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

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

Vehicle model development

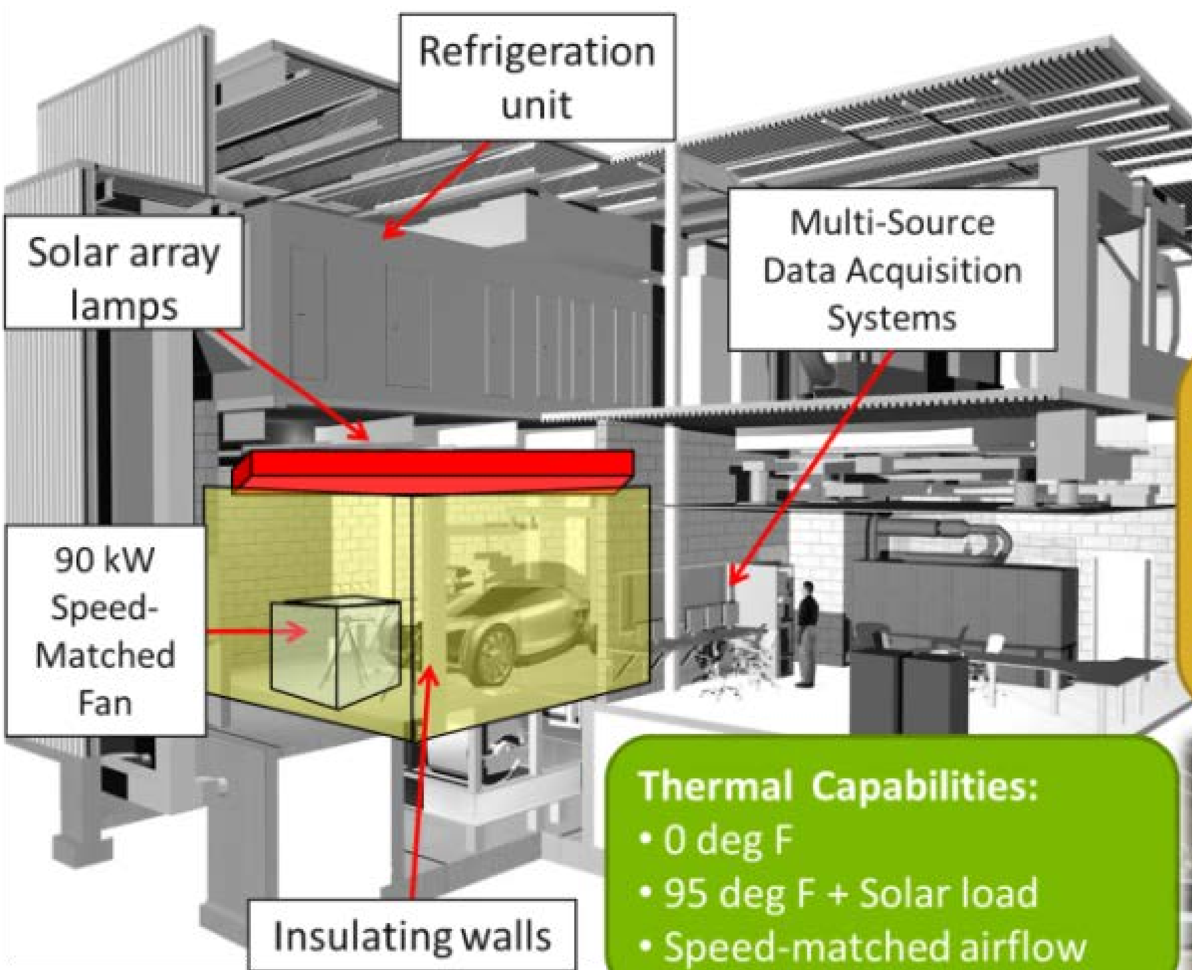
- Develop models
- Instantiate models
- Develop low and high level control strategies

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.

Advanced Vehicle Laboratory Capabilities



Advanced Powertrain Research Facility

Laboratory Enables:
- Studies in hot/cold effects on powetrain
- Measurements in A/C and heater power draw for advanced vehicles

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

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**

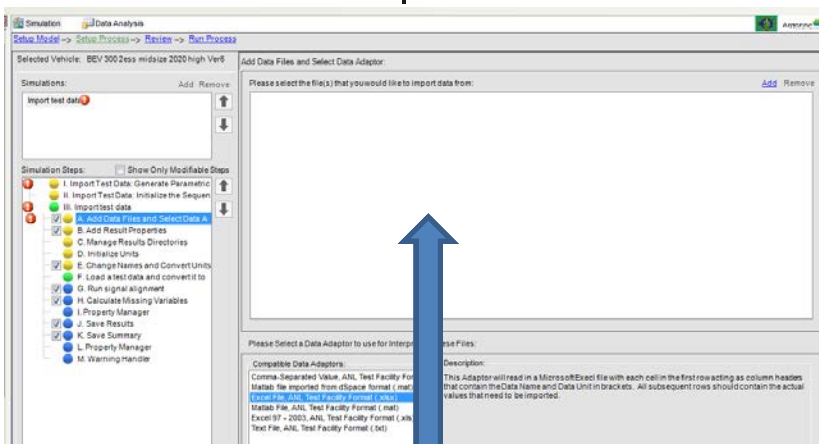
Large Number of Test Should be Performed

Example of some of the cycles for the Prius MY10

	Cycle	Cycle length(s)	Engine starting temp (°C)		Cycle	Cycle length(s)	Engine starting temp (°C)
1	Accels_merge	258.1	72.5 - 92	14	UDDS_prep_merge	1372.9	70 - 87.5
2	Cycle_505_2_merge	1019.5	75 - 88.5	15	UDDScs_merge	1372.9	22.5 - 78.5
3	Hwy_01_merge	764.9	88.5 - 88.5	16	UDDShs_01_merge	1372.9	66 - 85.5
4	Hwy_02_merge	764.9	88.5 - 88.5	17	UDDShs_02_merge	1372.9	69 - 86
5	JC08_01_merge	1204.9	55 - 85	18	UDDShs_03_merge	1372.9	74.5 - 87.5
6	JC08_02_merge	1204.9	68 - 88	19	US06_01_merge	599	78.5 - 90
7	LA92_01_merge	1431.5	46.5 - 90.5	20	US06_02_merge	598.9	92.5 - 89
8	LA92_02_merge	1433.9	74.5 - 90.5	21	SS_0pct_Grade	549.6	80 - 89
9	NEDC_01_merge	1164.9	70 - 88.5	22	SS_0p5pct_Grade	549.6	84.5 - 89.5
10	NEDC_02_merge	1164.9	77 - 88.5	23	SS_1pct_Grade	549.6	89.5 - 89.5
11	NYCC_merge	607.6	23 - 57.5	24	SS_2pct_Grade	549.6	88 - 90
12	SC03_01_merge	599.9	45 - 77	25	SS_4pct_Grade	549.6	90.5 - 89.5
13	SC03_02_merge	599.9	63 - 84.5	26	Long_SS_Warmups	1800	24 - 89.5

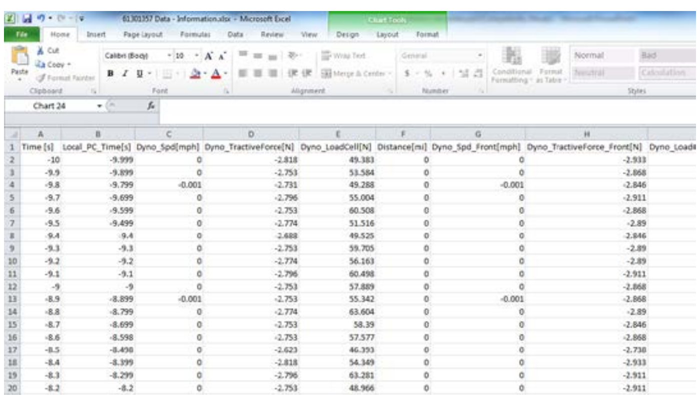
Importing Test Data into Same Environment as Models to Speed up Validation

Autonomie GUI for 'Import Test Data' function



- All post-process files
- Format conversion file
- Calculating missing signals file

Raw test data set



	A	B	C	D	E	F	G	H
1	Time [s]	Local_PC_Time[s]	Dyno_Spd[mph]	Dyno_TractiveForce[N]	Dyno_LoadCell[N]	Distance[mi]	Dyno_Spd_Front[mph]	Dyno_TractiveForce_Front[N]
2	-10	-9.999	0	-2.818	49.383	0	0	-2.933
3	-9.9	-9.899	0	-2.753	53.584	0	0	-2.868
4	-9.8	-9.799	-0.001	-2.731	49.288	0	-0.001	-2.846
5	-9.7	-9.699	0	-2.796	55.004	0	0	-2.911
6	-9.6	-9.599	0	-2.753	60.508	0	0	-2.868
7	-9.5	-9.499	0	-2.774	51.516	0	0	-2.89
8	-9.4	-9.4	0	-2.688	49.525	0	0	-2.846
9	-9.3	-9.3	0	-2.753	59.705	0	0	-2.89
10	-9.2	-9.2	0	-2.774	56.163	0	0	-2.89
11	-9.1	-9.1	0	-2.796	60.498	0	0	-2.911
12	-9	-9	0	-2.753	57.889	0	0	-2.868
13	-8.9	-8.899	-0.001	-2.753	55.342	0	-0.001	-2.868
14	-8.8	-8.799	0	-2.774	63.604	0	0	-2.89
15	-8.7	-8.699	0	-2.753	58.39	0	0	-2.846
16	-8.6	-8.598	0	-2.753	57.577	0	0	-2.868
17	-8.5	-8.498	0	-2.623	46.393	0	0	-2.738
18	-8.4	-8.399	0	-2.818	54.349	0	0	-2.933
19	-8.3	-8.299	0	-2.796	63.281	0	0	-2.911
20	-8.2	-8.2	0	-2.753	48.966	0	0	-2.911
21	-8.1	-8.099	0	-2.839	49.671	0	0	-2.955

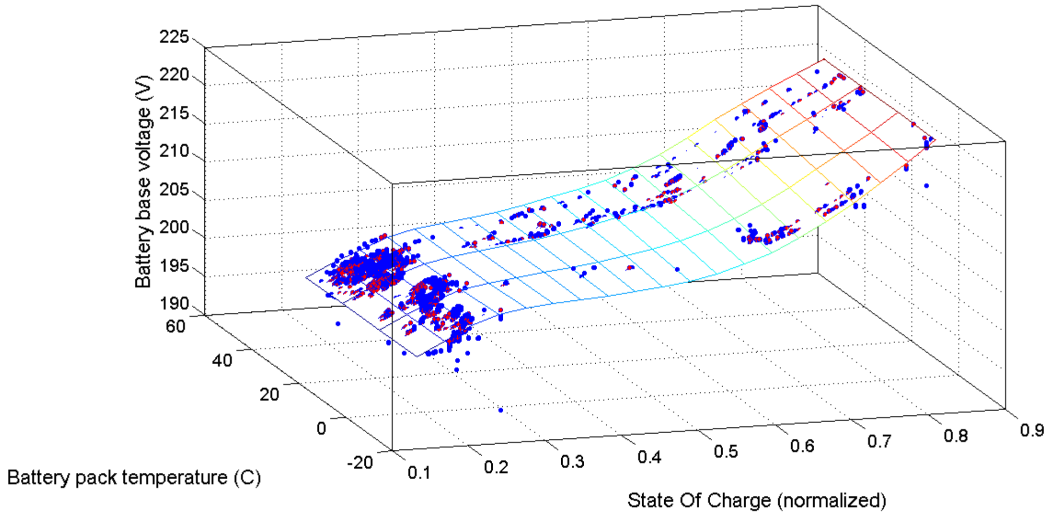
- Change signal names and convert unit type for Autonomie format

Test Name	Test Unit	Unit Type	Matching Autonomie Unit	Converted Name	Converted Unit (SI)
12VBatt_Curr_Hioki[A]	A	current	A	accelec_12vbatt_curr_hioki_raw_test	A
12VBatt_Volt_Hioki[V]	V	voltage	V	accelec_12vbatt_volt_hioki_raw_test	V
Batt_Coolant_Hose_Temp[C]	C	temperature	C	ess_coolant_hose_temp_raw_test	C
Cabin_Temp[C]	C	temperature	C	chas_cabin_temp_raw_test	C
Cabin_Vent_Temp[C]	C	temperature	C	chas_cabin_vent_temp_raw_test	C
Cell_Press[inHg]	inHg	pressure	inHg	env_cell_press_inhg_raw_test	Pa
Cell_RH[%]	%			env_cell_rh_raw_test	
Cell_Temp[C]	C	temperature	C	env_cell_temp_raw_test	C
DCDC_In_Curr_Hioki[A]	A	current	A	pc_in_curr_hioki_raw_test	A
DCDC-Motor-Inv_Clng_Hose_Te	C	temperature	C	pc_motor_inv_clng_hose_temp_raw_test	C
Delta t [s]	s	time	s	delta_t_s_test	s
DilAir_RH[%]	%			dilair_rh_test	
Distance[mi]	mi	distance	mile	chas_distance_raw_test	m
Drive_Schedule_Time[s]	s	time	s	drv_schedule_time_raw_test	s
Drive_Trace_Schedule[MPH]	MPH	linear_speed	mile/h	drv_trace_schedule_raw_test	m/s
Dyno_LoadCell[N]	N	force	N	dyno_loadcell_n_test	N
Dyno_LoadCell_Front[N]	N	force	N	dyno_loadcell_front_n_test	N
Dyno_LoadCell_Rear[N]	N	force	N	dyno_loadcell_rear_n_test	N
Dyno_Spd[mph]	mph	linear_speed	mile/h	chas_dyno_spd_raw_test	m/s
Dyno_Spd_Front[mph]	mph	linear_speed	mile/h	chas_dyno_spd_front_raw_test	m/s
Dyno_Spd_Rear[mph]	mph	linear_speed	mile/h	chas_dyno_spd_rear_raw_test	m/s
Dyno_TractiveForce[N]	N	force	N	chas_dyno_tractiveforce_raw_test	N
Dyno_TractiveForce_Front[N]	N	force	N	chas_dyno_tractiveforce_front_raw_test	N
Dyno_TractiveForce_Rear[N]	N	force	N	chas_dyno_tractiveforce_rear_raw_test	N
Exhaust_Bag				exhaust_bag_test	
Fan_Air_Spd[mph]	mph	linear_speed	mile/h	env_fan_air_spd_raw_test	m/s
Front_Tire_Temp[C]	C	temperature	C	whl_front_tire_temp_raw_test	C
Heater_Core_Hose_Temp[C]	C	temperature	C	accelec_heater_core_hose_temp_raw_test	C
Hioki_Time_H0[s]	s	time	s	hioki_time_h0_s_test	s
HVBatt_Curr_Hi_Hioki[A]	A	current	A	ess_hvbatt_curr_hi_hioki_raw_test	A
HVBatt_Curr_Hioki[A]	A	current	A	ess_hvbatt_curr_hioki_raw_test	A
HVBatt_Curr_Low_Hioki[A]	A	current	A	ess_hvbatt_curr_low_hioki_raw_test	A
HVBatt_Volt_Hioki[V]	V	voltage	V	ess_hvbatt_volt_hioki_raw_test	V
I1		current	A	ess_i1_500a_clamp_curr_raw_test	A
I2		current	A	ess_i2_200a_clamp_curr_raw_test	A
I3		current	A	ess_i3_20a_clamp_curr_raw_test	A
I4		current	A	pc_i4_dcdcin_curr_raw_test	A
I5		current	A	accelec_i5_12vbatt_curr_raw_test	A
I6		current	A	ess_i6_ac_charger_curr_raw_test	A
IH1		capacity	Ah	ess_ih1_500a_clamp_cum_cap_raw_test	Ah
IH2		capacity	Ah	ess_ih2_200a_clamp_cum_cap_raw_test	Ah
IH3		capacity	Ah	ess_ih3_20a_clamp_cum_cap_raw_test	Ah
IH4		capacity	Ah	pc_ih4_dcdcin_cum_cap_raw_test	Ah
IH5		capacity	Ah	accelec_ih5_12vbatt_cum_cap_raw_test	Ah

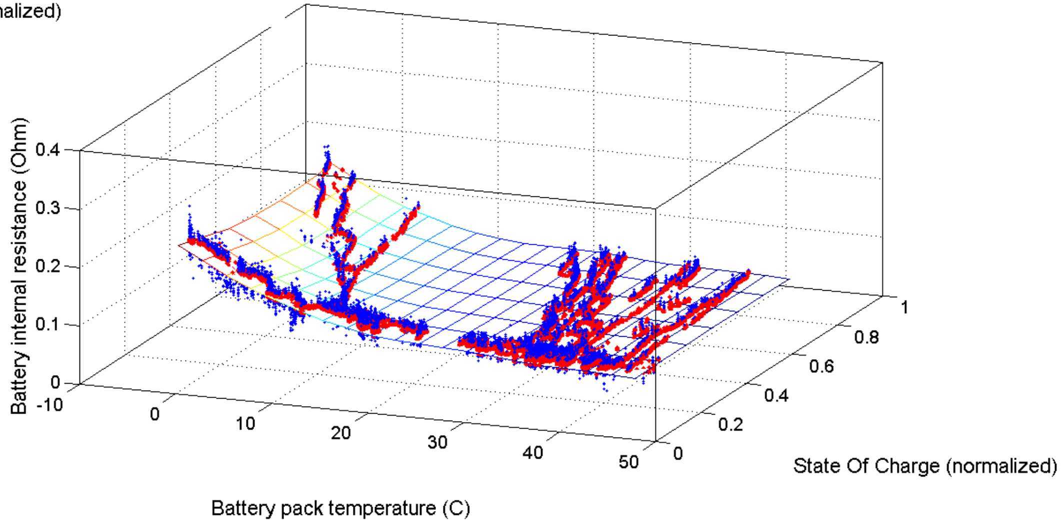
Signals used in the calculation of missing parameters.

