Autonomie Vehicle Validation Summary

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Outline

- Validation Process
- Component Model Development and Validation
- Vehicle Validation Examples
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids (Blended)
  - E-REV PHEV
  - BEV
- Thermal Model Validation Overview
Generic Process to Validate Models Developed over the Past 15 Years

**Vehicle Instrumentation, Test Selection**

- Develop models
- Instantiate models
- Develop low and high level control strategies
- Test data analysis using ‘Import Test Data’ function in Autonomie
  - Evaluate individual sensors (QC)
  - Estimate additional signals for each component
  - Component performance data estimation
  - Find key parameter values and control scheme

**Calibration and validation of the vehicle model with test data**

- Dynamic performance validation
- Energy consumption validation

To quickly and accurately predict or evaluate the energy consumption and dynamic performance of the vehicle under various driving conditions.

**Vehicle model development**

- Develop models
- Instantiate models
- Develop low and high level control strategies
Advanced Vehicle Laboratory Capabilities

- Refrigeration unit
- Multi-Source Data Acquisition Systems
- Solar array lamps
- 90 kW Speed-Matched Fan
- Insulating walls

Thermal Capabilities:
- 0 deg F
- 95 deg F + Solar load
- Speed-matched airflow

Laboratory Enables:
- Studies in hot/cold effects on powetrain
- Measurements in A/C and heater power draw for advanced vehicles
In-depth Approach to Vehicle Instrumentation

- Significant instrumentation contributes to detailed vehicle/component understanding (120+ signals collected)

Many Signal Sources

- Torque sensors (axles)
- Components Speeds
- Coolant flow sensors
- Coolant / Component temperatures
- Exhaust temperatures, emissions
- Fast CAN data
- Scan tool data
- Power analyzer on many nodes
- Dynamometer loads, speeds
- Direct fuel measurement

→ All integrated into one DAQ system
Large Number of Test Should be Performed
Example of some of the cycles for the Prius MY10

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cycle length(s)</th>
<th>Engine starting temp (°C)</th>
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<td>23 - 57.5</td>
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</tr>
<tr>
<td>Long_SS_Warmups</td>
<td>1800</td>
<td>24 - 89.5</td>
</tr>
</tbody>
</table>
Importing Test Data into Same Environment as Models to Speed up Validation

- Change signal names and convert unit type for Autonomie format

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Test Unit</th>
<th>Unit Type</th>
<th>Matching Autonomie Unit</th>
<th>Converted Name</th>
<th>Converted Unit (SI)</th>
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<tbody>
<tr>
<td>12VBus_Cur_High[4]</td>
<td>A</td>
<td>current</td>
<td>A</td>
<td>acc_elec_12v_bus_cur_high_new_test</td>
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<td>12VBus_Vol_High[4]</td>
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<td>voltage</td>
<td>V</td>
<td>acc_elec_12v_bus_vol_high_new_test</td>
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<tr>
<td>Battery_Coolant_Hole_Temp[1]</td>
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<td>temperature</td>
<td>C</td>
<td>eoa_coolant_hole_temp_new_test</td>
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<tr>
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<td>C</td>
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<tr>
<td>Cell_Temp[1]</td>
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<td>temperature</td>
<td>C</td>
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<td>A</td>
<td>pc_dc_cur_high_new_test</td>
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<td>s</td>
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<td>Distance[m]</td>
<td>m</td>
<td>distance</td>
<td>m</td>
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<td>C</td>
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<td>A</td>
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<tr>
<td>MiData_Cur_LH_High[4]</td>
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<td>current</td>
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<td>A</td>
<td>eoa_data_cur_lh_high_new_test</td>
<td>A</td>
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<tr>
<td>MiData_Vol_High[4]</td>
<td>V</td>
<td>voltage</td>
<td>V</td>
<td>eoa_data_vol_high_new_test</td>
<td>V</td>
</tr>
</tbody>
</table>

Signals used in the calculation of missing parameters.
Additional Signals Estimated Based on Measured Data

Prius PHEV Battery Example

Generic Processes to define performance maps have been developed for the main powertrain components.
New Powertrain Might Need to be Developed
Example - Honda PHEV System Structure

- Tow Motor Hybrid System: “i-MMD” (Intelligent multi-mode drive powertrain)

**Operation Mode**

**EV Drive (One-Motor EV)**
**Hybrid Drive (Series ER)**
**Engine Drive (Parallel ER)**

Change three modes according to system efficiency.
New Plant Models Might Be Necessary
Example - DCT Plant Model Development

- vpa_par_2wd_p2_dct_cpl1_1mc :
  “Parallel PreTrans HEV Dual Clutch
  Trans 2wd Midsize”
Thermal Models Required Based on Current Standards
Battery Thermal Management System (TMS)

- **Liquid cooling system**
  - Components: pump, radiator, radiator fan, chiller, heater
  - Cooling mode: Active cooling, Passive cooling, Bypass, Heating

- **Liquid cooled thermal system model**
Each Individual Model Needs to Be Independently Validated

Process available for all the powertrain component models
Normalized Cross Correlation Power (NCCP) Used to Quantify the Validation

- Definition of NCCP ([SAE 2011-01-0881 Test Correlation Framework for HEV System Model – Ford Motor Co.]

\[ NCCP = \frac{\max[R_{xy}(\tau)]}{\max[R_{xx}(\tau), R_{yy}(\tau)]} \]

\[ R_{xy}(\tau) = \lim_{T \to \infty} \int_{0}^{T} x(t) \circ y(t - \tau)dt \]

This metric estimates the correlation between two signals by considering their magnitude and linearity.

Here, \( x \) and \( y \) represent individual signals. When applied to a test signal and a simulation signal of the same quantity, a value of NCCP equal to or greater than 0.9 indicates a high level of correlation. Conversely, a value less than this indicates a relatively poor correlation.
NCCP Fully Integrated into Autonomie

- Loading signals to compare

Test data result from ‘Import Test Data’, and Simulation data result from Autonomie model

A user can apply the NCCP function to the various comparisons, for example, ‘simulation vs. simulation’ or ‘test result vs. test result’ as well as ‘test vs. simulation’.

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  - BEV
- Thermal Model Validation Overview
Generic Processes Used to Generate Component Performance Maps from Test Data

- Engine map example (2010 Prius)
  - From 25 tests, the engine map is generated.
Some Component Performance Maps Also Provided by Nat Lab System

- Motor map (2010 Prius example)
  - Motor map is obtained from Oak Ridge National Laboratory (ORNL).

Without current for each motor, it is not possible to obtain the motor efficiency.
Accurate Low Level Controls Are Critical
DCT Shifting Events Example

- Acceleration - U.S. performance process: $1^{st} \rightarrow 2^{nd}$

Par HEV Dual Clutch Trans

Pre-selection synchronizing

CL1 declutching
CL2 clutching
Shaft1 neutral
Accurate Low Level Controls Are Critical
Using the Motor for a Pre-Trans HEV during Shifting

- The controller reacts by setting a torque-increasing intervention that is added to the torque of the electric machine (speed increase phase)
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Advanced Vehicle Benchmark Testing

- Advanced Powertrain Research Facility (APRF)
  - Benchmark advanced technology
  - Disseminate data, analysis to U.S. OEM’s, national labs, and universities.

- Argonne has been conducting very extensive testing of advanced vehicles for technology assessment:

  - 4WD chassis dyno: opened 2000, upgraded 2011
  - 2WD chassis dyno: opened 2009

- Ford Fusion (6ATX)  
- Mercedes S400H (7ATX)  
- HMC Sonata (6ATX)

In-depth Benchmarking Instrumentation Expertise

- Direct Fuel Measurement
- Scan-tool OCR Module
- Engine Torque Sensor
Calculation of Additional Signals
Gear Ratio Calculation Algorithm Developed

- 2013 HMC Sonata Conv. I4 6ATX

Sonata 6ATX Gear Ratio: 4.212 2.637 1.800 1.386 1.000 0.772

Gear Ratio Calculation
0) Signals are aligned based on vehicle speed
1) $SR = \frac{\text{Speed In (Measured from Turbine Speed)}}{\text{Speed Out (Calculated from Vehicle Speed)}}$
2) $SR = 1$st Gear Ratio when Vehicle Speed =0 & Engine speed < idle speed
3) Rounds the elements of SR to the nearest value of gear ratio that we know.
4) Filter out SR to keep current gear ratio for 0.8 sec (minimum)
Calculation of Additional Signals

Gear Ratio Calculation Validation

- 2013 HMC Sonata Conv. I4 6ATX

The number of up shifts: 62
The number of down shifts: 44
The number of total shifts: 106

From ANL DOT NHTSA VOLPE Report: Numerous conventional vehicles were tested on the FTP cycle at Argonne’s APRF, including the Fusion (6-speed); the Toyota Echo (5-speed); the Mercedes Benz S400 (7-speed); and the Volkswagen Jetta (7-speed DCT).

