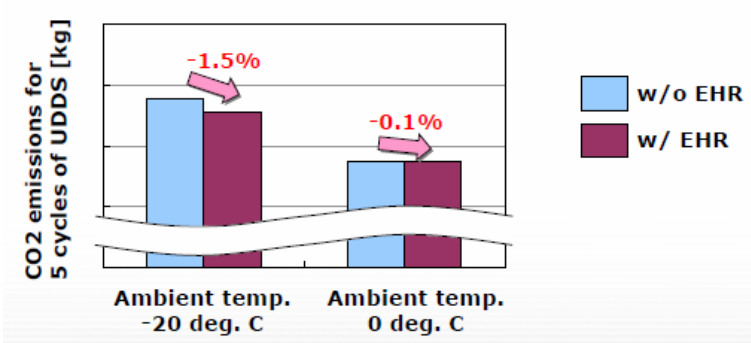
# GT-SUITE HEV Application w/ Thermal Management (Nissan)

- Effect of exhaust heat recovery on warm-up speed and F.E.?



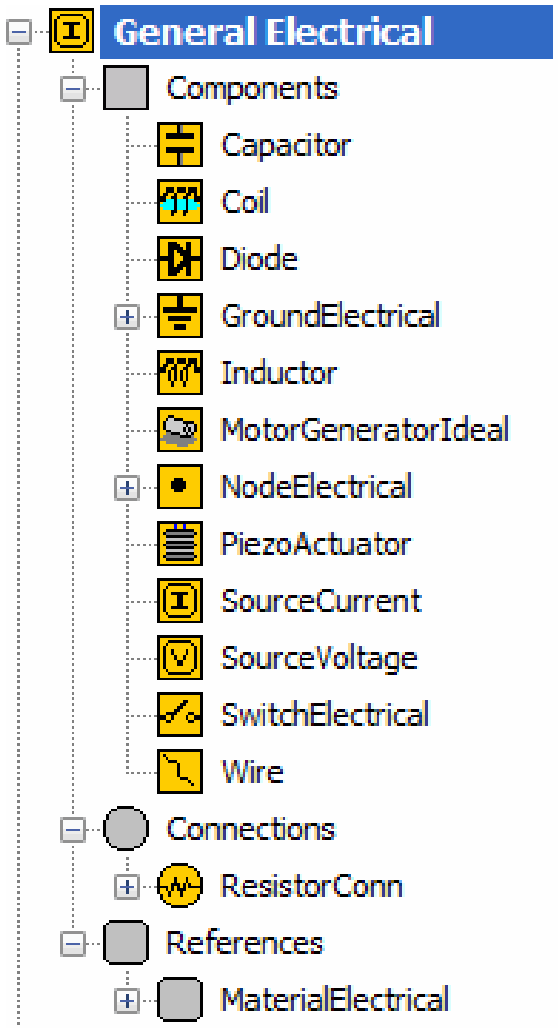

- Exhaust heat recovery reduces CO2 emissions
- Reduction of engine/transmission mechanical losses



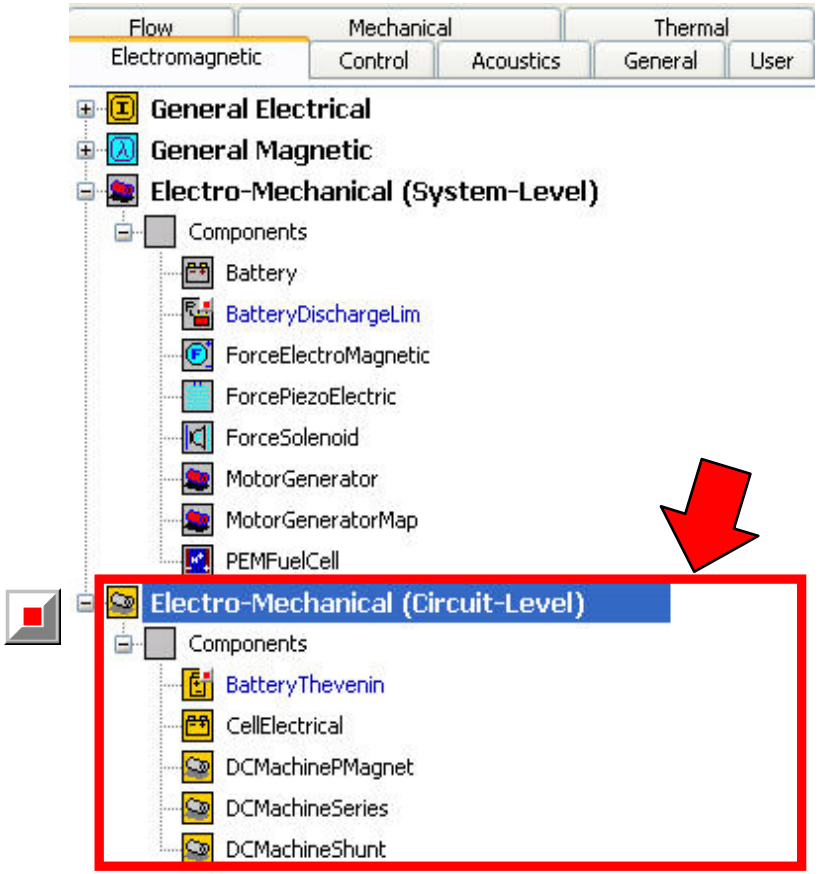
# End

# Circuit-Level Modeling

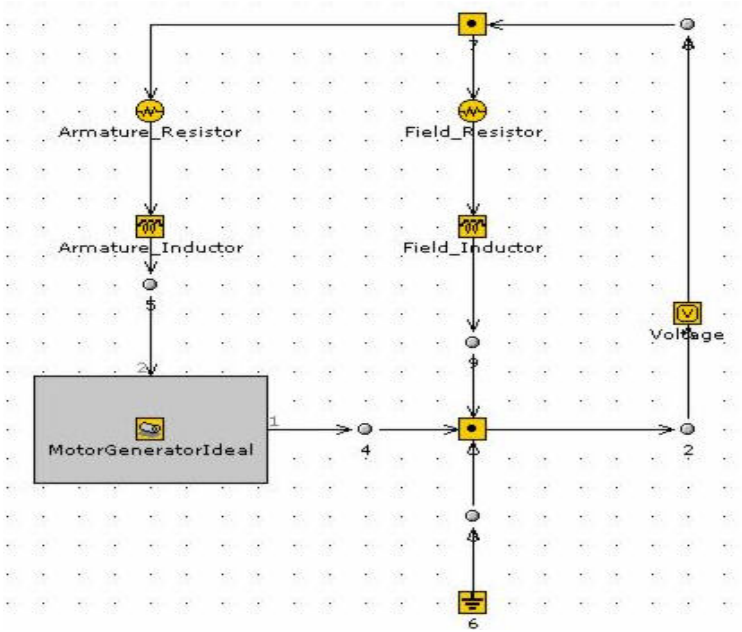
- Basic components from which one can build up elaborate electromagnetic and electromechanical systems
- Physically simulate an electrical or electromechanical



# Circuit-Level Modeling




- Easy-to-use, no submodel building required
- Contextual outputs
- Electrical, mechanical ports for connections to external circuits, shafts




•Internal circuit for shunt-type electric machine

# Circuit-Level Modeling

- Currently two available circuit-level battery models
- CellElectrical template is circuit-based equivalent to current map-based Battery
- BatteryThevenin compound adds internal battery capacitance and gives user a base model for more complex models

- Both models allow for independent charge/discharge dependencies
- Link losses to thermal model