Additional Signals Estimated Based on Measured Data

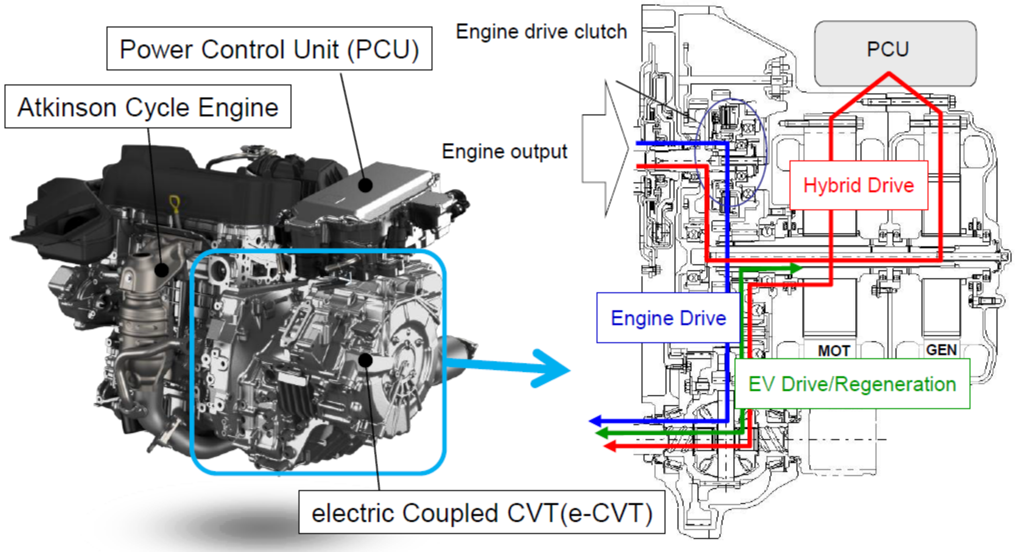
Prius PHEV Battery Example



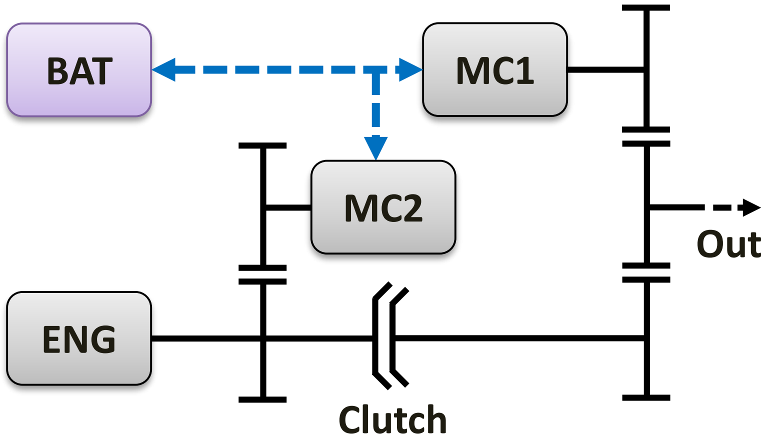
Generic Processes to define performance maps have been developed for the main powertrain components



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

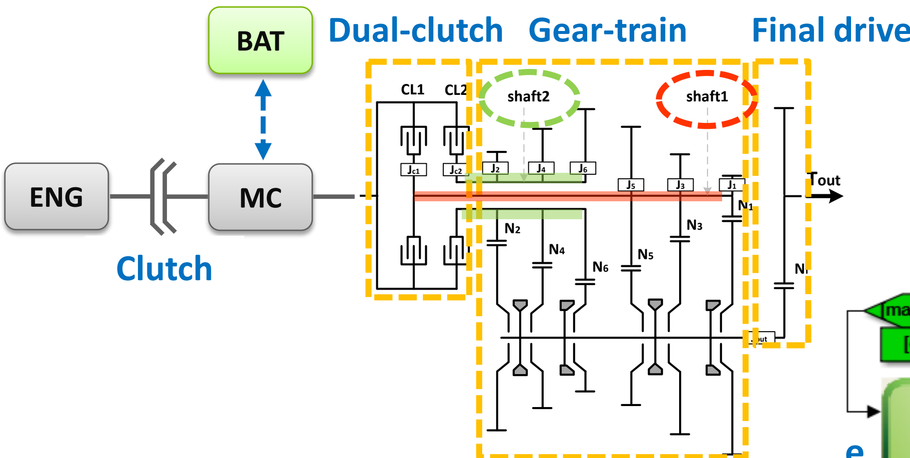
EV Drive (One-Motor EV)

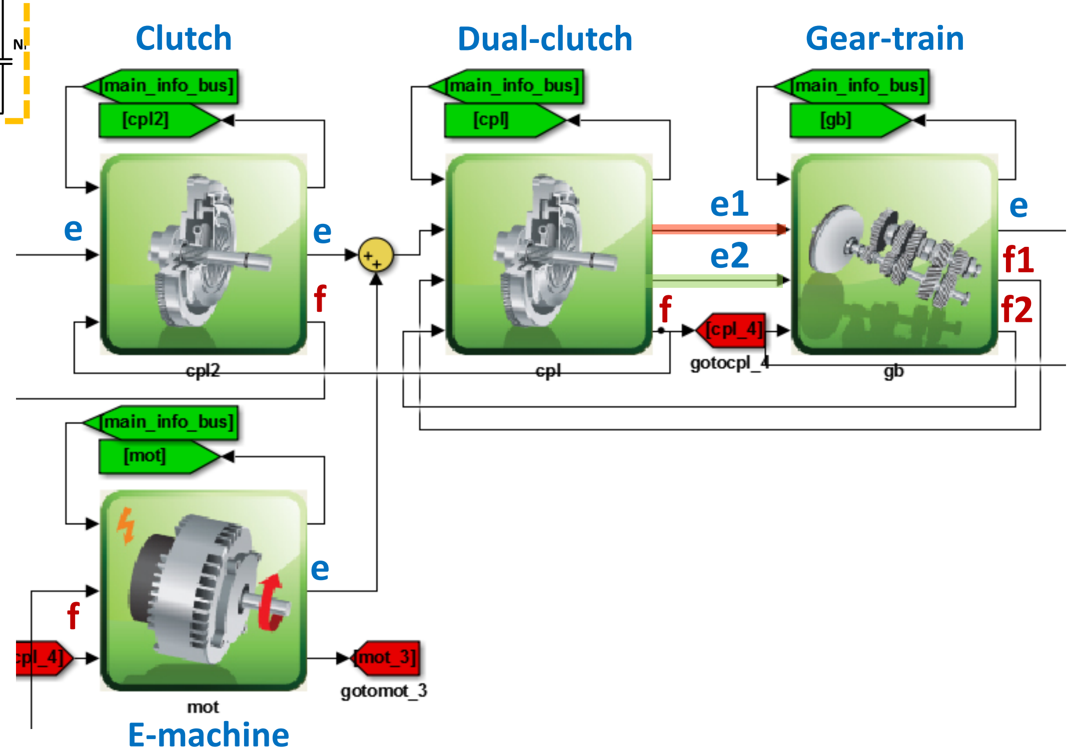
Hybrid Drive (Series ER)

Engine Drive (Parallel ER)

Change three modes according to system efficiency.

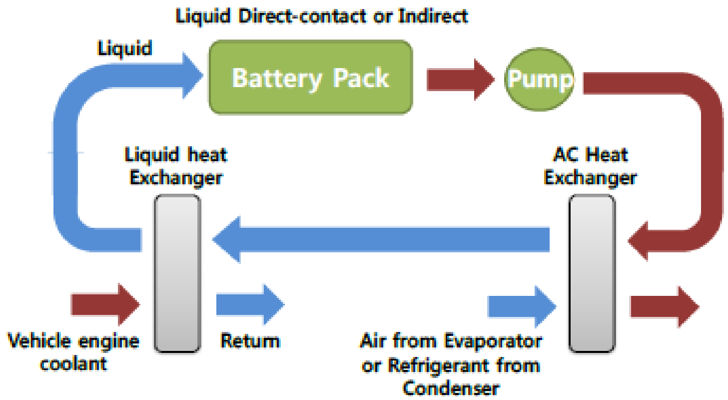
New Plant Models Might Be Necessary
Example - DCT Plant Model Development





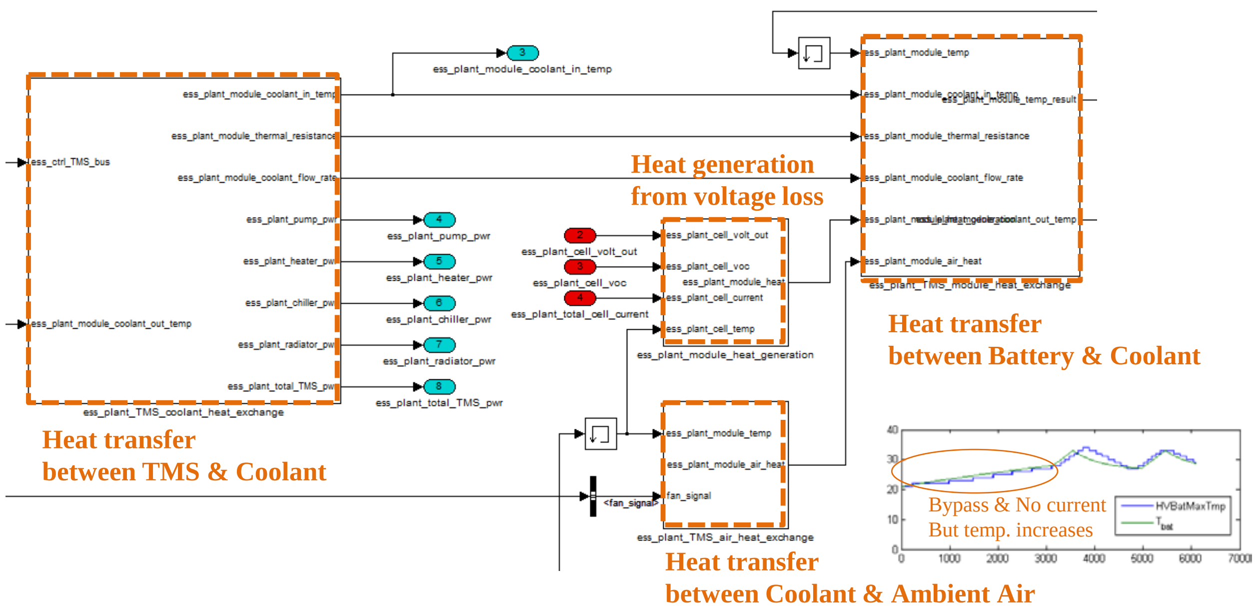
- vpa_par_2wd_p2_dct_cpl1_1mc : "Parallel PreTrans HEV Dual Clutch Trans 2wd Midsize"

Thermal Models Required Based on Current Standards
Battery Thermal Management System(TMS)



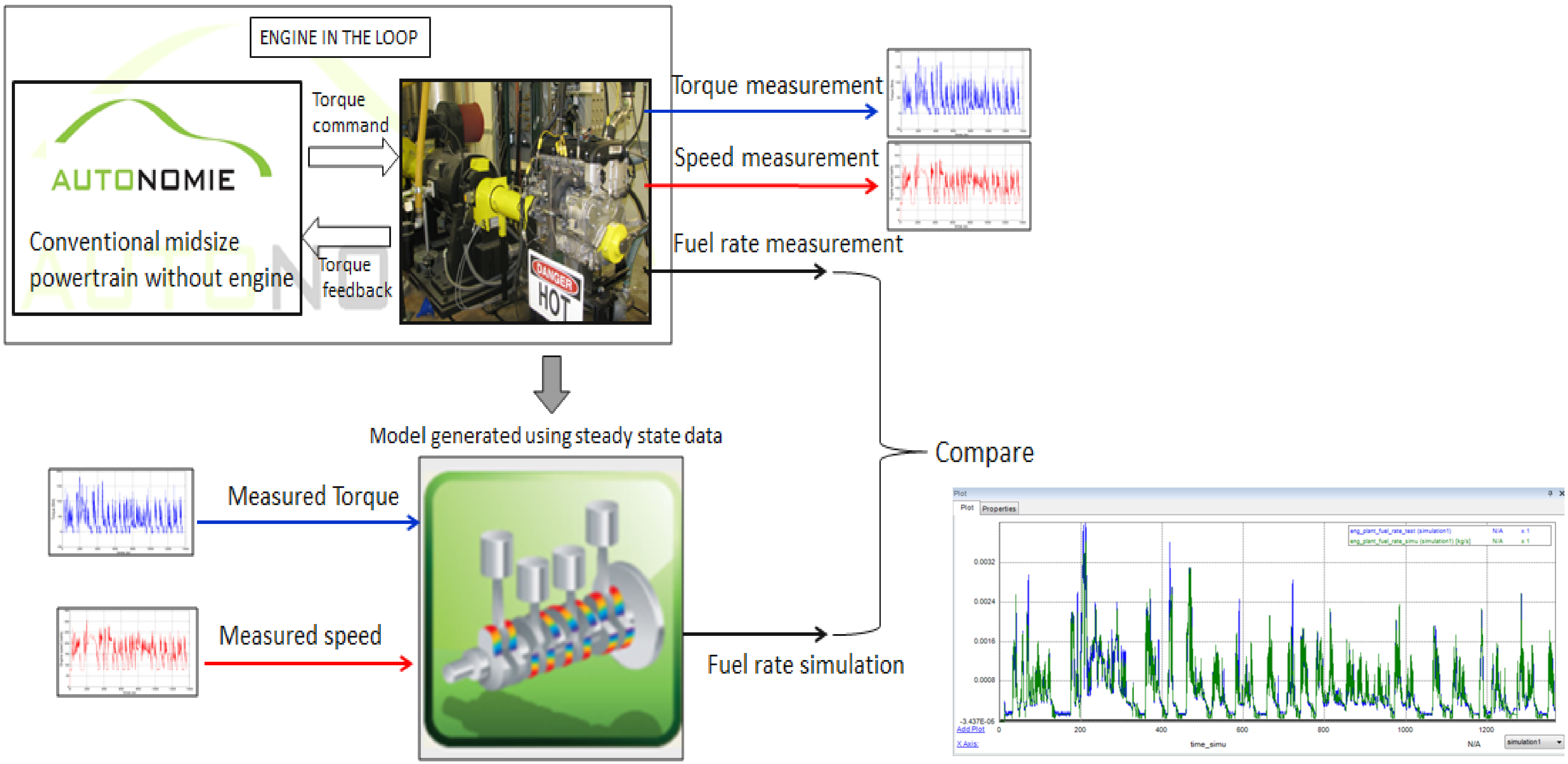
- Liquid cooling system
  - Components : pump, radiator, radiator fan, chiller, heater
  - Cooling mode : Active cooling, Passive cooling, Bypass, Heating

- 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.)