1) 5-speed automatic: 110 to 120
2) 6-speed automatic: **110 to 120**
3) 7-speed automatic: 130 to 140
4) 7-speed DCT: 130 to 140
Calculation of Additional Signals
Status of Torque Converter Lockup

- 2013 HMC Sonata Conv. I4 6ATX

  Speed In = Engine Speed (CAN)
  Speed Out = From Vehicle Speed

  Used torque ratio map as a function of speed ratio

When we do not know the status of the torque converter lockup for ATX

0) Signals are aligned based on vehicle speed
1) cpl_cmd = 1 (Locked)
   when the gap between speed in and out < 5 rad/s
2) cpl_cmd = 0 (unlocked)
   when 1st Gear Ratio
3) cpl_cmd = 0 (unlocked)
   when the accel of speed_in > 1 rad/s^2
4) Filter out cpl_cmd to keep current status for 1 sec (minimum)

Percentage Time Torque Converter is Locked (UDDS) : 10.1%
Test Data Analysis for Automatic Transmission
Impact of Powertrain Technology

- Sonata Conv. 6ATX vs. Sonata HEV 6ATX
Test Data Analysis for Automatic Transmission
Dedicated Analysis Functions Developed

- 2013 HMC Sonata Conv. 6ATX Example
Test Data Analysis for Automatic Transmission Functions to Develop Shifting Curves

- 2013 HMC Sonata Conv. 6ATX Example

Integrated and analyzed more than a dozen set of vehicle test data into Autonomie
Developing Shifting Maps Calibrations

Refined Shifting Algorithm / Calibration

- The new values of the parameters of shifting controller are added in the shifting initializer to defines the shifting maps created from test data.

Economical Shifting Speeds

- At very low pedal position

Performance Shifting Speeds

- At high pedal position

Example of engine speed range in economical driving, and economical shift

Maximum engine torque at wheels and performance upshift speeds
Developing Shifting Maps Calibrations

Refined Shifting Algorithm / Calibration

- Final shifting curves

**Economical Shifting Speeds**

\[ V_{up}^{dn} \quad V_{eco}^{up} \]

**Performance Shifting Speeds**

\[ V_{eco}^{dn} \quad V_{eco}^{up} \]

Refined Shifting Algorithm

\[ \alpha_{perf}^{dn} \quad \alpha_{eco}^{up} \]

Design of upshifting and downshifting speed curves for two adjacent gears

New shifting speed curves for a default light-duty vehicle in Autonomie
Developing Shifting Maps Calibrations
Refined Shifting Algorithm / Calibration

• Example: 2013 HMC Sonata Conv. I4 6ATX

“gb_ctrl_dmd_n_gen_eng_mot_not_included_detail.m” is created to match the shifting map based on test data.
Vehicle Model in Autonomie
Conv. ATX Configuration

- The ATX vehicles were simulated with two different shifting logic
  - *Shifting schedule analyzed from test data*
  - *Shifting schedule automatically generated by current and new shifting Initializer*
- The Lockup/Release used was the same for both vehicles
- The initialization files of transmission are created using public specification and test data.
- The vehicle specification including dyno losses, vehicle mass, wheel radius... are used from test data
- Rest of the vehicles were identical

2013 Hyundai Sonata Conv I4 6ATX
2012 Ford Fusion V6 6ATX
2012 Chrysler300 V6 8ATX
Model Validation in Autonomie
2013 Hyundai Sonata Conv. 6ATX

- UDDS – wheel power, engine fuel rate

Simulation 1 – current shifting Initializer
Simulation 2 – new shifting Initializer
Model Validation in Autonomie
2013 Hyundai Sonata Conv. 6ATX

- UDDS – gear number

Simulation 1 – current shifting Initializer
Simulation 2 – new shifting Initializer

UDDS - Vehicle Speed

UDDS - Gear number

NCCP = 0.982
NCCP = 0.983

NCCP : Normalized Cross Correlation Power
Model Validation in Autonomie
2013 Hyundai Sonata Conv. 6ATX

- HWFET – gear number

Simulation 1 – current shifting Initializer
Simulation 2 – new shifting Initializer

NCCP = 0.990

NCCP = 0.996
Model Validation in Autonomie
2012 Chrysler300 V6 8ATX

- UDDS – gear number

Simulation 1 – current shifting Initializer
Simulation 2 – new shifting Initializer

NCCP = 0.956

NCCP = 0.962
Model Validation in Autonomie
2012 Chrysler300 V6 8ATX

- NEDC – gear number

Simulation 1 – current shifting Initializer
Simulation 2 – new shifting Initializer

NCCP = 0.970

NCCP = 0.973

NCCP : Normalized Cross Correlation Power
Model Validation in Autonomie

2012 Chrysler300 V6 8ATX

- Accel. performance – gear number

Simulation 1 – current shiftingInitializer
Simulation 2 – new shiftingInitializer
# Shifting Algorithm Model Validation

- **2013 Hyundai Sonata Conv. (6ATX)**

<table>
<thead>
<tr>
<th></th>
<th>UDDS</th>
<th>HWFET</th>
<th>NEDC</th>
<th>LA92</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.982</td>
<td>0.990</td>
<td>0.980</td>
<td>0.986</td>
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<tr>
<td>Simulation 2 – new shifting Initializer</td>
<td>0.983 (0.10%)</td>
<td>0.996 (0.61%)</td>
<td>0.982 (0.20%)</td>
<td>0.991 (0.51%)</td>
</tr>
</tbody>
</table>

- **2012 Ford Fusion (6 ATX)**

<table>
<thead>
<tr>
<th></th>
<th>UDDS</th>
<th>HWFET</th>
<th>NEDC</th>
<th>LA92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation 1 – current shifting Initializer</td>
<td>0.968</td>
<td>0.998</td>
<td>0.951</td>
<td>0.994</td>
</tr>
<tr>
<td>Simulation 2 – new shifting Initializer</td>
<td>0.995 (2.79%)</td>
<td>0.998 (0%)</td>
<td>0.981 (3.15%)</td>
<td>0.988 (-0.61%)</td>
</tr>
</tbody>
</table>

- **2013 Chrysler 300 (8 ATX)**

<table>
<thead>
<tr>
<th></th>
<th>UDDS</th>
<th>HWFET</th>
<th>NEDC</th>
<th>LA92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation 1 – current shifting Initializer</td>
<td>0.956</td>
<td>0.984</td>
<td>0.970</td>
<td>0.938</td>
</tr>
<tr>
<td>Simulation 2 – new shifting Initializer</td>
<td>0.962 (0.63%)</td>
<td>0.993 (0.91%)</td>
<td>0.973 (0.31%)</td>
<td>0.957 (2.03%)</td>
</tr>
</tbody>
</table>

NCCP (the correlation for the gearbox) are above 0.93, that means we have a high level of correlation and that both simulations are very close to test data.
2013 VW Jetta HEV 7DCT Example

- UDDS – vehicle speed, SOC and gear number

Outstanding differences due to the fact that the vehicle level energy management was only correlated, not validated.
Nissan Altima Conventional CVT Example
UDDS cycle - vehicle speed, gear ratio and engine speed

UDDS - Vehicle Speed
Vehicle Speed (Simulation) vs Vehicle Speed (ANL Test)

UDDS - Gear ratio
Gear Ratio (Simulation) vs Gear Ratio (ANL Test)

NCCP : 0.993

UDDS - Engine Speed
Engine Speed (Simulation) vs Engine Speed (ANL Test)

NCCP : 0.980
Conventional Vehicle Summary

- **Test data were imported for numerous vehicles:**
  - We defined the input name and unit conversion data to import test data into Autonomie.
  - We calculated missing signals and developed a new process for analysis (gear ratio and input and output effort and flow for each component).