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

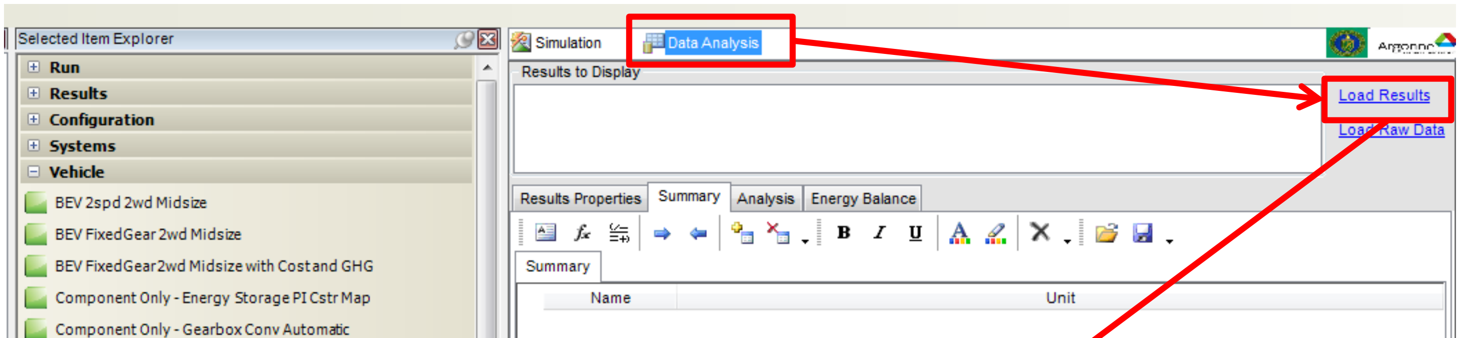
$$R_{xy}(\tau) = \lim_{T \to \infty} \int_0^T x(t) \circ y(t-\tau)dt$$

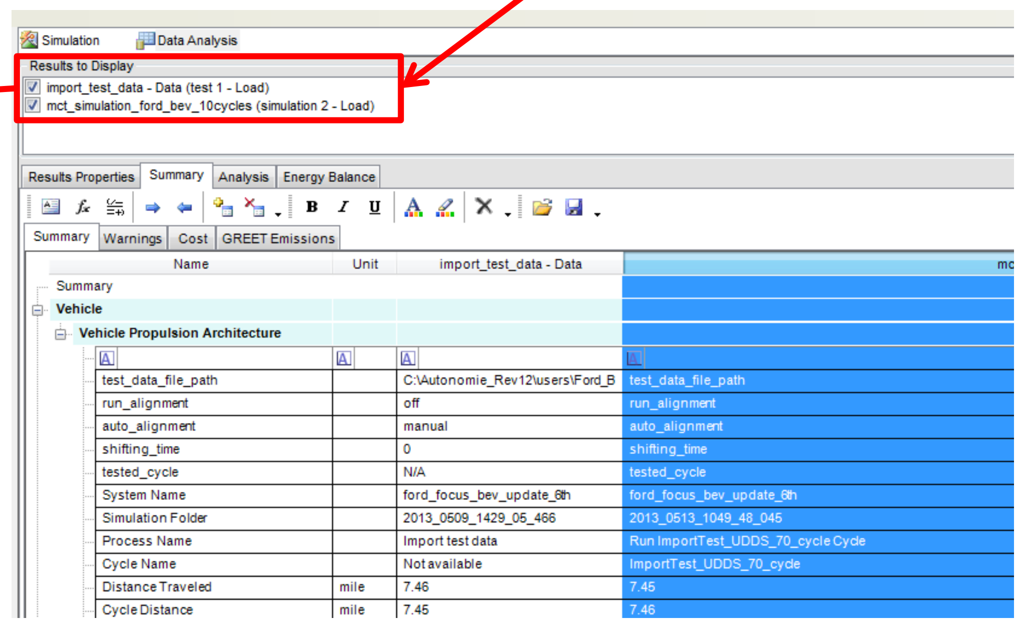
This metric estimates the correlation between two signals by considering their magnitude and linearity.

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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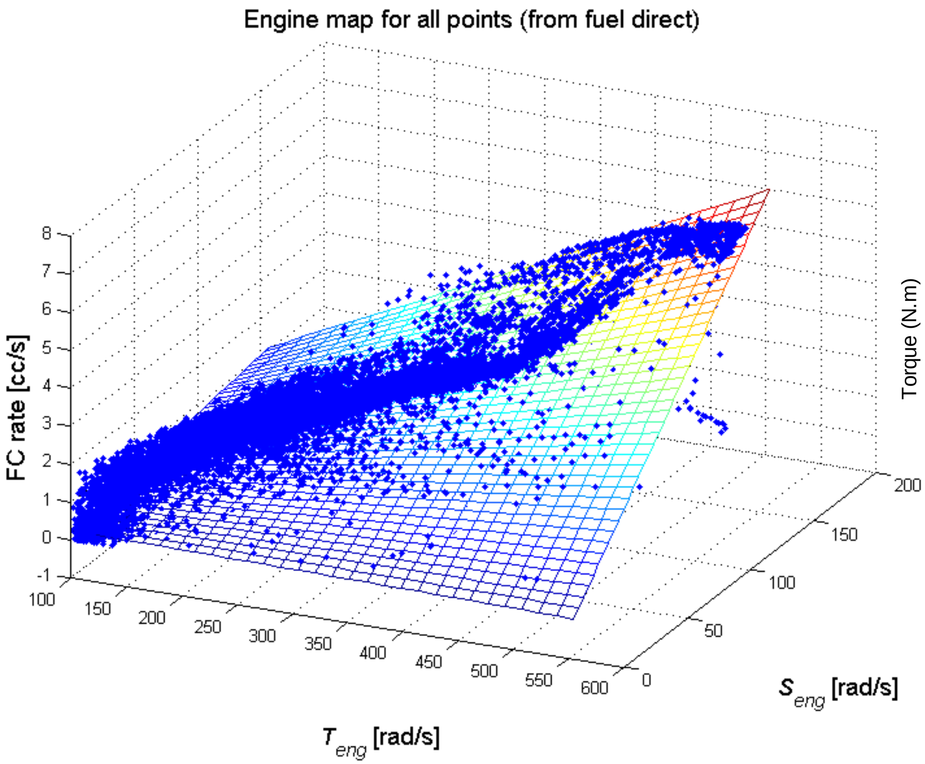
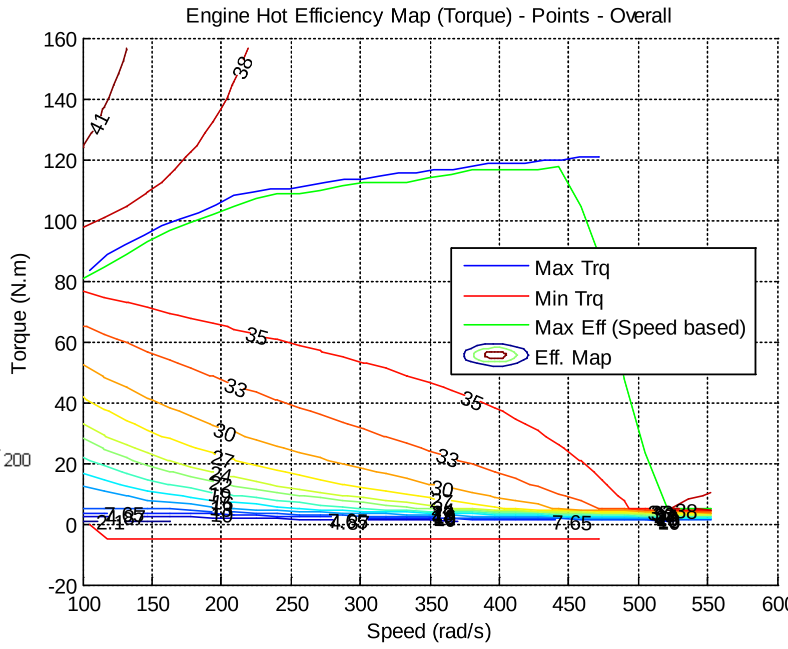
Generic Processes Used to Generate Component Performance Maps from Test Data

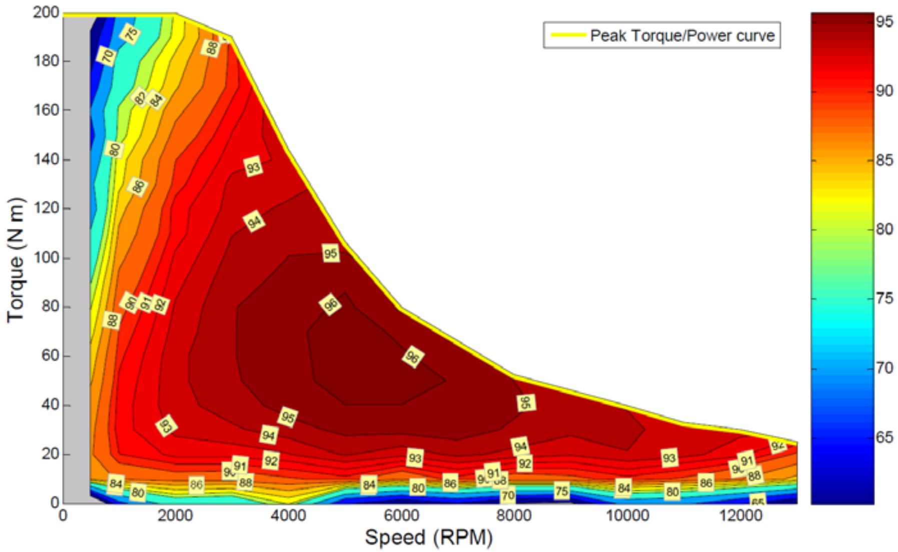
- Engine map example (2010 Prius)
  - From 25 tests, the engine map is generated.



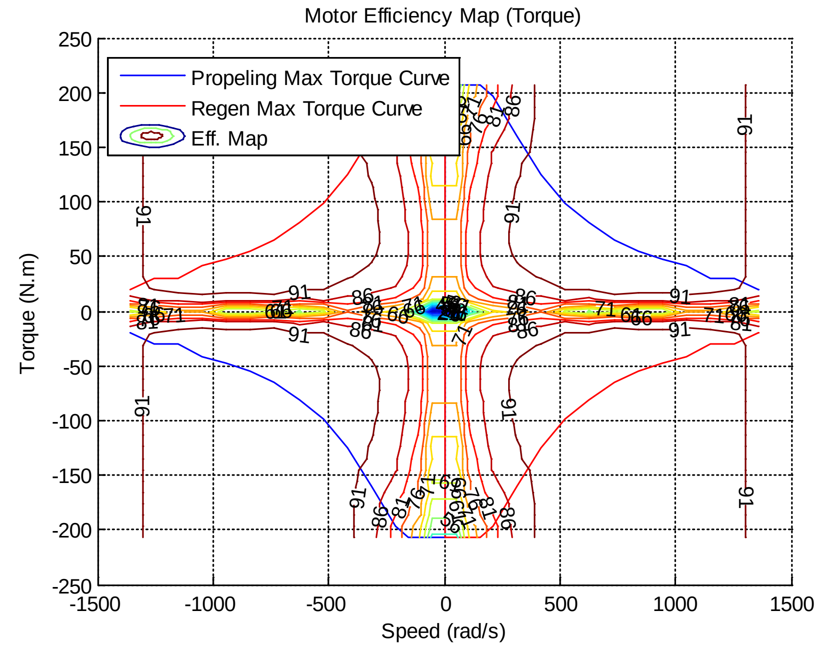


Some Component Performance Maps Also Provided by Nat Lab System

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



Mitch Olszewski, EVALUATION OF THE 2010 TOYOTA PRIUS HYBRID SYNERGY DRIVE SYSTEM



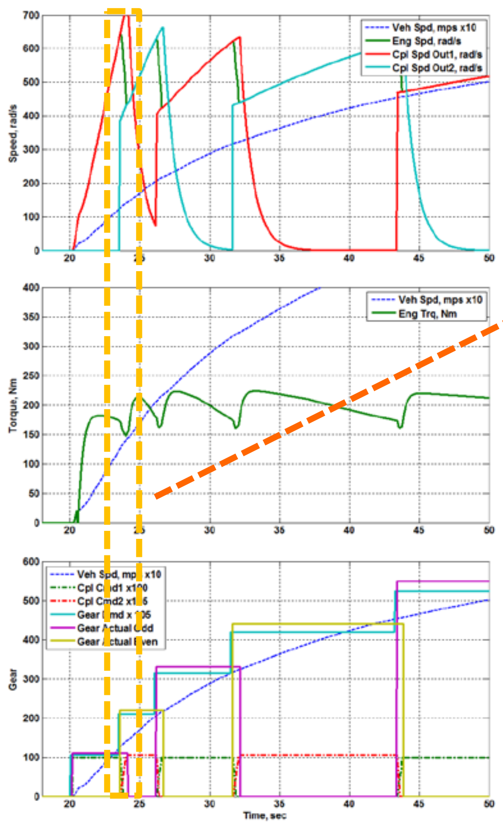
Without current for each motor, it is not possible to obtain the motor efficiency.

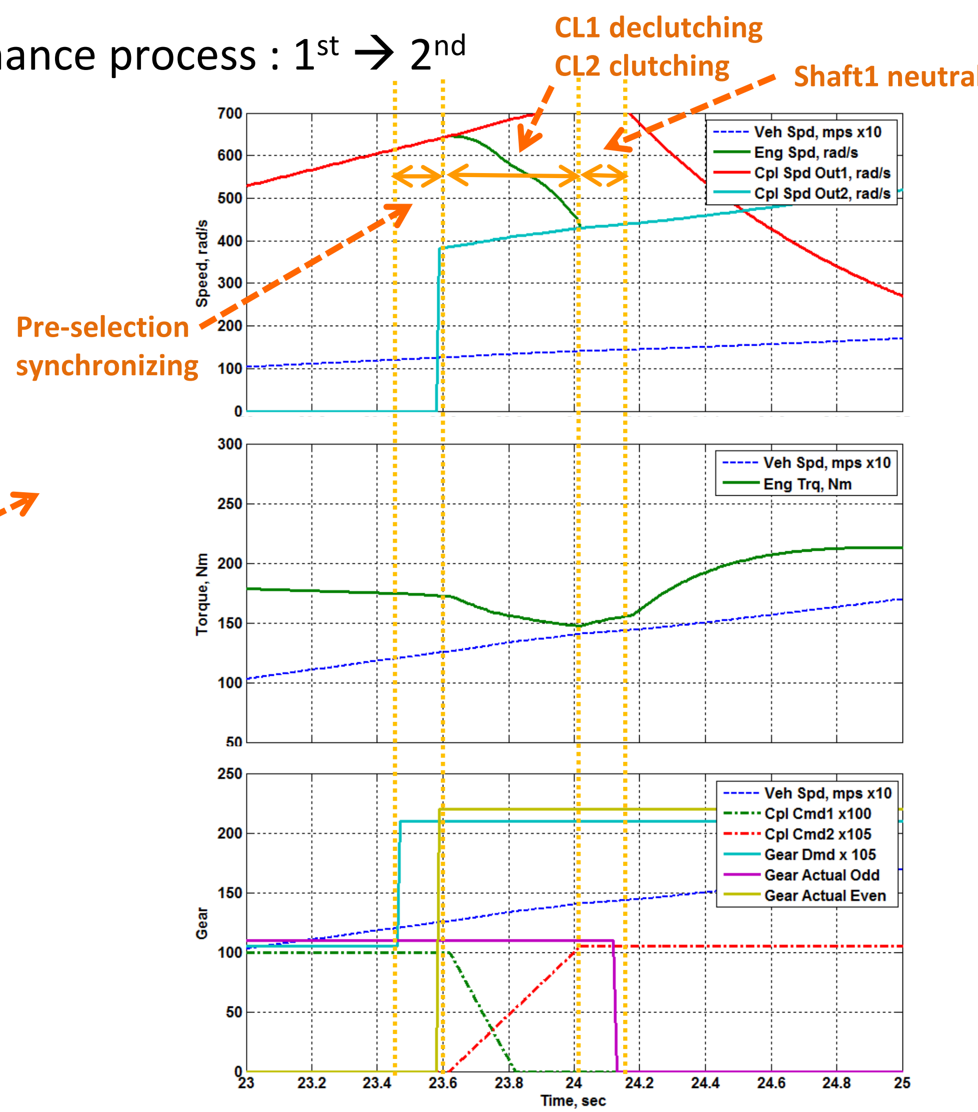
Accurate Low Level Controls Are Critical

DCT Shifting Events Example

- Acceleration - U.S. performance process : 1st → 2nd

Par HEV Dual Clutch Trans

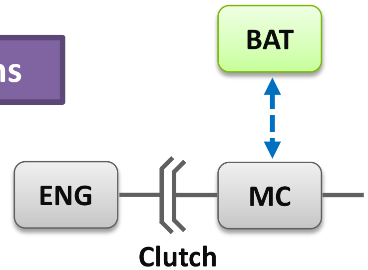




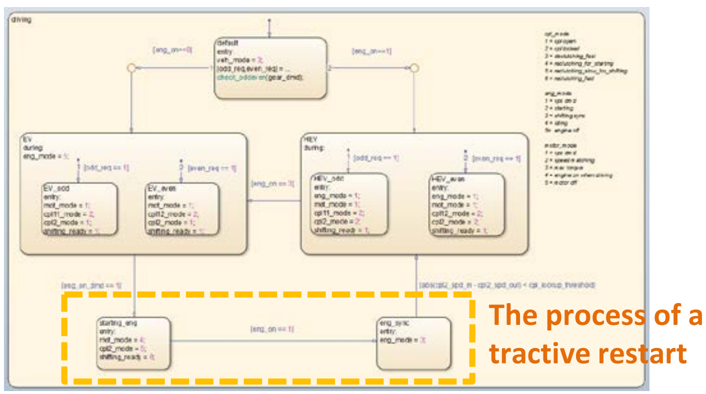
Accurate Low Level Controls Are Critical

Using the Motor for a Pre-Trans HEV during Shifting

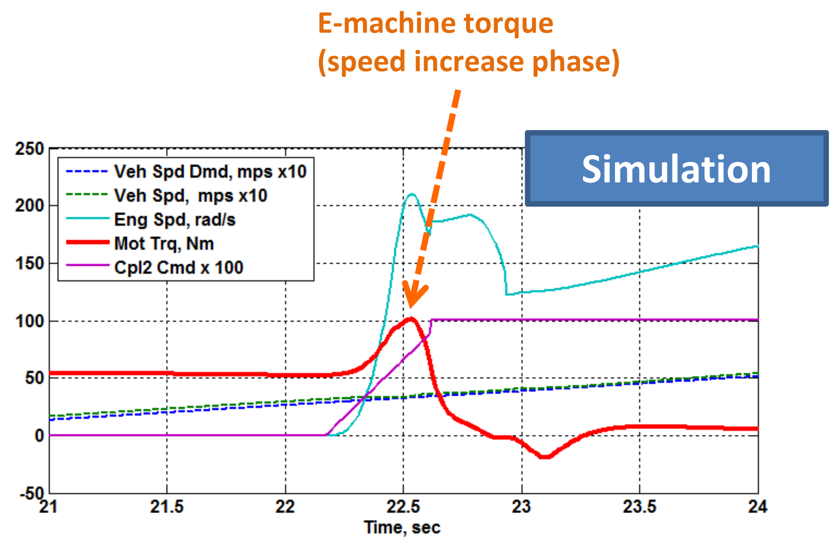
Par HEV Dual Clutch Trans

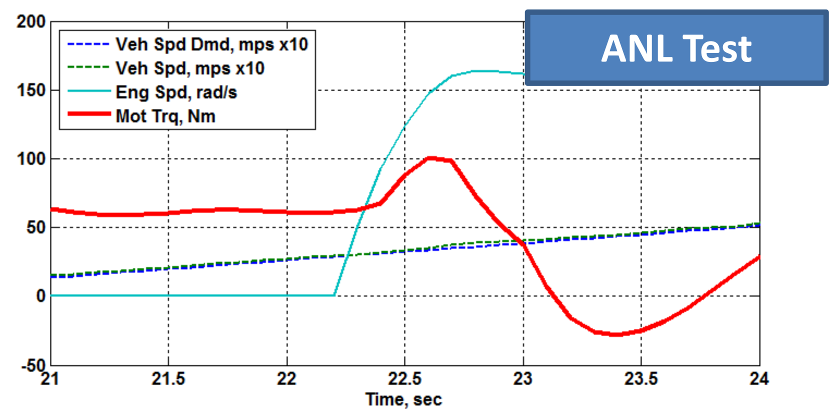


Vehicle mode 3 : driving



- 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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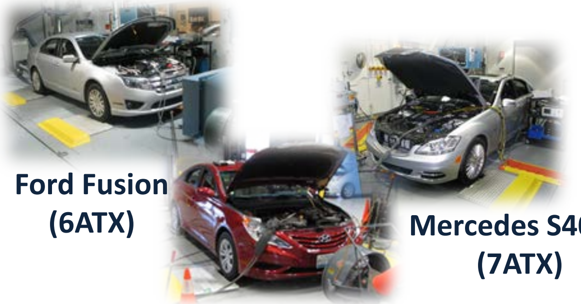
Advanced Vehicle Benchmark Testing

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

4WD chassis dyno

2WD chassis dyno

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



Ford Fusion (6ATX)

HMC Sonata (6ATX)

Mercedes S400H (7ATX)

…

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

Speed In (Measured from Turbine Speed)

Speed Out (Calculated from Vehicle Speed)

Gear Ratio Calculation

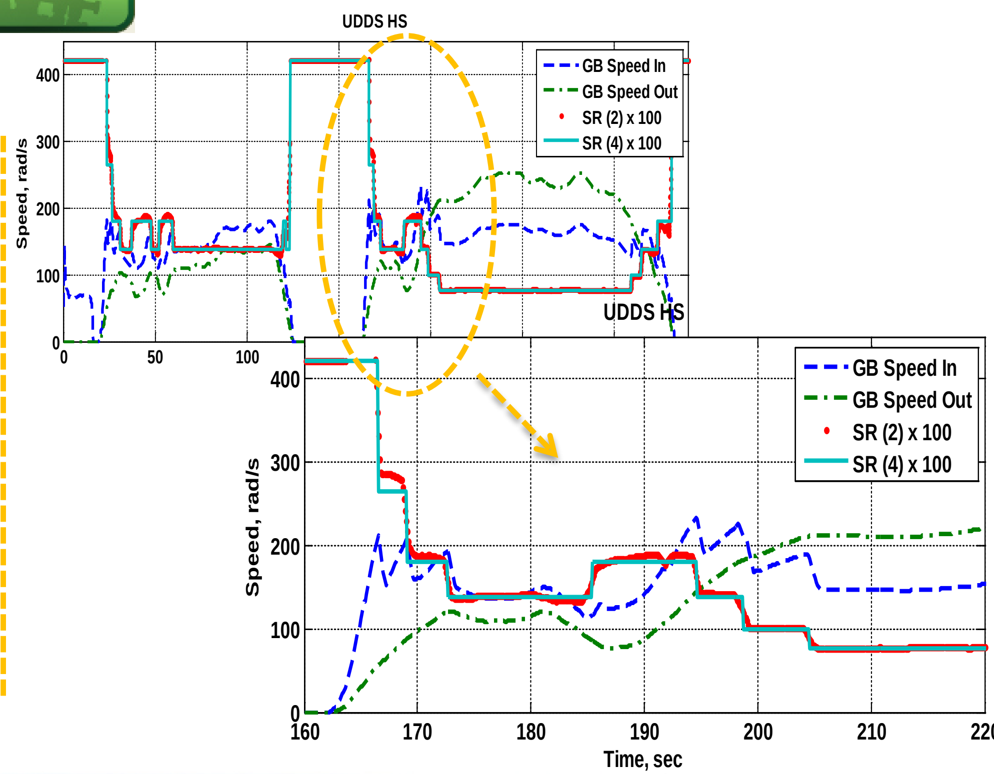
0) Signals are aligned based on vehicle speed

1) SR = Speed In (Measured from Turbine Speed) / Speed Out (Calculated from Vehicle Speed)

2) SR = 1st 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)

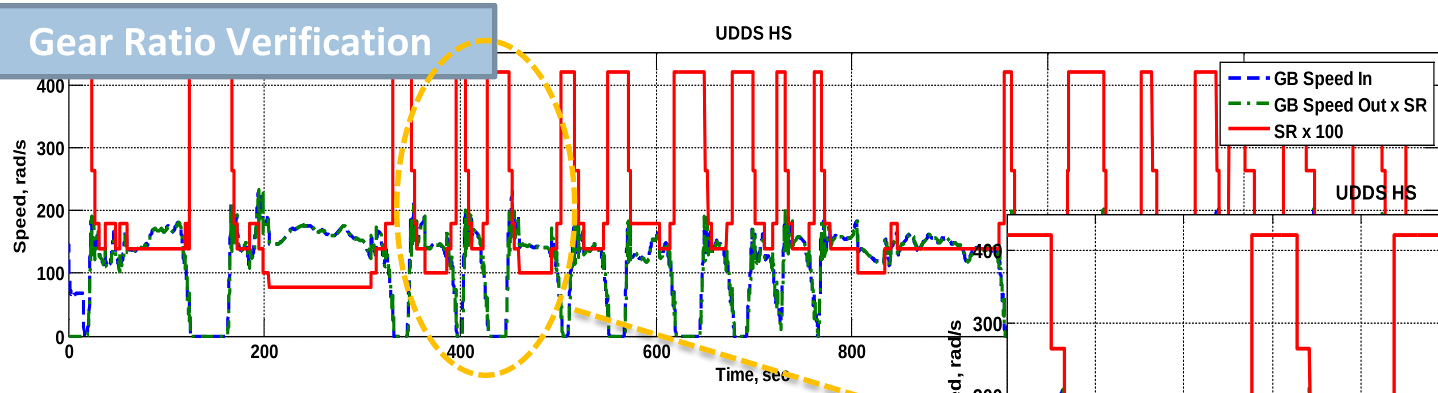


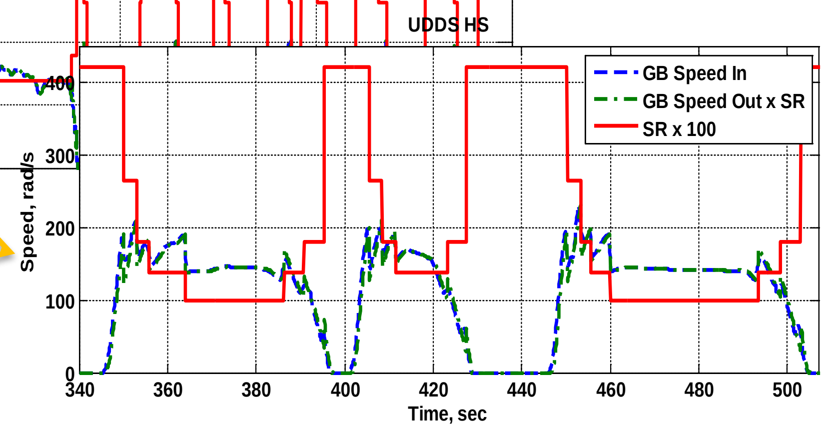
Calculation of Additional Signals

Gear Ratio Calculation Validation

- 2013 HMC Sonata Conv. I4 6ATX

Gear Ratio Verification





- 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)

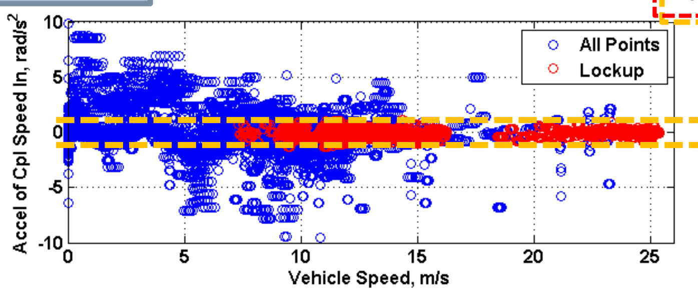
Speed Out
= From Vehicle Speed

Used torque ratio map
as a function of speed ratio

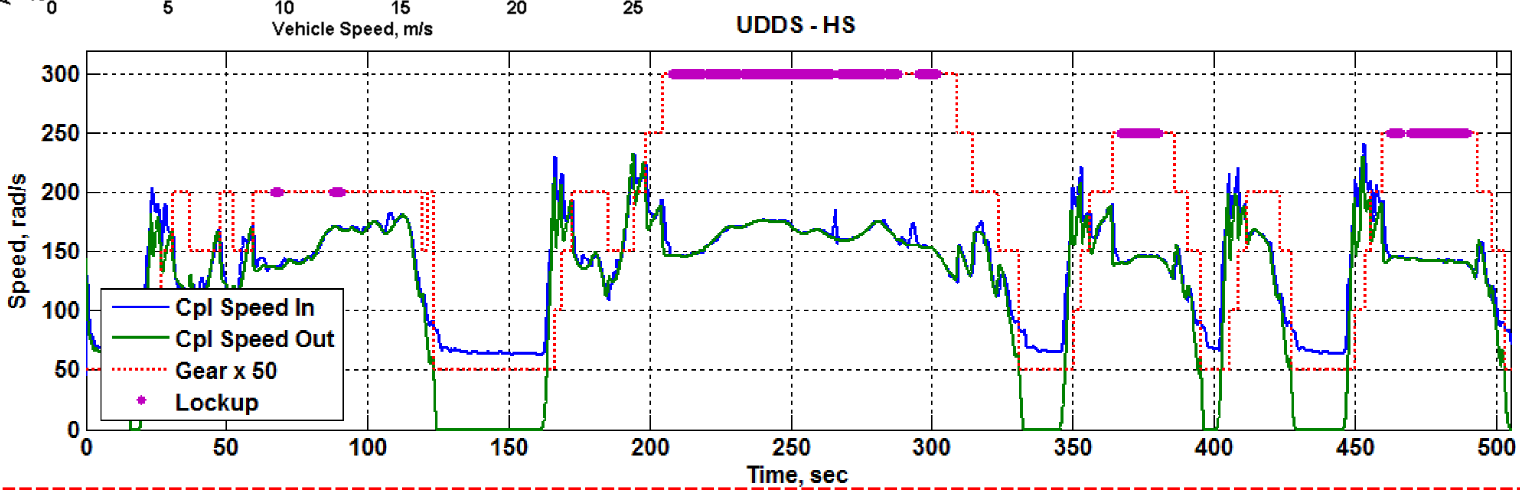
When we do not know the status of the torque converter lockup for ATX

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)

Step 3), 4)



Percentage Time Torque Converter is Locked (UDDS) : **10.1%**



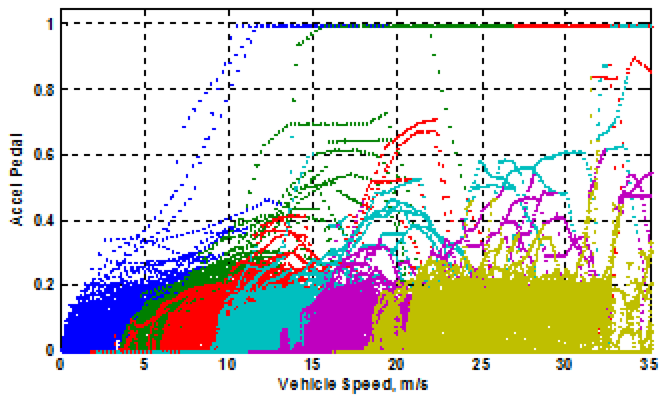
Test Data Analysis for Automatic Transmission