- **Dedicated analysis functions for shifting logic were developed.**

- **Shifting algorithm for several vehicles was calibrated by using two approaches:** calibration of initial algorithm and refined algorithm and calibration.

- **The simulation shows closed correlation with test data (NCCP > 0.9).**

- **Future work will focus on:**
  - Develop and validate algorithm to select optimum gear ratios for advanced transmissions (i.e. DCT, CVT)
  - Automating the shifting map calibration process from vehicle test data
  - Optimization of gear shift patterns to refine the gearshift patterns for immediate usage and thus the reduction of transmission calibration effort
Outline

- Validation Process
- Component Model Development and Validation
- Vehicle Validation Examples
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids (Blended)
  - E-REV PHEV
  - BEV
- Thermal Model Validation Overview
Honda Insight Validation

Motor used to compensate 12V load
Honda Insight Validation

Japan 10-15
Honda Insight Validation

Japan 10-15 SOC Comparison

![SOC Comparison Graph]

- **SOC (%)** vs **Time (s)**
- Dotted line: Measured
- Solid line: Simulated
## Honda Insight Validation Results

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Cons test mpg</th>
<th>Cons simul mpg</th>
<th>Diff in %</th>
<th>SOC init</th>
<th>SO Cf test</th>
<th>SO Cf simul</th>
<th>Diff in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan 10-15</td>
<td>57.9</td>
<td>58.8</td>
<td>1.5</td>
<td>0.596</td>
<td>0.610</td>
<td>0.611</td>
<td>0.4</td>
</tr>
<tr>
<td>NEDC</td>
<td>60.6</td>
<td>60.2</td>
<td>0.6</td>
<td>0.600</td>
<td>0.602</td>
<td>0.583</td>
<td>3.6</td>
</tr>
<tr>
<td>HWFET</td>
<td>74.2</td>
<td>75.3</td>
<td>1.4</td>
<td>0.590</td>
<td>0.588</td>
<td>0.589</td>
<td>0.2</td>
</tr>
<tr>
<td>UDDS</td>
<td>58.3</td>
<td>57.8</td>
<td>0.8</td>
<td>0.728</td>
<td>0.706</td>
<td>0.720</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Outline

- Validation Process
- Component Model Development and Validation
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  - Conventional Vehicles
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Toyota Prius 2010
2010 Toyota Prius
Vehicle Configuration

- **Motor**: 60kW
- **Net power**: 100kW
- **Final drive**: 3.268
- **FE (EPA)**: 50 MPG (comb.), 51/48 MPG (city/hwy)
- **0-60mph**: 10.0 s

**Engine Specifications**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>1.8L, 73kW</td>
</tr>
<tr>
<td>Battery</td>
<td>Ni-MH, 6.5Ah, 27kW</td>
</tr>
<tr>
<td>Motor</td>
<td>60kW</td>
</tr>
<tr>
<td>Net power</td>
<td>100kW</td>
</tr>
<tr>
<td>Final drive</td>
<td>3.268</td>
</tr>
<tr>
<td>FE (EPA)</td>
<td>50 MPG (comb.), 51/48 MPG (city/hwy)</td>
</tr>
<tr>
<td>0-60mph</td>
<td>10.0 s</td>
</tr>
</tbody>
</table>
Motor usually provides the propulsion power at low power demand.
Supervisory Control Analysis
Mode Decision Control (Engine On/Off)

The engine is turned on if the demand power is higher than a given threshold power.
Supervisory Control Analysis
Energy Management Strategy (SOC Balancing)

The engine is turned on if the demand power is higher than a given threshold power.
The engine torque is controlled according to the engine speed.

Generator speed and torque are determined by the engine speed and torque.
Impact of Thermal Condition on Control
Engine On/Off Is Changed By the Thermal Condition

The engine is forced to be turned on if the coolant temperature is low.

The engine is not turned off if the coolant temperature is low.

(a) Vehicle speed (m/s) [x 10]
(b) Engine speed (rad/s)
Engine torque (N.m)
Coolant temperature (C)

The engine is not turned off if the coolant temperature is low.
Impact of Thermal Condition on Control
Engine On/Off Is Changed By the Thermal Condition

The engine coolant temperature is maintained above $53^\circ\text{C}$. 

![Graph showing the impact of thermal condition on engine control](image)

- Normal ambient (21°C)
- Cold ambient (-7°C), Heater on
- Cold ambient (-7°C), Heater off

- Cold start

- Engine turned on
- Engine turned off
Impact of Thermal Condition on Control

Battery Power Is Constrained by the Battery Temperature

Maximum charging and discharging power are constrained by battery temperature.
The engine tries to use higher torque if the coolant temperature is lower.
More fuel is consumed if the coolant temperature is lower.
Internal resistance of the battery decreases as the temperature increases.
Thermal Impact on Component Performance
Round Trip Efficiency of the Battery

The loss is mostly caused by the Internal resistance.

Graph showing the relationship between Battery pack temperature (C) and Round-trip efficiency (%). The graph indicates that efficiency decreases as temperature increases. The efficiency is represented by two lines: one for Efficiency by $V_{\text{base}}$ (blue dots) and one for Efficiency by $V_{\text{output}}$ (red dots). The graph also includes a circuit diagram illustrating the components involved in the efficiency calculation.
Vehicle Model Development in Autonomie

Control Development for the Thermal Model

Control concept based on the analyzed results

Target generating

- Driver power demand
- SOC
- Thermal conditions

Mode decision (Engine on/off)

Energy management (SOC balancing)

Engine target generating

- Engine on/off demand
- Engine power demand
- Battery power demand

Target tracking

- Engine on/off demand
- Engine torque demand
- Motor 2 torque demand
- Motor torque demand
- Motor: torque target generation
- Driver power demand

Control signals

System feedback

Target generating

Target tracking

Mode decision

Energy management

Engine target generating

Motor 2: Engine speed tracking

Motor: torque target generation
Vehicle Model Development In Autonomie
Control Development for the Thermal Model

Driver power demand
SOC

Mode decision
(Engine on/off)

Energy management
(SOC balancing)

Thermal conditions

Engine target generating

Engine on/off demand

Engine torque demand
Engine speed demand

Motor 2: Engine speed tracking

Motor 2 torque demand

Motor:
torque target
generation

Battery power demand

Engine off (PEV mode)

Demand or Cold

Cranking

Cold

Idling

Hot

Fuel cut

Engine on (HEV mode)

Hot

Hot

Engine on/off demand

Engine torque demand

Motor 2 torque demand

Motor torque demand

All points
Selected points

Wheel speed (rad/s)

Wheel torque demand (Nm)

Vehicle speed (m/s)

Wheel torque demand (Nm)

Wheel speed (rad/s)

-200
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600

0
2
4
6
8
10
12
14
16
18

0
10
20
30
40
50
60

0
200
400
600
800
1000
1200
1400
1600
1800

0
200
400
600
800
1000
1200
1400
1600
1800

0
2
4
6
8
10
12
14
16
18

0
2
4
6
8
10
12
14
16
18

0
10
20
30
40
50
60

0
200
400
600
800
1000
1200
1400
1600
1800

0
200
400
600
800
1000
1200
1400
1600
1800
Vehicle Model Development In Autonomie
Control Development for the Thermal Model

- Driver power demand
- SOC
- Mode decision (Engine on/off)
- Thermal conditions
- Engine target generating
- Engine on/off demand
- Engine speed demand
- Engine torque demand
- Motor 2: Engine speed tracking
- Motor 2 torque demand
- Motor: torque target generation
- Battery power demand
- Motor torque demand
- Instant power
- Rating power
- Regenerative power

Graphs showing battery output power vs. SOC and battery output power vs. temperature, emphasizing energy management and thermodynamic conditions.
Vehicle Model Development In Autonomie