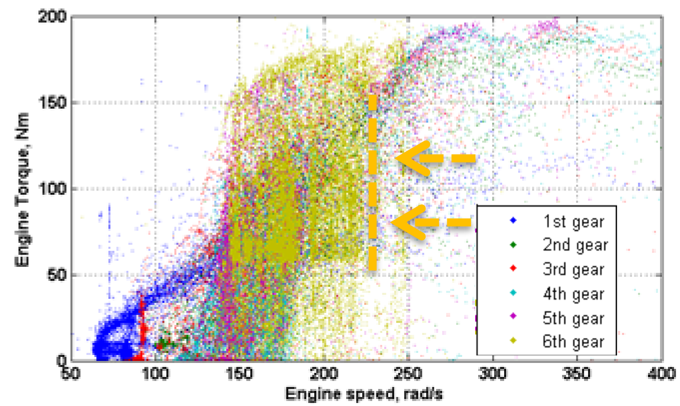
Impact of Powertrain Technology

- Sonata Conv. 6ATX vs. Sonata HEV 6ATX

Sonata Conv 6ATX

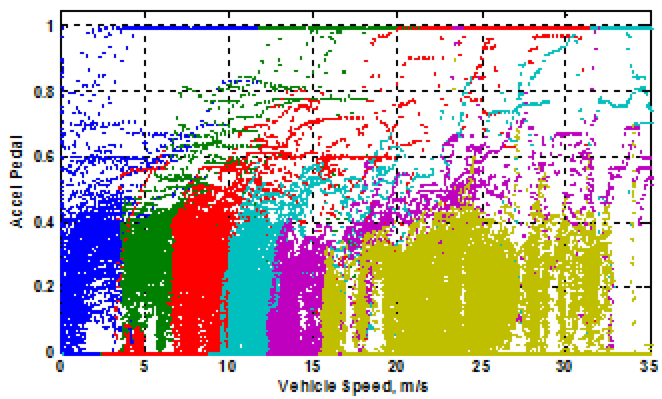
1st : 4.21
2nd : 2.64
3rd : 1.80
4th : 1.39
5th : 1.00
6th : 0.77
FD : 2.89

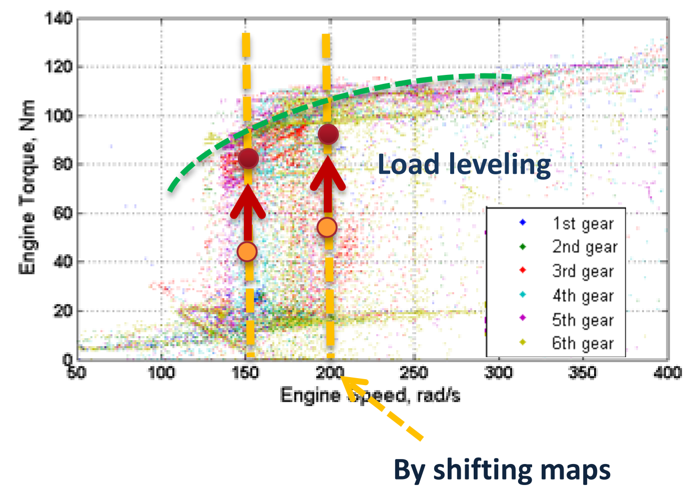




Sonata HEV 6ATX

1st : 4.21
2nd : 2.64
3rd : 1.80
4th : 1.39
5th : 1.00
6th : 0.77
FD : 3.32

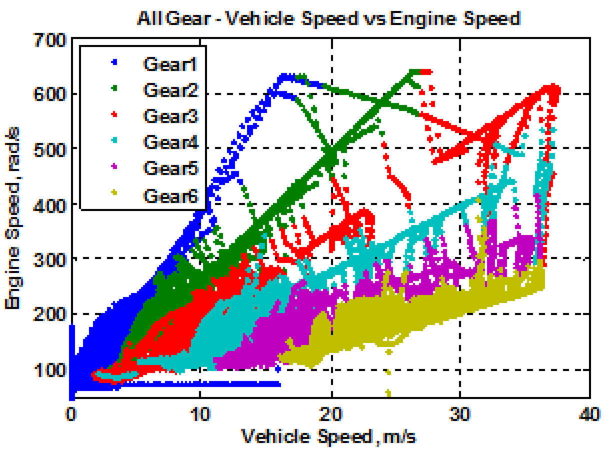


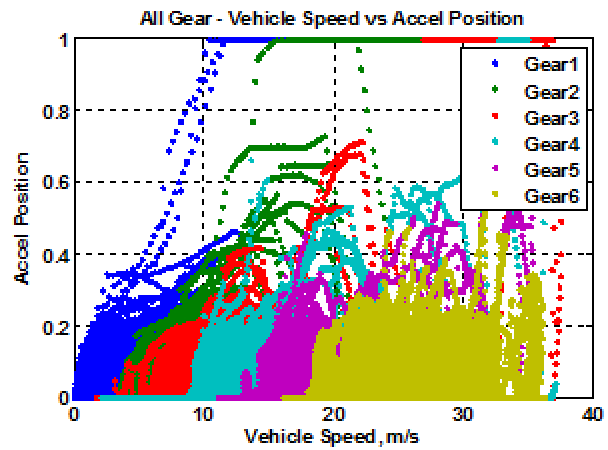


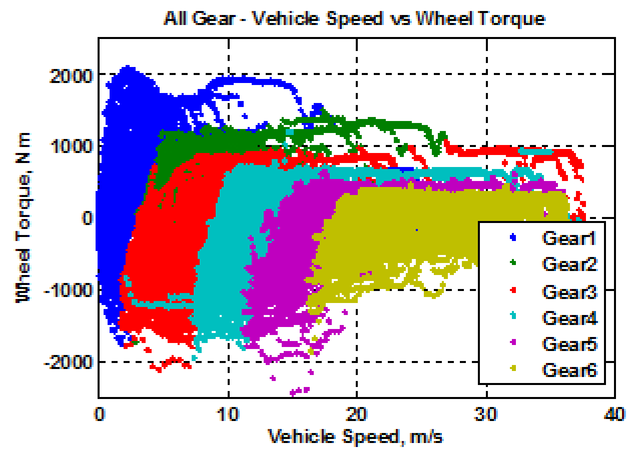
Test Data Analysis for Automatic Transmission

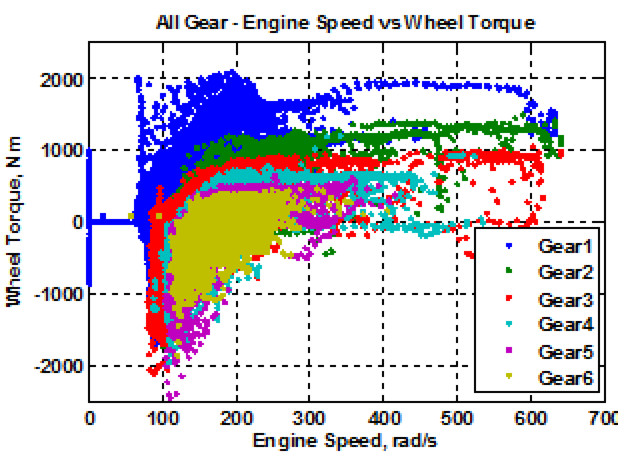
Dedicated Analysis Functions Developed

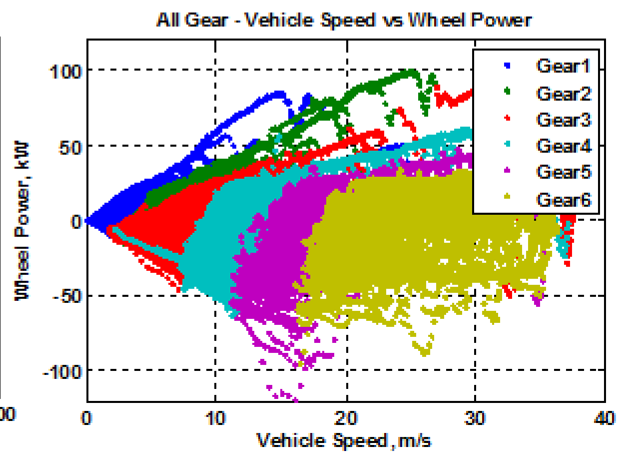
- 2013 HMC Sonata Conv. 6ATX Example

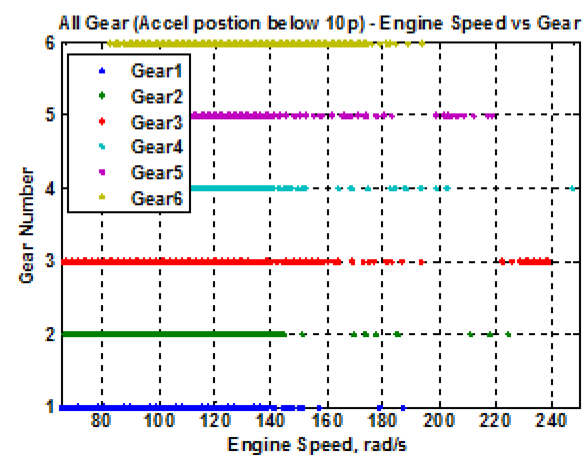










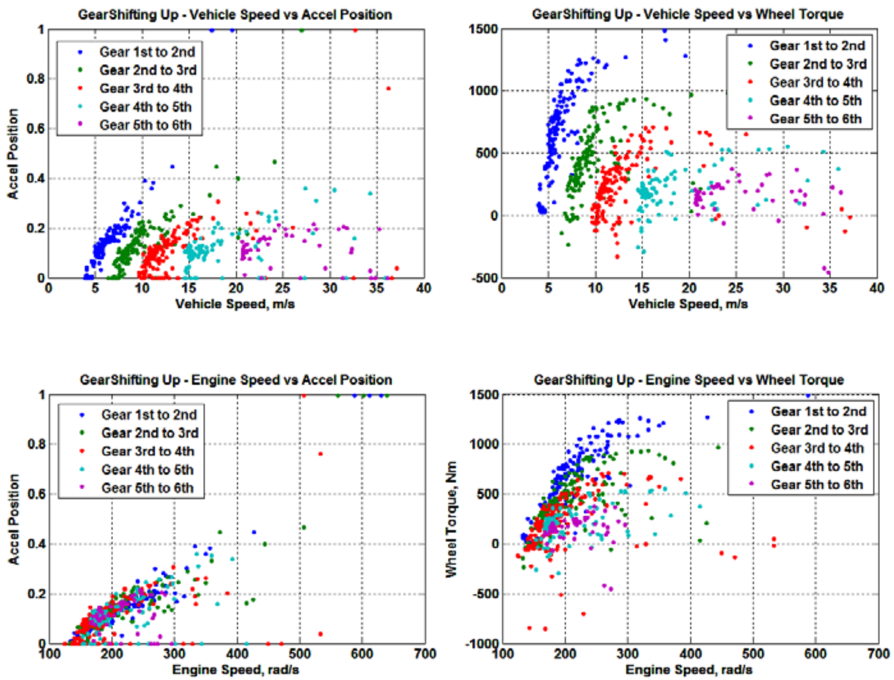


Test Data Analysis for Automatic Transmission

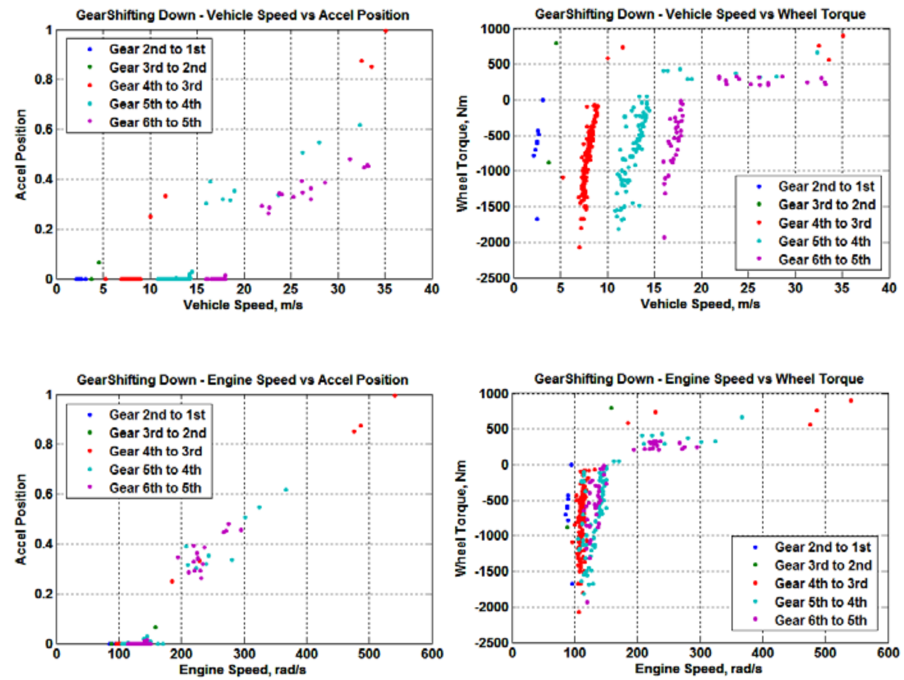
Functions to Develop Shifting Curves

- 2013 HMC Sonata Conv. 6ATX Example

Upshifting



Downshifting



Integrated and analyzed more than a dozen set of vehicle test data into Autonomie

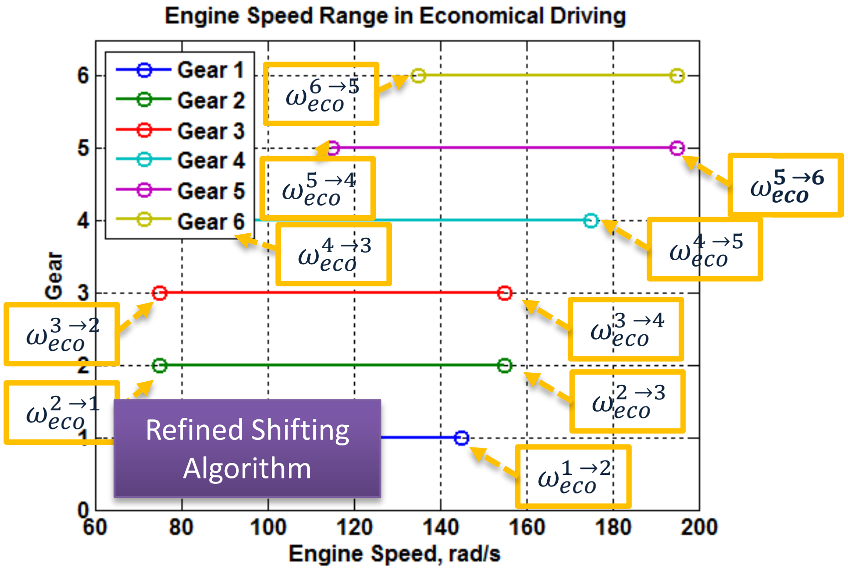
Developing Shifting Maps Calibrations

Refined Shifting Algorithm / Calibration

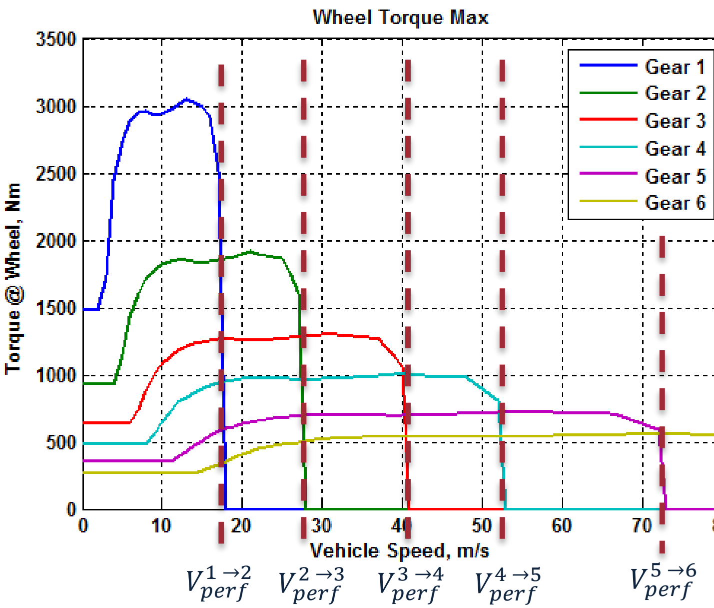
- The new values of the parameters of shifting controller are added in the shifting initializer to defines the shifting maps created from test data.