Control Development for the Thermal Model

Driver power demand

SOC

Mode decision 
(Engine on/off)

Energy management 
(SOC balancing)

Thermal conditions

Engine on/off demand

Engine target generating

Engine torque demand

Engine speed demand

Motor 2: Engine speed tracking

Motor 2 torque demand

Motor: torque target generation

Engine torque demand

Motor torque demand
Vehicle Model Development In Autonomie
Integration of Thermal Models

Generic component models are replaced by thermal component models
Simulation Results
UDDS (Hot Ambient, 35°C)
Simulation Results
HWFET (Cold Ambient, -7°C)

- Vehicle speed (m/s)
- Engine speed (rad/s)
- Engine torque (Nm)
- SOC (%)
- Fuel consumption (kg)
- Temperature (°C)
### Prius HEV Thermal Model Validation under Different Ambient Temperature

<table>
<thead>
<tr>
<th></th>
<th>Fuel Mass Consumed (kg)</th>
<th>Final SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>test</td>
<td>simu</td>
</tr>
<tr>
<td>UDDS(Normal)</td>
<td>0.300</td>
<td>0.303</td>
</tr>
<tr>
<td>UDDS(Cold)</td>
<td>0.523</td>
<td>0.543</td>
</tr>
<tr>
<td>UDDS(Hot)</td>
<td>0.478</td>
<td>0.462</td>
</tr>
<tr>
<td>HWFET(Normal)</td>
<td>0.914</td>
<td>0.915</td>
</tr>
<tr>
<td>HWFET(Cold)</td>
<td>1.035</td>
<td>1.012</td>
</tr>
<tr>
<td>HWFET(Hot)</td>
<td>1.089</td>
<td>1.104</td>
</tr>
</tbody>
</table>
Nissan HEV CVT
Metal V belt CVT

- CVT can provide high engine thermal efficiency by continuous ratio control independent of the vehicle velocity
- CVT has disadvantages such as low torque capacity, mechanical and hydraulic loss
Overall CVT Structure

Variator working principles and lay-out

- Primary pulley (engine side)
- Secondary pulley (road side)

Final reduction

Secondary pulley

Primary pulley

Hydraulic unit

Engine

Output

High ratio

Low ratio (OD)

- \( P_p \): provide ratio adjustment of the belt.
- \( P_s \): provide clamping. Torque is transmitted by the friction between belt and pulley

\[ \begin{align*}
N_s & \times \frac{P_p}{P_s} = N_{dle}
\end{align*} \]
Hydraulic pump loss and mechanical loss (variator belt & pulley loss)

- Hydraulic pump loss: major part in the total loss at low vehicle speeds
- Mechanical loss: major part in the total loss at high vehicle speeds

Vehicle Configuration

- Parallel hybrid configuration

The engine and motor speed can be controlled independently of the vehicle speed, owing to the CVT’s continuously variable feature

\[ \omega_{\text{engine}} = \omega_{\text{motor}} \]

\[ \omega_{\text{motor}} = i_{\text{cvt}} \times \omega_{\text{wheel}} \]

<table>
<thead>
<tr>
<th>&lt; Vehicle specifications &gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine</strong></td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>Torque</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td><strong>Motor</strong></td>
</tr>
<tr>
<td>Max. power/torque</td>
</tr>
<tr>
<td>Max. speed</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
</tr>
<tr>
<td>Number of cells</td>
</tr>
<tr>
<td>Nominal cell voltage</td>
</tr>
<tr>
<td>Rated pack energy</td>
</tr>
<tr>
<td><strong>TM</strong></td>
</tr>
<tr>
<td>CVT ratio</td>
</tr>
<tr>
<td>Final drive ratio</td>
</tr>
<tr>
<td><strong>Vehicle</strong></td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Tire radius</td>
</tr>
</tbody>
</table>
Oil pump efficiency depends on the line pressure and input speed

- Oil pump efficiency map from experiment is used

\[
P_{\text{pump,loss}} = P_{\text{line}} D_{\text{pump}} \omega_{\text{pump}} / \eta_{\text{pump}}
\]

\[
\Rightarrow T_{\text{pump,loss}} = P_{\text{line}} D_{\text{pump}} / \eta_{\text{pump}}
\]

\[
\eta_{\text{pump}} = f(i_{\text{CVT}}, P_{\text{line}})
\]

\[
i_{\text{CVT}} = \omega_p / \omega_s : \text{CVT ratio}
\]

\[
P_{\text{line}} : \text{line pressure}
\]

\[
D_{\text{pump}} : \text{pump displacement}
\]

\[
\omega_{\text{pump}} : \text{pump speed}
\]

\[
\eta_{\text{pump}} : \text{oil pump efficiency}
\]

*W. Ryu “A Study on Metal Belt CVT Control for System Efficiency Improvement”, Dissertation of Sungkyunkwan University, 2006
Mechanical losses depend on the speed ratio, input torque and vehicle speed

- Mechanical loss model

**CVT mechanical efficiency**

\[ \eta_{mech} = f(i_{cvt}, T_t, V_v) \]

- \( i_{cvt} = \frac{\omega_s}{\omega_p} \): speed ratio
- \( T_t \): turbine torque
- \( V_v \): vehicle speed

\[ \eta_{mech} = \left( \frac{T_{in} - T_{mech.loss}}{T_{in}} \right) \]

\[ T_{mech.loss} = (1 - \eta_{mech})T_{in} \]

\[ T_{in} = T_{engine} - T_{pump.loss} \]

Mechanical losses depend on the speed ratio, input torque and vehicle speed

- CVT shift dynamics model

\[ \frac{di}{dt} = \beta(i) \cdot \omega_p \cdot (P_p - P_p^*) \]

Ratio changing speed is dependent on the deviation of \((P_p - P_p^*)\) and input speed.

**FpFs map**

- The CVT ratio-torque ratio-thrust ratio characteristic is shown by FpFs map*
- The FpFs map* is obtained from SKKU experiments

\[ FpFs = \frac{F_p}{F_s} = f(i_{cvt}, T_r) \]

\( F_p \): primary clamping force
\( F_s \): secondary clamping force
\( i_{cvt} \): CVT ratio
\( T_r = \frac{T_{in}}{T_{max}} \): torque ratio


** J. Park “A Study on Shift Control Algorithm for a 2 stage CVT”, Dissertation of Sungkyunkwan University, 2012
Overall New CVT Model

- The each pressure are determined to control the demanded CVT ratio

**CVT system block diagram**
Development of vehicle performance simulator

- The component and models developed in this study are integrated into Autonomie
Driving Mode Control Analysis

- In the target HEV, the engine is a main power source and the motor assists the engine according to the vehicle operating conditions.

**Acceleration**
- Engine on
- Motor
- Transmission
- Battery
- Motor assist or off

**Cruising**
- Engine off
- Motor
- Transmission
- Battery
- Motor operate (propel)

**Deceleration (regenerative braking)**
- Engine off
- Motor
- Transmission
- Battery
- Motor regenerate

**Idling**
- Engine off
- Motor
- Transmission
- Battery
- Motor operate (starting)
Driving Mode Control Analysis

- Control analysis was performed for a hybrid electric vehicle (HEV) equipped with a continuously variable transmission (CVT) under various driving conditions.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Operating Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV mode</td>
<td>Low-speed cruise/low power</td>
</tr>
<tr>
<td>Engine mode</td>
<td>Slow acceleration/high-speed cruise</td>
</tr>
<tr>
<td>HEV mode</td>
<td>Start-up/aggressive acceleration</td>
</tr>
</tbody>
</table>
Driving Mode Control Analysis

- The OOL_high and OOL_low curves were determined from the experimental results by considering the engine operation for each vehicle driving mode.

Driving mode control analysis in HEV mode
Results

UDDS cycle

HWFET cycle

Vehicle speed, mile.