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

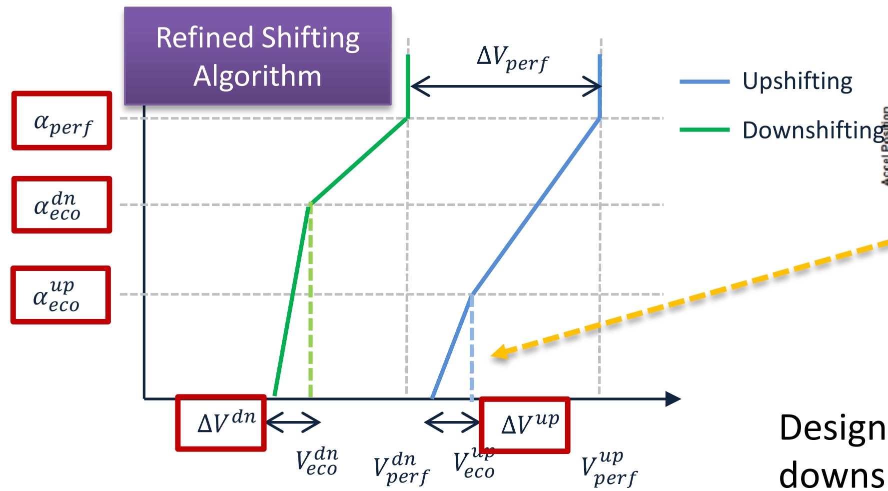
- Final shifting curves

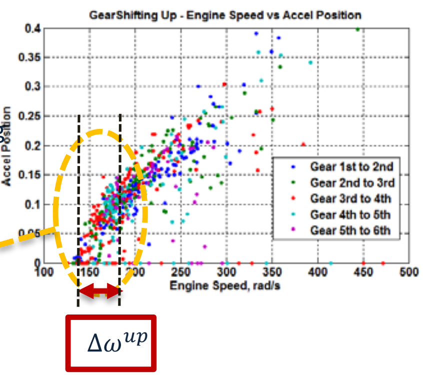
Economical Shifting Speeds

V^{dn}_{perf} V^{up}_{perf}

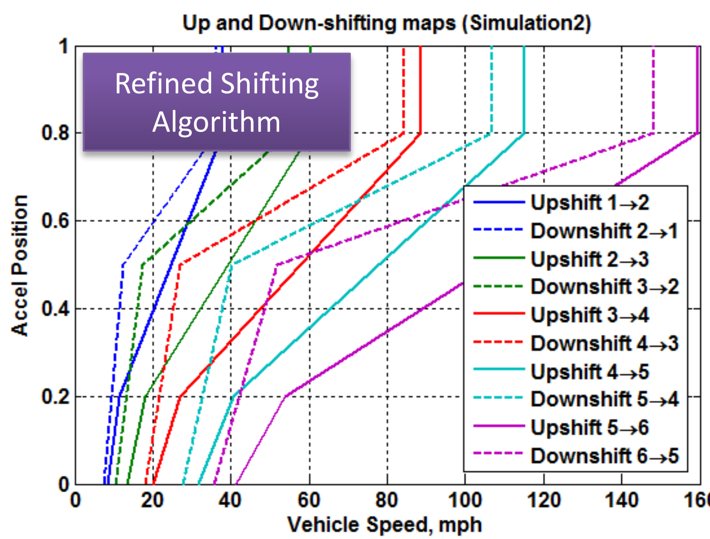
Performance Shifting Speeds

V^{dn}_{eco} V^{up}_{eco}





Design of upshifting and downshifting speed curves for two adjacent gears

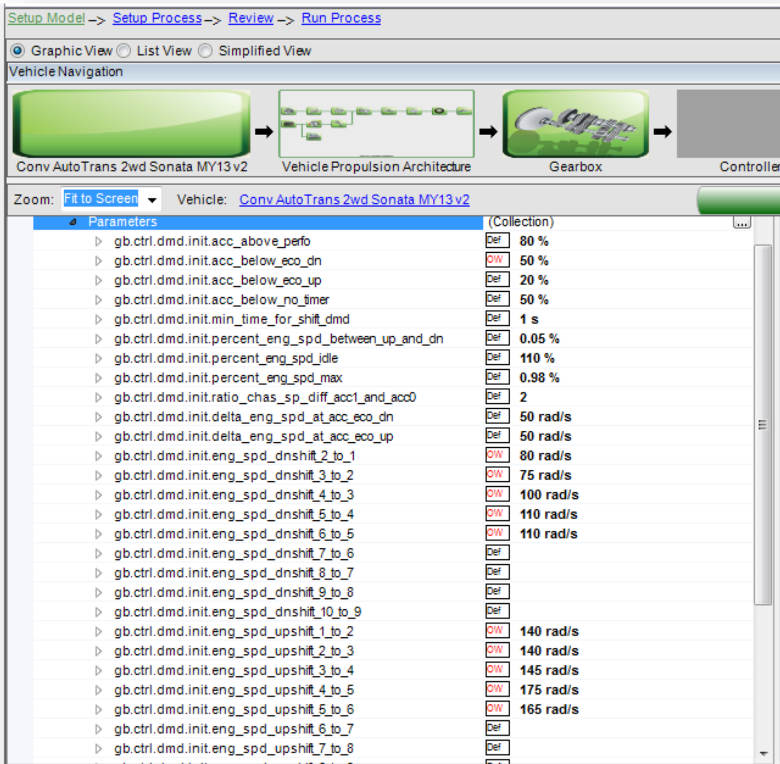


New shifting speed curves for a default light-duty vehicle in Autonomie

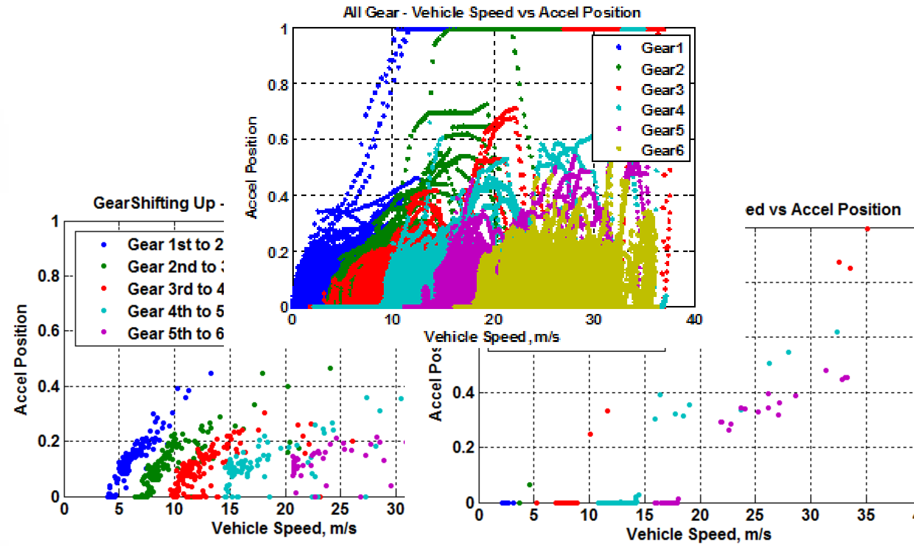
Developing Shifting Maps Calibrations

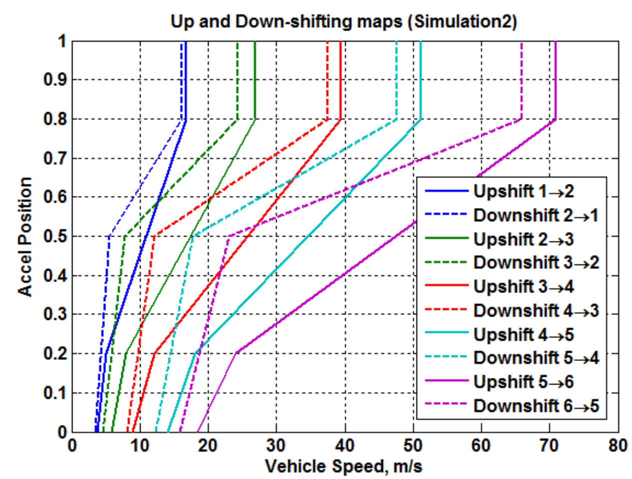
Refined Shifting Algorithm / Calibration

- Example : 2013 HMC Sonata Conv. I4 6ATX



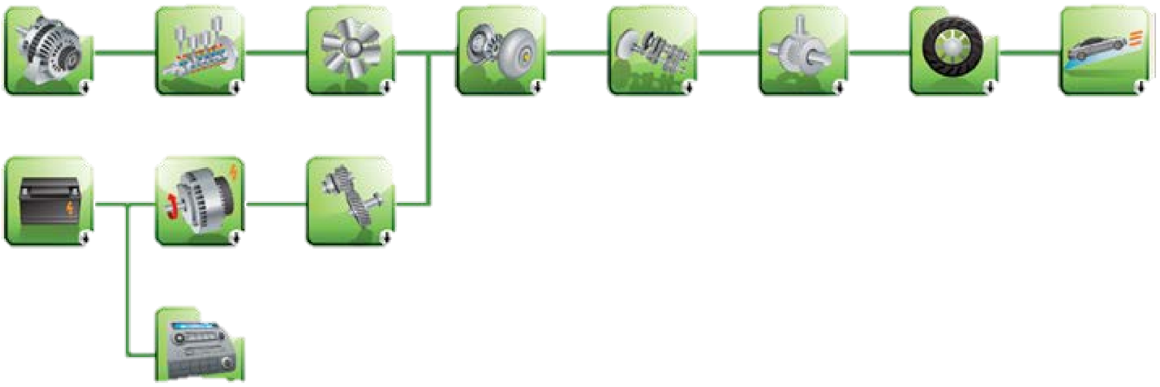
“gb_ctrl_dmd_n_gen_eng_mot_not_included_detail.m” is created to match the shifting map based on test data.