Gear ratio

Engine torque, Nm

Battery SOC

Time, sec

Simulation

ANL Test
Validation Results

- The normalized cross correlation power (NCCP) value, which shows the correlation level, was used to compare the simulation and experimental results quantitatively.

\[
NCCP = \frac{\max[R_{xy}(\tau)]}{\max[R_{xx}(\tau), R_{yy}(\tau)]}
\]

\[
R_{xy}(\tau) = \lim_{\tau \to \infty} \frac{1}{T} \int_{0}^{\tau} x(t) \cdot y(t - \tau) dt
\]

### NCCP values for UDDS and HWFET cycles

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Vehicle Speed</th>
<th>Gear Ratio</th>
<th>Engine Torque</th>
<th>Battery SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWFET</td>
<td>0.99</td>
<td>0.98</td>
<td>0.90</td>
<td>0.97</td>
</tr>
<tr>
<td>UDDS</td>
<td>0.99</td>
<td>0.93</td>
<td>0.90</td>
<td>0.96</td>
</tr>
</tbody>
</table>
Outline

- Validation Process
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Prius PHEV
Mode Control: Engine On/Off Determined by Demand Power and Vehicle Speed

- Vehicle operating points according to engine status
  - Wider range of motor only operation in PHEV due to CD mode

<table>
<thead>
<tr>
<th>Engine Operation</th>
<th>Engine Speed</th>
<th>Fueling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine off</td>
<td>0</td>
<td>Off</td>
</tr>
<tr>
<td>Cranking</td>
<td>Accelerating</td>
<td>Ready to fuel</td>
</tr>
<tr>
<td>Idling</td>
<td>Idle speed</td>
<td>Idling</td>
</tr>
<tr>
<td>Fuel cut</td>
<td>Idle speed</td>
<td>Off</td>
</tr>
<tr>
<td>Engine on</td>
<td>Controlled</td>
<td>Controlled</td>
</tr>
</tbody>
</table>
Mode Control: Engine Is Turned On Differently in CS & CD Modes

- Engine turn on condition
  - CD mode: Turned on if the demand power > power threshold (35kW, battery maximum)
  - CS mode: Turned on mostly if the demand power > defined power threshold line

The on/off strategy in CS mode looks similar to the strategy of HEV
  - More EV driving in PHEV
  - Change of driving pattern (CD to CS)
**Mode Control: CD or CS modes Can Be Determined by Engine On Points and SOC**

- **Driving mode change**
  - Analysis of driving mode according to engine turn on point change
  - When SOC is over 28% engine is turned on in higher power demand (30kW) than under 28% (under 15kW)
  - \(\Rightarrow\) reasonable to select 28% for mode change between CD mode to CS mode

![Mode Control Diagram](image-url)

- ACC > Max. electric power?
  - Yes: Power performance mode
  - No: EV mode (CD mode)
- SOC > 28%?
  - Yes: Engine turns on according to CS mode
  - No: Engine on map and proportional to SOC

Mode control flowchart:

- **Engine on when Temp. of Eng. > 90C and SOC > 28%**
- **Engine on when Temp. of Eng. > 90C and SOC < 28%**
Mode Control: Engine Is Turned On If Battery Cannot Provide All Power Required In CD Mode

Engine turn on when the vehicle requires the power exceed battery maximum output power (< 35kW)
Mode Control: Engine Is Turned ON If Demand Torque Exceeds a Threshold Line In CS Mode

Threshold line is changed according to SOC
We can say that the threshold power is lower if SOC is lower.
Energy Management Strategy: SOC Balancing Strategy Is The Same As the HEV Strategy In CS mode

- SOC Balancing Strategy
  - ACC pedal > 80% → engine and battery working together
  - CS mode: Battery power is proportional to SOC (the same as HEV)
  - CD mode: output power of the battery is 0kW to 10kW
Energy Management Strategy: The Battery Produces Constant Power On Highway Driving In CD Mode

- Strategy in CD mode
  - Normal speed driving (28m/s ≈ 100km/h): Engine provides all required power.
  - High speed driving (> 28m/s): Output power of the battery is about 10kW (Battery supporting mode)

In CD mode, the engine is basically not used. However, the engine is mostly turned on for highway driving, so this special control concept is necessary for highway driving.
Component Operation Control: Engine Target Is The Same As The Engine Target of HEV

- Engine is operated followed by a specific line
- No difference between CD and CS mode
PHEV Has Similar Regenerative Performance Than Prius HEV

The battery in PHEV is constrained by SOC. (not observed in HEV due to SOC range)

Instead, constraint by temperature in PHEV is not observed because the temperature is really well controlled

PHEV uses slightly wider range due to benefit of the larger battery.
Summary of Operation

- Summary (at normal temperature)

**CD mode**
- Engine off (EV)
- Brake signal & Vehicle speed < 28m/s
- Required power > Max. electric power

**CS mode**
- Engine off (EV)
- Brake signal & Vehicle speed < 20m/s

**Engine on**
- Vehicle speed < 28m/s
  - Engine only mode \( P_{bat} = 0 \)
- Vehicle speed > 28m/s
  - Battery supporting mode \( P_{bat} = 10kW \)

SOC < 28%

SOC > 30%

- Battery output power is proportional to SOC
In CD Mode, Engine Is Forced To Be Turned On To Provide Heat To The Cabin

- Normal and hot ambient tests
  - Leave the engine off
- Cold ambient tests
  - On if the coolant temp. < 40°C
  - (no electrical heater for the cabin)

Engine is turned by the demand power or by the temperature condition.
In Cold Start Case, The Engine Is Turned On All The Time On UDDS Driving Cycle Even In CD Mode

- Engine is not able to reach to 65°C for UDDS driving cycle under cold + cold case
In CS Mode, Engine Is Turned On At Launch If Coolant Temp. Is Below 65 °C

- In CD mode, the engine was allowed to be off even if the coolant temp < 65°C
- No exception for CS mode at the launch of the vehicle, (the same as HEV)
- The coolant temperature does not go below 40°C because of frequent engine operations (In HEV, the threshold for the engine on was about 53°C)
Cold Start Condition Keeps the Engine On For the First UDDS Cycle

- The impacts of cold start under cold ambient tests (Three consecutive UDDS tests)

  1st

  2nd

  3rd

  2\textsuperscript{nd} and 3\textsuperscript{rd} look similar.

  The coolant temperature cannot reach to 65°C under cold start

Whatever the mode is CS or CD, the first UDDS test of each day keeps the engine on under the cold ambient.
There Is No Significant Impact(s) On Energy Management Strategy For SOC Balancing

CD mode: The battery output power reduced under cold ambient tests

Only when the engine is on

No special impact on the control observed in CS mode
The Impact On Engine Target Control Is The Same As The Change Observed In HEV Control

- In low coolant temperature $\Rightarrow$ engine torque is controlled in higher range than normal.
**Summary of Operation with Thermal Condition**

**CD mode**
- **Engine off (EV)**
  - Required power > Max. electric power
    - OR
    - Heater on & Engine coolant Temp. < 40C
    - OR
    - Cold start: Heater on & (Engine coolant Temp. < 65C)

- **Brake signal & Vehicle speed < 28m/s AND Engine coolant Temp. > 65C (Heater on)**

- **Engine on**
  - Vehicle speed < 28m/s
    - Engine only mode (Pbat = 0)
  - Vehicle speed > 28m/s
    - Battery supporting mode (Pbat = 10kW)
  - Cold condition
    - Battery supporting mode (Pabt = 5kW)

**CS mode**
- **Engine off (EV)**
  - Brake signal & Vehicle speed < 20m/s

- **Engine on**
  - Engine turn on map: vehicle speed and SOC
    - OR (Engine coolant Temp. < 40C)
    - OR Cold start: Engine coolant Temp. < 65C
  - Battery output power is proportional to SOC
Model Development and Validation

- **Control model development (Change from HEV model)**
  - CD & CS mode decision
  - Engine turn on map(condition) both in CD and CS
  - Battery management strategy map(Output power of battery according to SOC)
  - Cold start condition and other behavior depending on temperature

- **Comparison of simulation results and test data in PHEV**
  - Difference in 5% between test and simulation results based on fuel economy or SOC difference
  - Different coefficient of rolling resistance and accessory power applied depending on the temperature and driving cycles

<table>
<thead>
<tr>
<th>Temperature</th>
<th>CD: FE discrepancy (%) (SOC difference)</th>
<th>CS: FE discrepancy (%) (SOC difference)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UDDS</td>
<td>HWFET</td>
</tr>
<tr>
<td>22C</td>
<td>- (0.7%)*</td>
<td>- (-0.8%)*</td>
</tr>
<tr>
<td>35C</td>
<td>- (-0.15%)*</td>
<td>- (-1.95%)*</td>
</tr>
<tr>
<td>-7C</td>
<td>2.02 (-2%)</td>
<td>0.04 (1.25%)</td>
</tr>
</tbody>
</table>

*Not FE but SOC discrepancy: no or very few fuel consumption
Model Validated Within Test to Test Repeatability

Comparison of simulation results and test data in PHEV

- Difference mostly in 5% between test and simulation results based on fuel consumption or SOC
- Different coefficient of rolling resistance and accessory power applied depending on the temperature and driving cycles

<table>
<thead>
<tr>
<th>Cycle name</th>
<th>Ambient Temperature</th>
<th>Driving mode</th>
<th>Fuel consumption (g)</th>
<th>ΔSOC (%)</th>
<th>Final SOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Test</td>
<td>Simulation</td>
<td>diff.(%)</td>
</tr>
<tr>
<td>UDDS</td>
<td>22C</td>
<td>CD</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>286.5</td>
<td>287.1</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>35C</td>
<td>CD</td>
<td>67.1</td>
<td>52.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>405.4</td>
<td>392.8</td>
<td>-3.1%</td>
</tr>
<tr>
<td></td>
<td>-7C</td>
<td>CD</td>
<td>450.3</td>
<td>459.2</td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>357.1</td>
<td>371.4</td>
<td>4.0%</td>
</tr>
<tr>
<td>HWFET</td>
<td>22C</td>
<td>CD</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>442.3</td>
<td>443.9</td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td>35C</td>
<td>CD</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CS</td>
<td>521.3</td>
<td>527.4</td>
<td>1.2%</td>
</tr>
<tr>
<td></td>
<td>-7C</td>
<td>CD</td>
<td>413.9</td>
<td>413.7</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>2015-01-1157</td>
<td>CS</td>
<td>497.1</td>
<td>516.5</td>
<td>3.9%</td>
</tr>
</tbody>
</table>
Conclusion

- **APRF test data analysis**
  - Engine on/off condition depend of the battery SOC (CD/CS mode)
  - CD mode: Operates in EV unless the battery cannot provide the requested power
    - No blended mode operation: EV or engine only except high speed (battery supporting)
  - CS mode: Similar operation as for the Prius HEV (engine turns on followed by map)
    - Battery output power is proportional to SOC
  - Thermal management
    - Only keep engine coolant temperature high (40~65) when the heater is on in CD mode
    - Always maintain high engine coolant temperature in CS mode
    - Two types of cold start according to engine coolant temperature

- **Model development and validation**
  - Parameters for individual component models have been developed based on test data
  - Developed the vehicle energy management for the PHEV model based on the HEV
  - Validated the model on the UDDS and HWFET cycles for multiple ambient temperature (-7C, 22C and 35C) under different operating modes (CD and CS)
  - Difference between test and simulation is within test to test repeatability (5%) for both vehicle energy consumption and battery SOC.
Outline

- Validation Process
- Component Model Development and Validation
- Vehicle Validation Examples
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids (Blended)
  - E-REV PHEV
  - BEV
- Thermal Model Validation Overview
Test Data Analysis for Control Model
- Energy management strategy analysis

- SOC balancing during charge sustaining

**Strategy 1.**

SOC is too low $\Rightarrow$ Engine is turned on at low power ($\Rightarrow$ HEV mode)

**Strategy 2.**

Compute battery power demand as a function of wheel power demand

**Strategy 3.**

In normal level, compute battery power demand for SOC regulation
Test Data Analysis for Control Model
- Engine operating target analysis

- Engine operating target from all tests.

![Graphs showing engine power demand, speed optimal, and torque desired.]

- Engine power demand
- Engine speed optimal
- Engine torque desired

- Series mode
- Split mode

Eng Temp < 76°C
Eng Temp > 76°C
Test Data Analysis for Control Model
- Transmission operation modes

- GB Mode on electric mode (EV) / Extended range (ER) driving

After we convert ER driving results into new map by using vehicle speed and engine speed indexes, the mode selection rule can be defined based on the speed ratio:

\[ SR = 1.43 \]

(Note that GB is the gearbox)
Test Data Analysis for Control Model

- Engine warm up strategy (-6.7 °C)

- Constant speed and constant power for 150 seconds used to warm-up battery and heat on under cold conditions (@ high SOC)

Warm up strategy
- 1450 rpm
- 1.1 g/s fuel
- 150 seconds to reach 50°C of engine temp
Model Validation in Autonomie
- urban driving schedule (EV) : 35 °C

- Battery SOC & power
Model Validation in Autonomie
- urban driving schedule (ER) : 35 °C

- Engine speed & torque

Warm up phase to reach the engine temperature
Model Validation in Autonomie
- urban driving schedule (EV) : -6.7 °C

- Engine speed & torque

Warm up phase
To reach the engine temperature
Model Validation in Autonomie
- urban driving schedule (ER) : -6.7 °C

- Battery SOC, engine fuel

UDDS CS (20 degF) - Battery SOC

UDDS CS (20 degF) - Engine Integrated Fuel
Model Validation in Autonomie  
- summary (Urban driving schedule)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Battery Electric consumption (Wh/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
</tr>
<tr>
<td>EV(CD) : 22.2 °C</td>
<td>214.3</td>
</tr>
<tr>
<td>EV(CD) : 35 °C (A/C on)</td>
<td>302.3</td>
</tr>
<tr>
<td>EV(CD) : 35 °C (A/C off)</td>
<td>203.3</td>
</tr>
<tr>
<td>EV(CD) : -6.7 °C (Heater on)</td>
<td>416.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Fuel Consumption (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
</tr>
<tr>
<td>ER(CS) : 22.2 °C</td>
<td>0.454</td>
</tr>
<tr>
<td>ER(CS) : 35 °C (A/C on)</td>
<td>0.758</td>
</tr>
<tr>
<td>ER(CS) : -6.7 °C (Heater on)</td>
<td>0.555</td>
</tr>
</tbody>
</table>

(Note that EV is the electric vehicle driving mode and ER is the extended range mode. A/C is an air conditioner.)
Transmission Thermal Management System

- Thermal system in GB_Plant: Heat transfer between TM & Oil

\[ q_{motor, oil} \]
Heat flow between Motors & Oil

\[ q_{cool} = m_{cool} c_{p, oil} (T_{oil_out} - T_{oil_in}) \]
Coolant heat flow:

\[ m_{cool} \]
Convective heat flow between TM & Ambient Air

Lumped TM mass as a thermal capacitor

Coolant heat flow:

\[ m_{cool} \]
Convective heat flow between TM & Oil

Transmission oil as a thermal capacitor

\[ Q_{TM} \]
TM losses from GB plant block

Convective heat flow between TM & Ambient Air

Lumped TM mass as a thermal capacitor

Heat flow between TM & Oil
Test Data Analysis for Control Model
- Charge sustaining operation on Hot UDDS

Distinctive Volt Operation:
- Longer EV only operation
- Engine operates at higher loads

Prius 04 (UDDS)

Volt CS mode driving (UDDS)
Test Data Analysis for Control Model
- motor operating on regeneration mode

- Motor operating as a function of coolant temp.