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

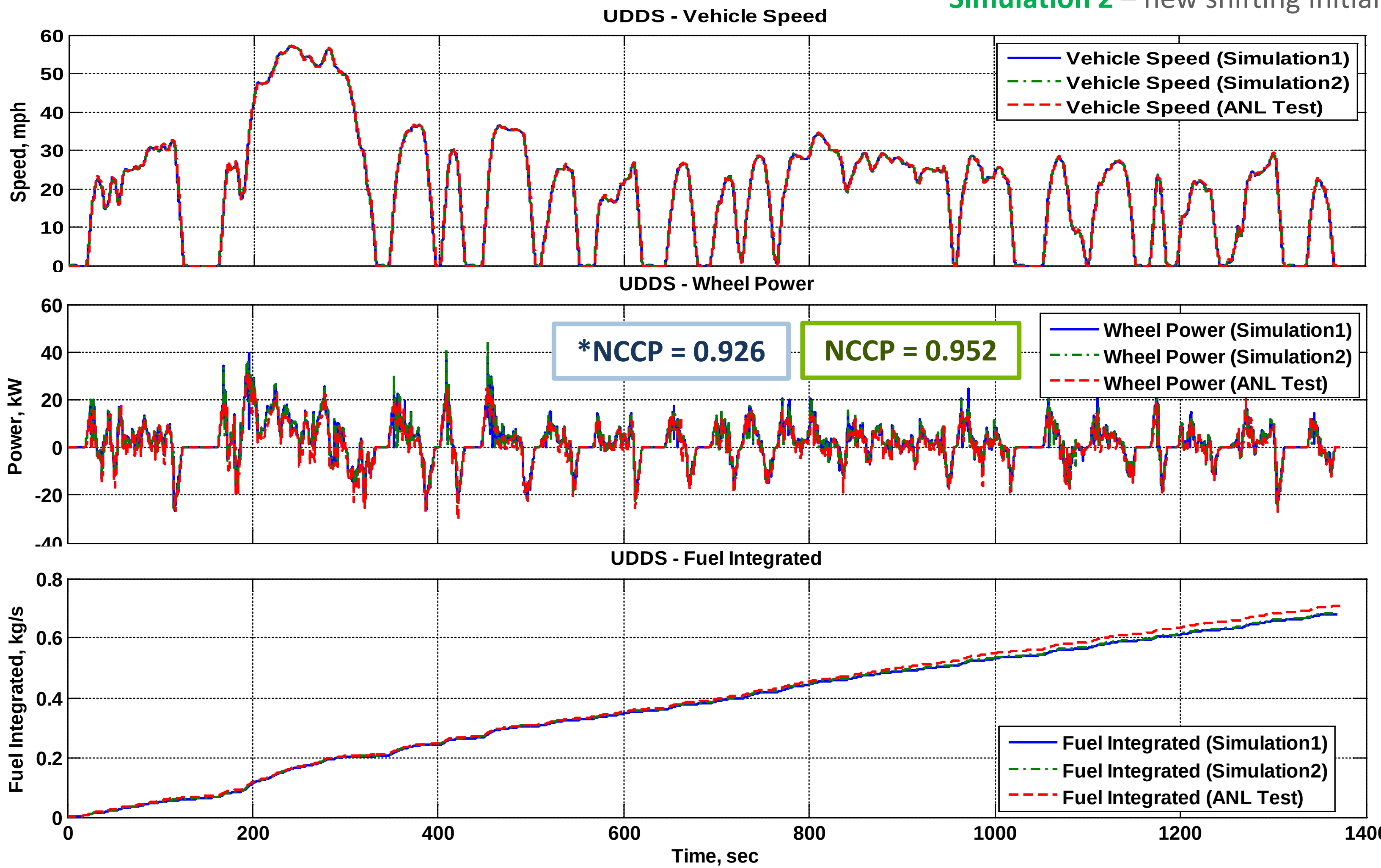
2012 Chrysler300 V6 8ATX

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

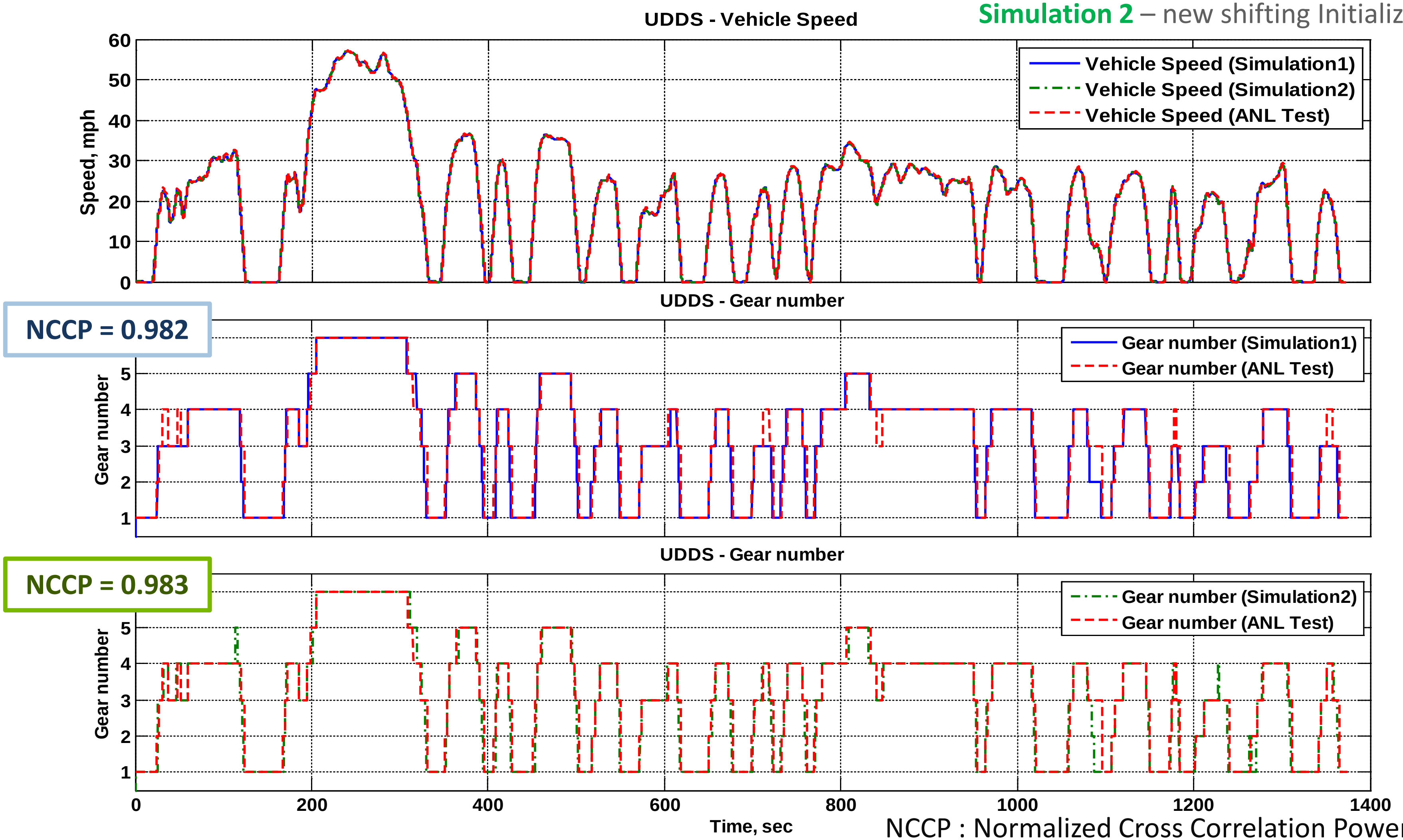


Model Validation in Autonomie

2013 Hyundai Sonata Conv. 6ATX

- UDDS – gear number

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



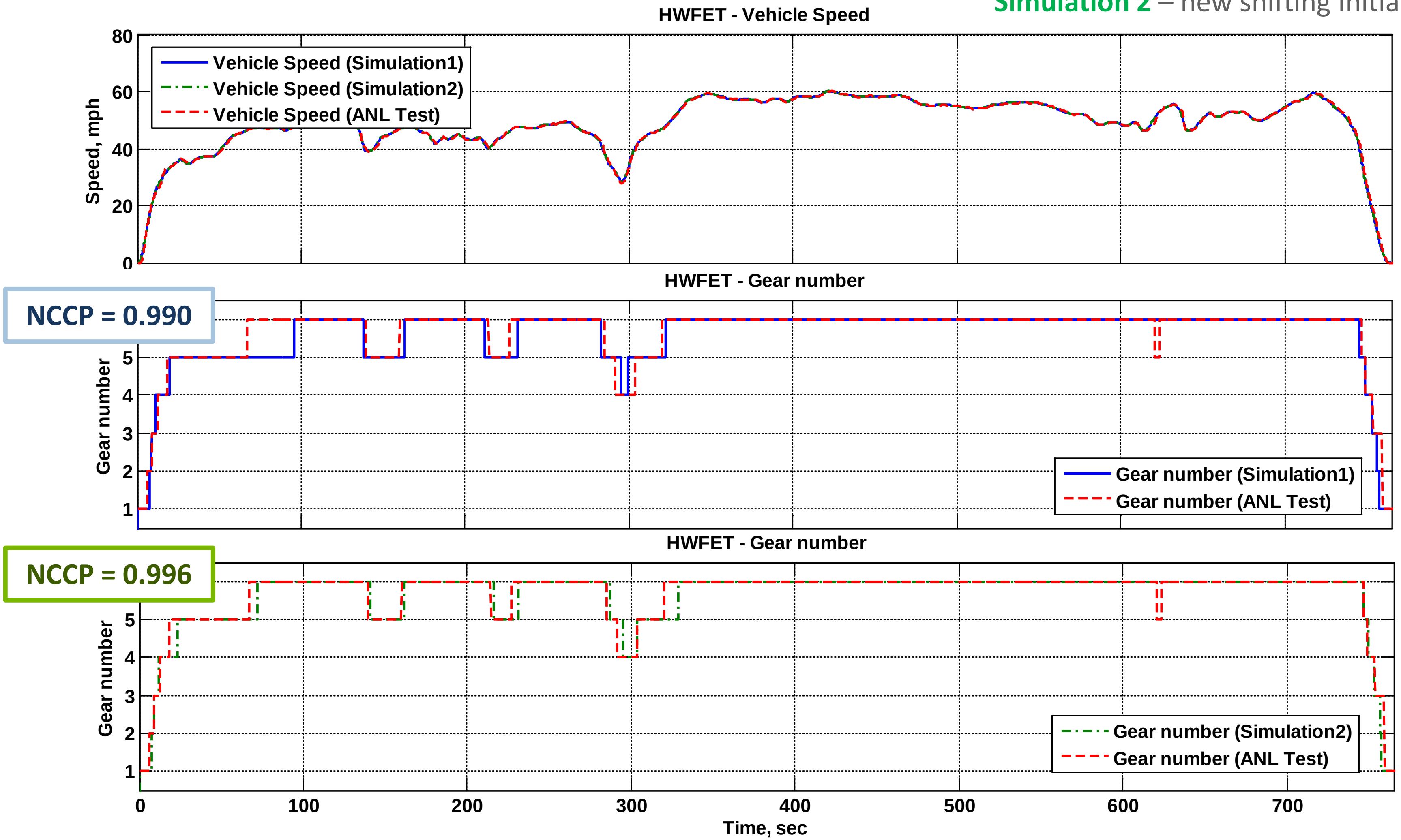
NCCP : Normalized Cross Correlation Power

Model Validation in Autonomie

2013 Hyundai Sonata Conv. 6ATX

- HWFET – gear number

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



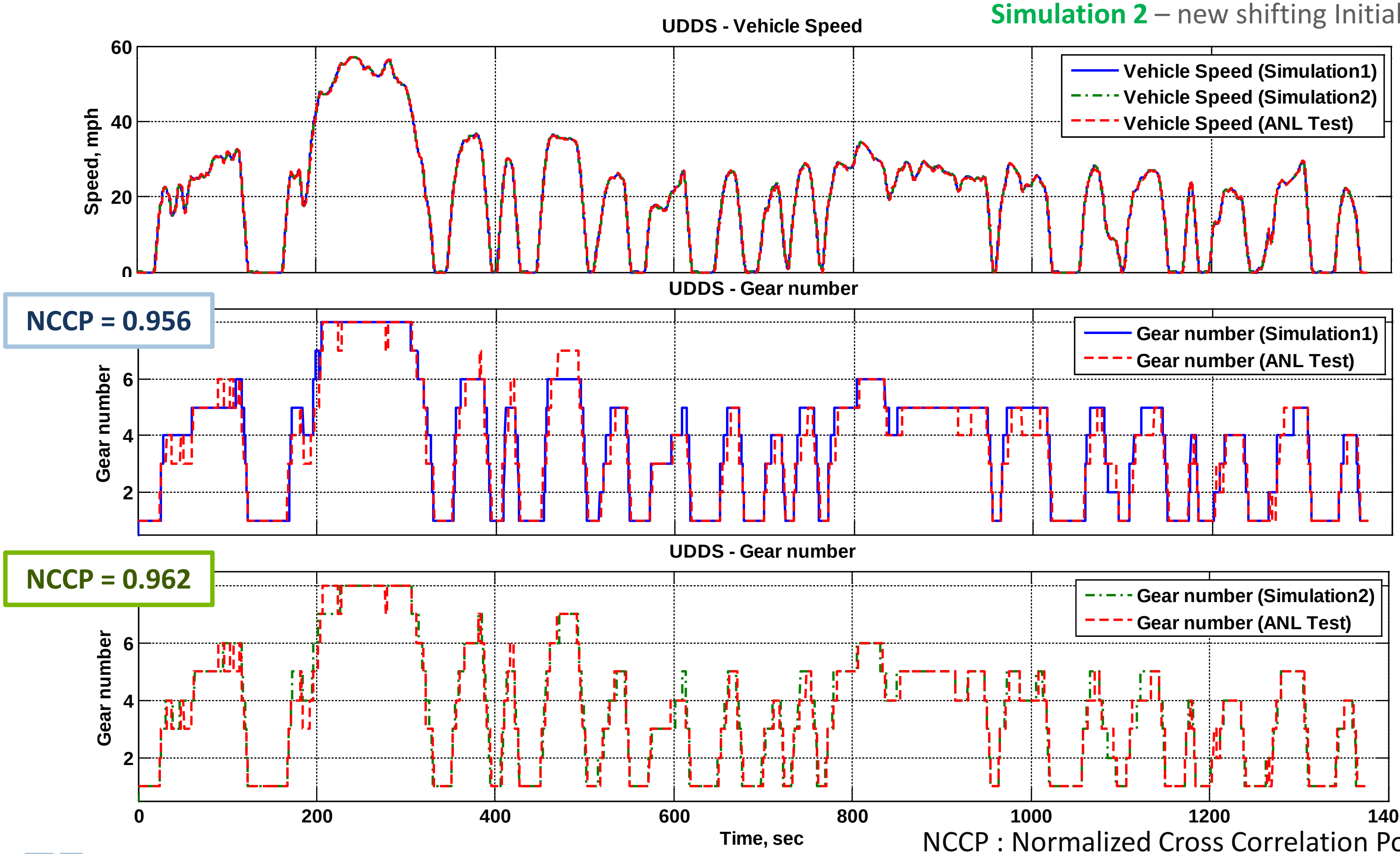
Model Validation in Autonomie

2012 Chrysler300 V6 8ATX

- UDDS – gear number

Simulation 1 – current shifting Initializer

Simulation 2 – new shifting Initializer

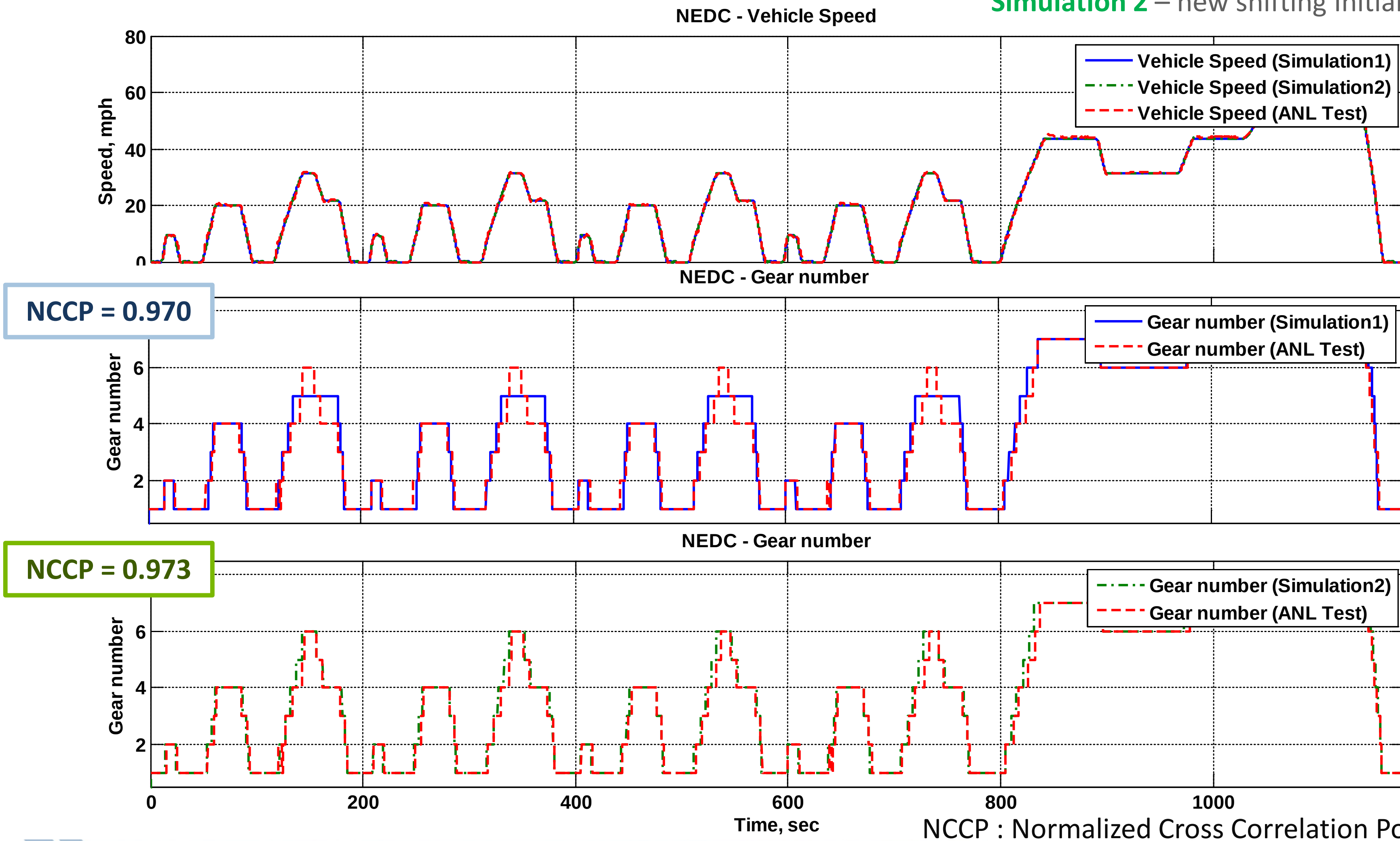


NCCP : Normalized Cross Correlation Power

Model Validation in Autonomie
2012 Chrysler300 V6 8ATX

- NEDC – gear number

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

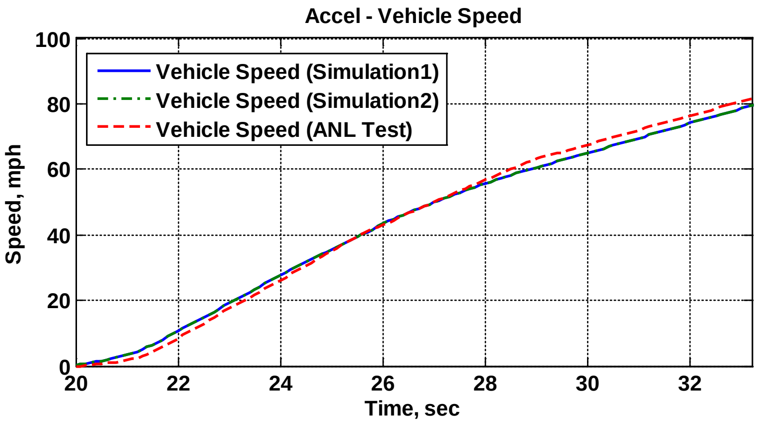


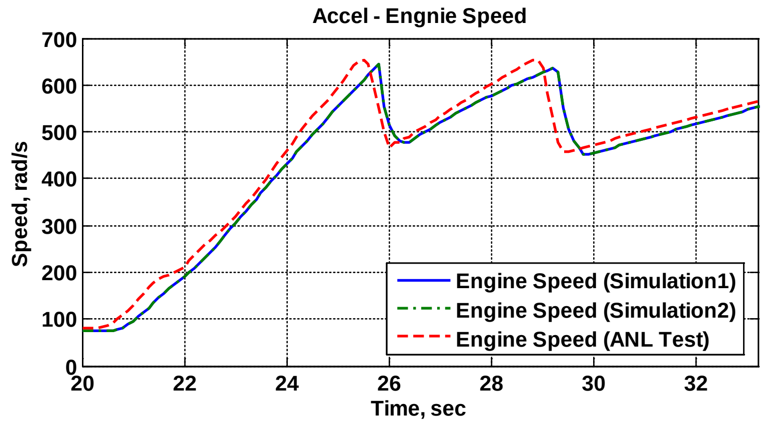
NCCP : Normalized Cross Correlation Power

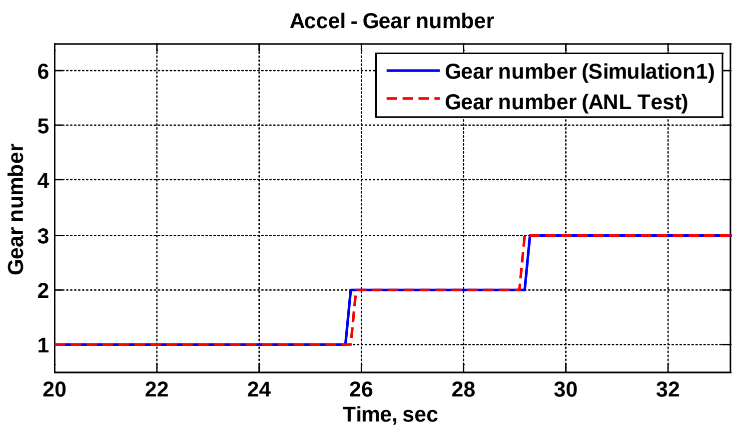
Model Validation in Autonomie
2012 Chrysler300 V6 8ATX

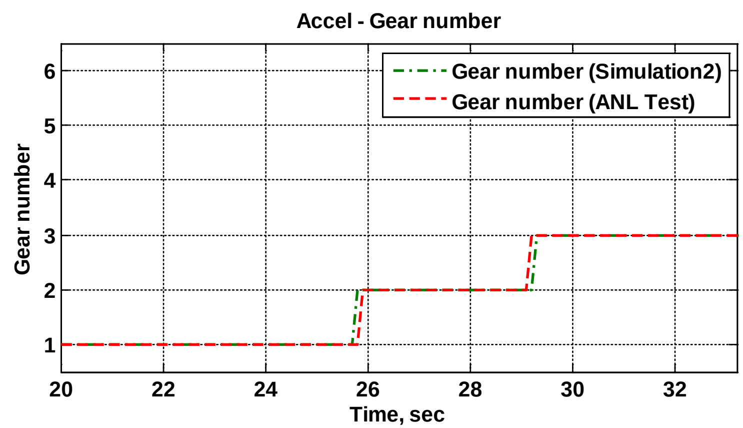
- Accel. performance – gear number

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









Shifting Algorithm Model Validation

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

	UDDS	HWFET	NEDC	LA92
Simulation 1 – current shifting Initializer	0.982	0.990	0.980	0.986
Simulation 2 – new shifting Initializer	0.983 (0.10%)	0.996 (0.61%)	0.982 (0.20%)	0.991 (0.51%)