- Current limit on low/high temperature

- Battery maximum regenerative power ~ 70kW
Model Validation in Autonomie
- urban driving schedule (ER) : 35 °C

- Battery SOC, engine fuel

UDDS CD (95 degF) - Battery SOC

UDDS CS (95 degF) - Engine Integrated Fuel
Model Validation in Autonomie - urban driving schedule (EV) : -6.7 °C

- Battery SOC & power
Outline

- Validation Process
- Component Model Development and Validation
- Vehicle Validation Examples
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids (Blended)
  - E-REV PHEV
  - BEV
- Thermal Model Validation Overview
Ford Focus BEV
Import Test Data into Autonomie
Assumption to Calculate Additional Signals

Vehicle Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire radius</td>
<td>0.321 m</td>
</tr>
<tr>
<td>Final drive ratio</td>
<td>7.82</td>
</tr>
<tr>
<td>Final drive efficiency</td>
<td>97.5%</td>
</tr>
<tr>
<td>Torque coupler ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Torque coupler efficiency</td>
<td>98%</td>
</tr>
<tr>
<td>Vehicle mass</td>
<td>1700 kg</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>2.42 m²</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.26</td>
</tr>
<tr>
<td>Driving motor power/torque</td>
<td>107 kW/250 N-m</td>
</tr>
<tr>
<td>Battery pack capacity</td>
<td>23 kWh</td>
</tr>
</tbody>
</table>

Motor efficiency map
- Newly generated Ford BEV motor map (Assumption)
- Based on the init file of Nissan Leaf motor and test data

Battery pack efficiency map
- Newly generated Ford BEV battery map (Assumption)
- Based on the init file of Nissan Leaf battery data and test data

Transmission efficiency
- 1 speed gear ratio (FD ratio)
To calculate $V_{out}$, the battery model needs $V_{ocv}$ and $R_{int}$ as the initialization data. Therefore, we have newly developed the characteristic data based on the test results of the Ford BEV, and by modifying the original Leaf battery data.

File name:
- `ess_plant_li_65_430_Ford_Focus_EV.m`
- `ess_plant_li_65_430_Ford_Focus_EV.init`
Import Test Data into Autonomie

Results of Estimated OCV from MCT Data

UDDS 1 - 61301070

- $V_{\text{out}}$ - Test
- $V_{\text{oc}}$ - Estimated value
- Vehicle Speed

HWY 1 - 61301071

- $V_{\text{out}}$ - Test
- $V_{\text{oc}}$ - Estimated value
- Vehicle Speed
Verification of Estimated Signals
Comparison between Test Data and Calculated Signals
Verification of Electric Current Input to the Driving Motor
✓ 61301071_HWY

![Graphs showing validation of input current for motor - 61301071](image-url)
Verification of Estimated Signals
Comparison between Test Data and Calculated Signals

Verification of Electric Current Input to the Driving Motor

✓ 61301072_UDDS

Verification Conclusion:
Comparison signals between measured data and calculated value show good coincident result. Therefore, we can think that the Ford motor map data developed is reasonable and can be applied to a vehicle model.
Verification of Estimated Signals
Example of Energy Balance of Vehicle System

Energy valance results of each component calculated by using test data

UDDS - 61301073 : 1 bag, cycle 4 of J1634 full charge test
Estimated initial SOC: 75.28%
Unit : kWh

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical consumption [DC Wh/mile]</td>
<td>281.72</td>
</tr>
<tr>
<td>Electrical consumption [DC Wh/km]</td>
<td>175.09</td>
</tr>
<tr>
<td>Initial SOC [%]</td>
<td>75.28</td>
</tr>
<tr>
<td>Final SOC [%]</td>
<td>64.70</td>
</tr>
<tr>
<td>SOC Swing (max-min) [%p]</td>
<td>11.01</td>
</tr>
<tr>
<td>Percent of Regen. Braking at Battery [%]</td>
<td>82.66</td>
</tr>
<tr>
<td>Percent of Regen. Braking at Wheel [%]</td>
<td>94.15</td>
</tr>
<tr>
<td>Regen Braking Energy Recovered at Battery [Wh]</td>
<td>-641.79</td>
</tr>
<tr>
<td>Regen Braking Energy Available at Wheel [Wh]</td>
<td>-727.54</td>
</tr>
<tr>
<td>Total Braking Energy at Wheel [Wh]</td>
<td>-772.75</td>
</tr>
</tbody>
</table>

‘DC Wh/mile’ represents the total output energy of the battery divided by distance, where the battery internal resistance is not considered in the electric consumption value.
Vehicle Model Development and Validation
Introduction of Vehicle Model in Autonomie

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire radius</td>
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<td>97.5%</td>
</tr>
<tr>
<td>Torque coupler ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Torque coupler efficiency</td>
<td>98%</td>
</tr>
<tr>
<td>Electric accessory loss</td>
<td>400W</td>
</tr>
<tr>
<td>Vehicle mass</td>
<td>1700 kg</td>
</tr>
<tr>
<td>Battery pack capacity</td>
<td>23 kWh</td>
</tr>
</tbody>
</table>

Init file: ess_plant_li_66_430_Ford_Focus_EV.m
modified from the Leaf battery data

Init file: mot_plant_pm_53_107_Ford_Focus_EV.m
modified from the Leaf motor data
Vehicle Model Development and Validation

Validation Results: HWFET #1 - 61301071

SOC [%]

NCCP = 0.9882

Battery Voltage [V]

NCCP = 0.9903

Battery Current [A]

NCCP = 0.9653

Battery Power [kW]

NCCP = 0.9687
Vehicle Model Development and Validation

Validation Results : UDDS #2 - 61301072

SOC [%]

NCCP = 0.9936

Battery Voltage [V]

NCCP = 0.9945

Battery Current [A]

NCCP = 0.9516

Battery Power [kW]

NCCP = 0.9539

SOC [%] vs. time_simu

NCCP = 0.9936

Battery Voltage [V] vs. time_simu

NCCP = 0.9945

Battery Current [A] vs. time_simu

NCCP = 0.9516

Battery Power [kW] vs. time_simu

NCCP = 0.9539
## Vehicle Model Development and Validation

### Verification Results - NCCP

<table>
<thead>
<tr>
<th>Driving Cycle</th>
<th>Test Number</th>
<th>ESS SOC</th>
<th>ESS Voltage Out</th>
<th>ESS Current Out</th>
<th>ESS Power Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOTx4</td>
<td>61301057</td>
<td>0.9696</td>
<td>0.9976</td>
<td>0.9652</td>
<td>0.9630</td>
</tr>
<tr>
<td>UDDS #1</td>
<td>61301070</td>
<td>0.9948</td>
<td>0.9941</td>
<td>0.9362</td>
<td>0.9386</td>
</tr>
<tr>
<td>UDDS #2</td>
<td>61301072</td>
<td>0.9936</td>
<td>0.9945</td>
<td>0.9516</td>
<td>0.9539</td>
</tr>
<tr>
<td>UDDS #3</td>
<td>61301077</td>
<td>0.9895</td>
<td>0.9955</td>
<td>0.9560</td>
<td>0.9567</td>
</tr>
<tr>
<td>UDDS #4</td>
<td>61301079</td>
<td>0.9866</td>
<td>0.9926</td>
<td>0.9573</td>
<td>0.9575</td>
</tr>
<tr>
<td>Hwy #1</td>
<td>61301071</td>
<td>0.9882</td>
<td>0.9903</td>
<td>0.9653</td>
<td>0.9687</td>
</tr>
<tr>
<td>Hwy #2</td>
<td>61301078</td>
<td>0.9861</td>
<td>0.9909</td>
<td>0.9804</td>
<td>0.9828</td>
</tr>
<tr>
<td>US06 #1</td>
<td>61301073</td>
<td>0.9872</td>
<td>0.9888</td>
<td>0.9462</td>
<td>0.9533</td>
</tr>
<tr>
<td>US06 #2</td>
<td>61301076</td>
<td>0.9867</td>
<td>0.9914</td>
<td>0.9531</td>
<td>0.9589</td>
</tr>
<tr>
<td>SSS 55MPH #1</td>
<td>61301075</td>
<td>0.9892</td>
<td>0.9949</td>
<td>0.9919</td>
<td>0.9879</td>
</tr>
<tr>
<td>SSS 55MPH #2</td>
<td>61301080</td>
<td>0.9822</td>
<td>0.9864</td>
<td>0.9890</td>
<td>0.9925</td>
</tr>
</tbody>
</table>

### NCCP of each signal

![NCCP Graph](image-url)
Conclusion

Analysis of preliminary test data for the missing signals of each component

- Newly generated Ford BEV motor map – Motor efficiency map (Assumption)
- Newly generated Ford BEV battery pack data – Open Circuit Voltage and Internal Resistance (Assumption)
- Auxiliary loss power – average 400~450W / frequent peak power loss 600W ~ 1200W
- Rolling resistance force of tires - Front 130~150N / Rear 80~120 N
- The mechanical brake operation in a rear wheel– Less than around 10km/h (6.2mi/h)

Effort-Flow of each component (Energy Balance) and verification of estimated missing signals

- Compared signals between measured data and calculated value show good coincident result. Therefore, we can think that the motor efficiency map data developed is reasonable and can be applied to a vehicle model.

Development of a vehicle model and validation with test data

- Based on the default BEV model in Autonomie
- Using of ‘[DC Wh/mile]’ at the output terminal of the battery system (not internally consumed energy) due to the test method
- For 11 preliminary test data, good estimated results within around 3% except for one US06
Outline

- Validation Process
- Component Model Development and Validation
- Vehicle Validation Examples
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids (Blended)
  - E-REV PHEV
  - BEV
- Thermal Model Validation Overview
Thermal Models and Controls Developed Over Multiple Years

Ford Fusion Conv.
Toyota Prius HEV
Toyota Prius PHEV
GM Volt
Ford Focus BEV
Multi-Entity Collaboration Leveraged

Engine: APRF & OEM

Cabin: OEM & Labs.

Air Conditioner: OEM & Labs

Electric Machine: OEM and ANL

Transmission: OEM

Battery: Battery Supplier

Funded under this project

Funded under another project

Collaboration with Other Institutions
Multiple Powertrain Configurations Considered

- Conventional Vehicle – **Ford Fusion**
- Extended Range Electric Vehicles (E-REV) – **GM Volt**
- Hybrid Electric Vehicles (HEV) – **Toyota Prius Hybrid**
- Battery Electric Vehicles (BEV) – **Ford Focus BEV**
- Plug-In HEVs (PHEV) – **Toyota Prius Plug-in Hybrid**
Standard Model Validation Process

Developed

Test data from APRF (ANL)

Test data

Control and Performance Analysis

Control and Performance Analysis

Model Validation

Simulation data

Model Development (Autonomie)

Component

Controller

Engine

Mechanical Assembly

Grinder

Battery

Booster

Motor 2

Motor

DC/DC

Electrical Accessory

Mode decision

Engine on/off demand

Driver power demand

Battery power demand

Motor torque demand

Engine speed demand

Engine torque demand

Model Development (Autonomie)

Engine operation target

Heat capacity estimation

mode behaviors
Component Performance Data Developed from Vehicle Testing

Engine performance analysis

- Engine efficiency decreases as the coolant temperature decreases.

Battery performance analysis

- Round-trip efficiency decreases as the battery temperature decreases.
Vehicle Level Controls Analysis Performed

Mode Control (Engine On/Off)

The engine is forced to be turned on if the coolant temperature is low.

The engine is not turned off if the coolant temperature is low.

Desired battery power is proportional to SOC.

SOC Balancing

Battery power is constrained by the battery temperature.

e.g. Prius HEV
Comparative Analysis for Ctrl. & Perfo.

Target Control (Engine Operating)

Performance of battery
Component & Vehicle Model Developed

Component model development

- e.g. Battery

Component level validation

- Control analysis
  - Instant power
  - Rating power
  - Regenerative power
  - Battery temperature

- Internal resistance

Validations with test data in component level

Example Thermal System

- Control development
- Component model integration
- Vehicle model validation

System Integration and vehicle level validation

Vehicle level validation with test data

Control model development
Components Integrated into Vehicle

- Fan
- Heatercore
- Valve
- Radiator
- Exhausted gas
- Fuel
- Tamb
- Fan
- Radiator
- Battery
- Pmech
- Qheating
- Qfuel
- Qexhausted
- Qair
- Qcoolant
- Teng
- Qloss
- Qmot1
- Qmot2
- Tamb
- Qgb_loss
- Qcoolant
- Qair
- Ttra
- Tmot1
- Tmot2
- Prius PHEV
- Tread
- Carcass
- Prolling resistance
- Pconduction
- Pconvection
- Pfriction
- Cabin
- Condenser
- Compressor
- Evaporator
- Ventilation
Models Validated within Test to Test Uncertainty

Conv.

HEV

PHEV (CS)

EREV (CS)

Fuel consumption (kg)

Test  Simulation

-7°C  22°C  35°C

-7°C  22°C  35°C

-7°C  22°C  35°C

-7°C  22°C  35°C
Models Validated within Test to Test Uncertainty

![Graphs showing test vs simulation fuel consumption for different models and temperatures.]

- Conv.
  - Test: Blue bars
  - Simulation: Red bars

- HEV
  - Test: Blue bars
  - Simulation: Red bars

- PHEV (CS)
  - Test: Blue bars
  - Simulation: Red bars

- EV
  - Test: Blue bars
  - Simulation: Red bars

Fuel consumption (kg) vs temperature for each model.
Thermal Impact on Energy Consumption

VTMS Development
- Vehicle tests at APRF
- Control and performance analysis
- Thermal model developments
- Model integration and validation

Driving Conditions
- Ambient temperature
- Driving cycles
- Starting conditions
- Technologies
- Fleet Distribution

Simulation techniques
- Large scale simulation process
- Database analysis

Thermal Impact on Energy
- Energy consumptions
- Impact of driving conditions

Advanced Powertrains with VTMS
- Conv.
- HEV
- EV
- PHEV
- E-REV

From various studies
- Large scale simulation process
- Database analysis

Simulation techniques
- Energy consumptions
- Impact of driving conditions

Tech. impact
- Temp. impact
Thermal Impact On Energy Consumption

Conv.

HEV

Cold Start initial condition
- all initial temperatures of components are the same as the ambient temperature

Hot Start initial condition
- Engine and coolant temp. (90°C)
- Cabin temp. (22°C)
- Transmission and oil temp. (60°C)

Initial condition is the same as the Conv.

Hot Start initial condition
- Battery temp. (30°C)

Cabin is sized, so that all vehicles have the similar hvac power consumption
Thermal Impact On Energy Consumption

PHEV

- Cold Start initial condition
  - The same as the ambient temp.
  - Not cold when ambient temp > 30°C

- Hot Start initial condition
  - Battery temperature (30°C)
  - Cabin temperature (22°C)

There is a drastic change of the pattern by the engine on threshold for Cold Start.

EV

- Cold Start initial condition
  - the same as the ambient temp.
  - Not cold when ambient temp > 30°C

- Hot Start initial condition
  - Battery temperature (30°C)
  - Cabin temperature (22°C)
Real-World Scenario with VTMS

**ASSUMPTIONS**
- from multi-resources

**AUTONOMIE**
- on high performance computing

**ANALYSIS**
- by database tool

**Comparative studies**

**Energy distribution**

**Assessment**
- PHEV
- Conv.
- E-REV
- EV

**ANALYSIS**
- Temp. Conditions
- Real World Driving Cycles

**Cycle synthesizing**

**Date:** 18-Apr-2014

**User:** nakim

**Copyright Program:** 1.0

**Drive Cycles:**
- UDDS
- HWFET
- US06
- SC03
Validation Methodology Summary

- Accurate validation requires significant constant investment (Inc sensors, testing, modeling, control, calibration...) over a very long period of time
- Matching component operating conditions over a wide range of driving cycles and temperatures is critical
- NCCP used by Argonne to quantify the validation quality (all core parameters should be >0.9)
- Using validated individual vehicle models does not mean one can properly estimate future technology benefits
  - Generic algorithms sometimes cannot be used for multiple technologies (i.e. 6 speed vs 8 speed)
  - Calibration has to be carefully defined to take into account individual advanced technologies (i.e. light weighting, advanced engines...) as well as combined (i.e. adv ICE + BISG)
  - Drive quality (i.e. # ICE ON/OFF, # shifting events, pedal tip-in, reserve torque...)
  - ...

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List of References

- N. Kim, J. Jeong, A. Rousseau, and H. Lohse-Busch, “Control Analysis and Thermal Model Development of PHEV”, SAE 2015-01-1157, SAE World Congress, Detroit, April15