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

	UDDS	HWFET	NEDC	LA92
Simulation 1 – current shifting Initializer	0.968	0.998	0.951	0.994
Simulation 2 – new shifting Initializer	0.995 (2.79%)	0.998 (0%)	0.981 (3.15%)	0.988 (-0.61%)

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

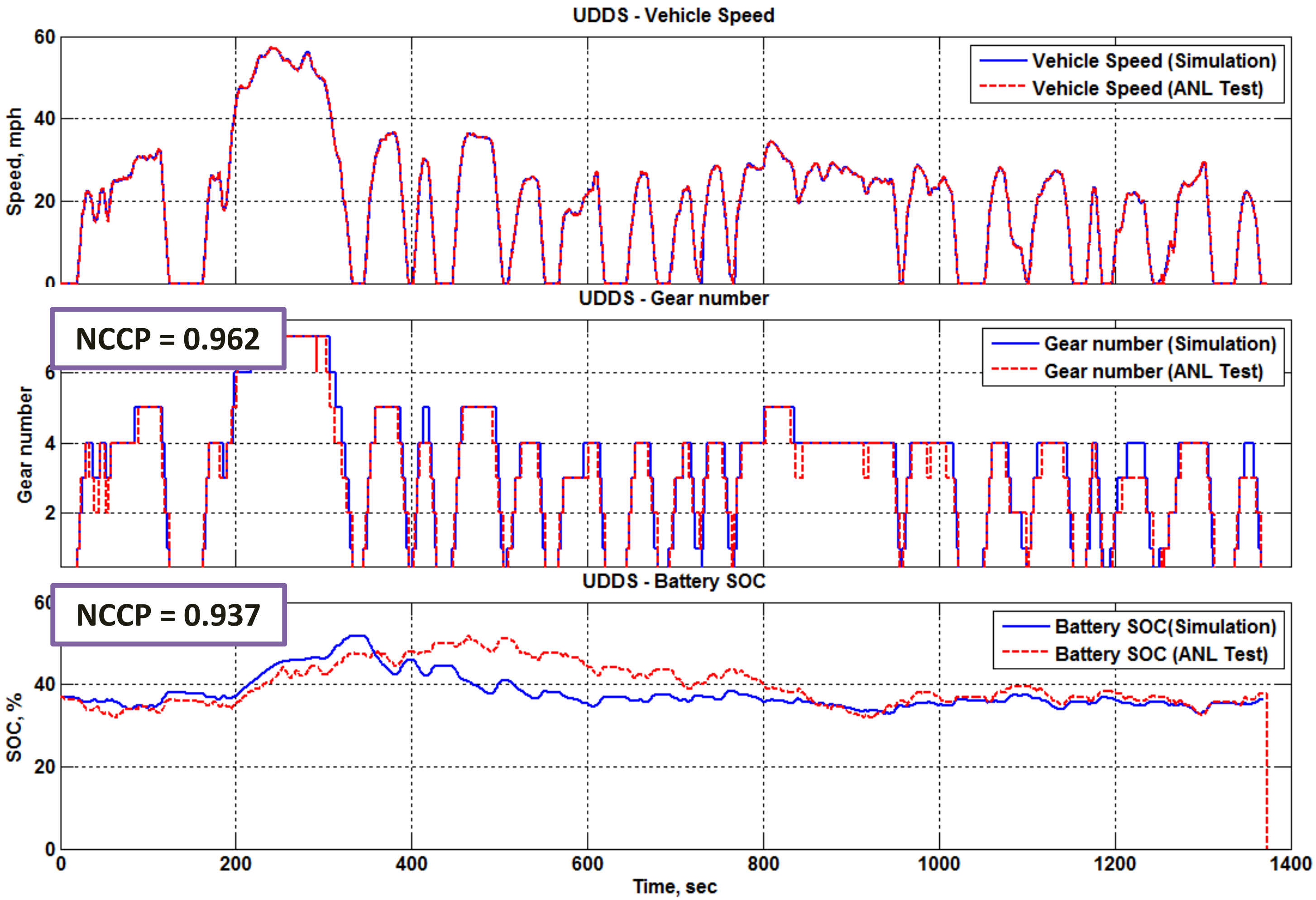
	UDDS	HWFET	NEDC	LA92
Simulation 1 – current shifting Initializer	0.956	0.984	0.970	0.938
Simulation 2 – new shifting Initializer	0.962 (0.63%)	0.993 (0.91%)	0.973 (0.31%)	0.957 (2.03%)

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

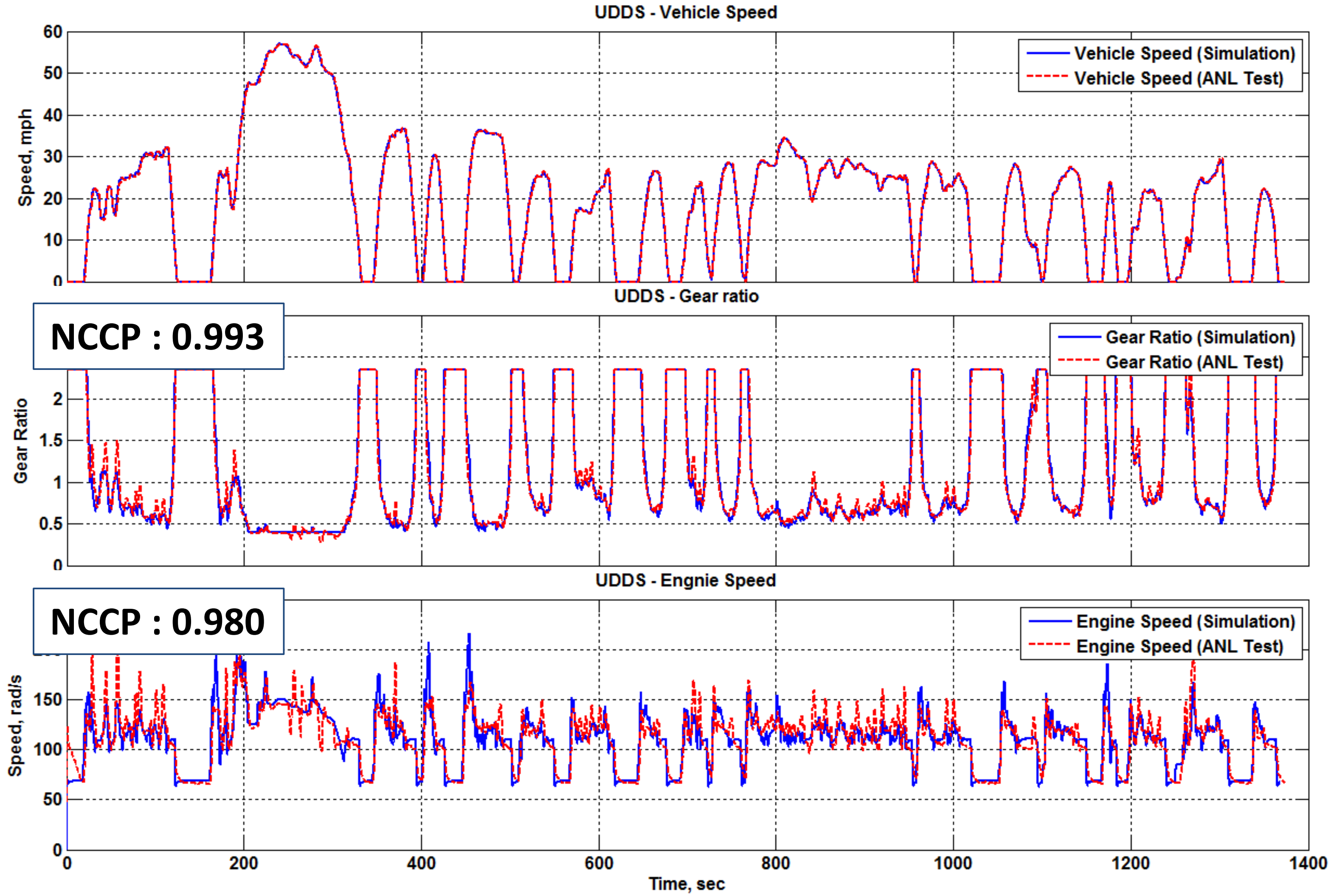
Outstanding differences due to the fact that the vehicle level energy management was only correlated, not validated

- UDDS – vehicle speed, SOC and gear number



Nissan Altima Conventional CVT Example

UDDS cycle – vehicle speed, gear ratio and engine speed



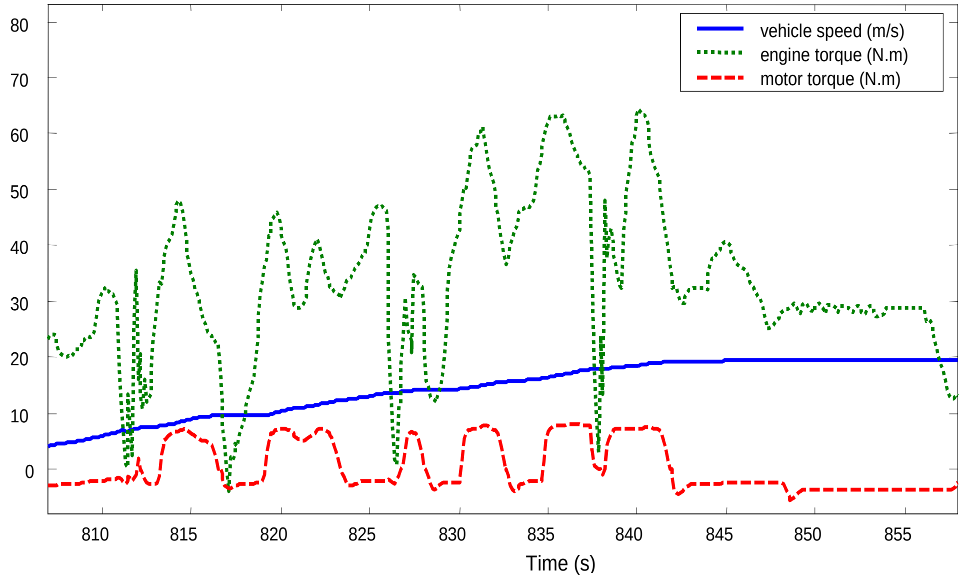
Conventional Vehicle Summary

- **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

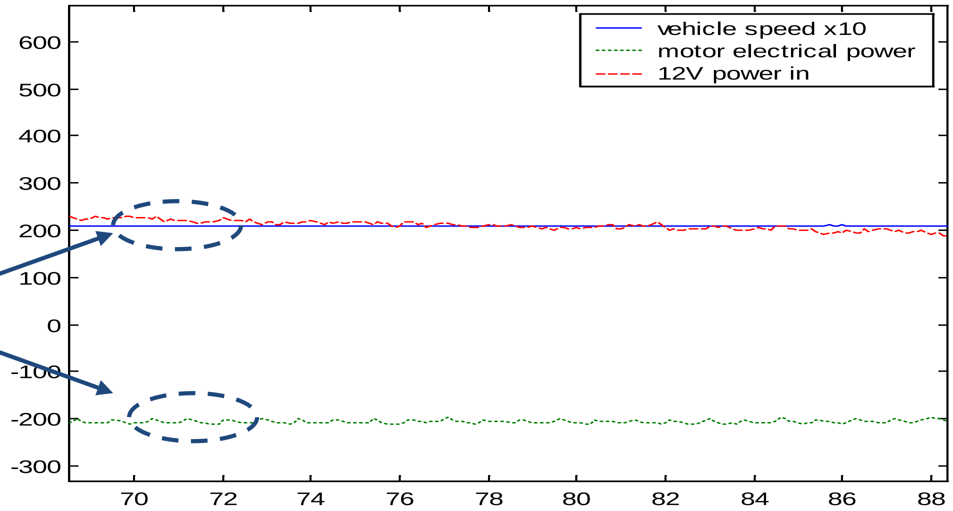
Outline

- 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

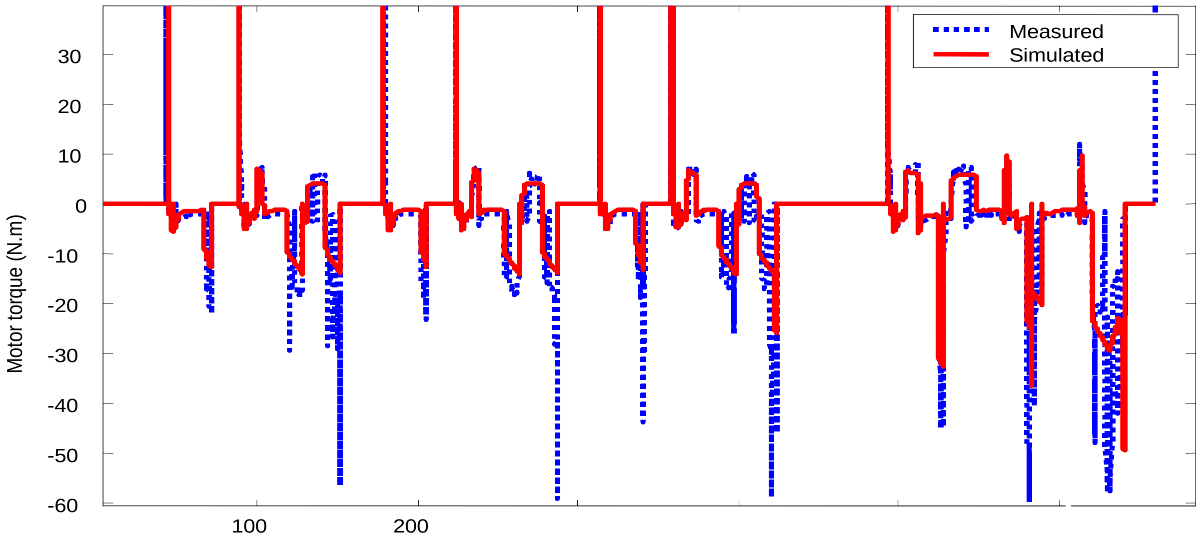
Honda Insight Validation



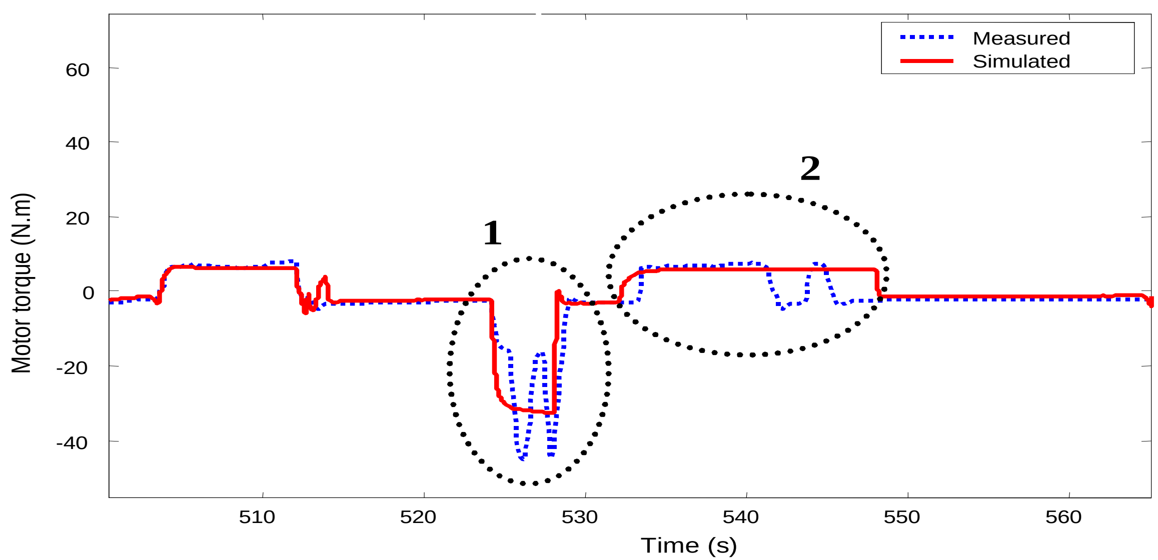
Motor used to compensate 12V load



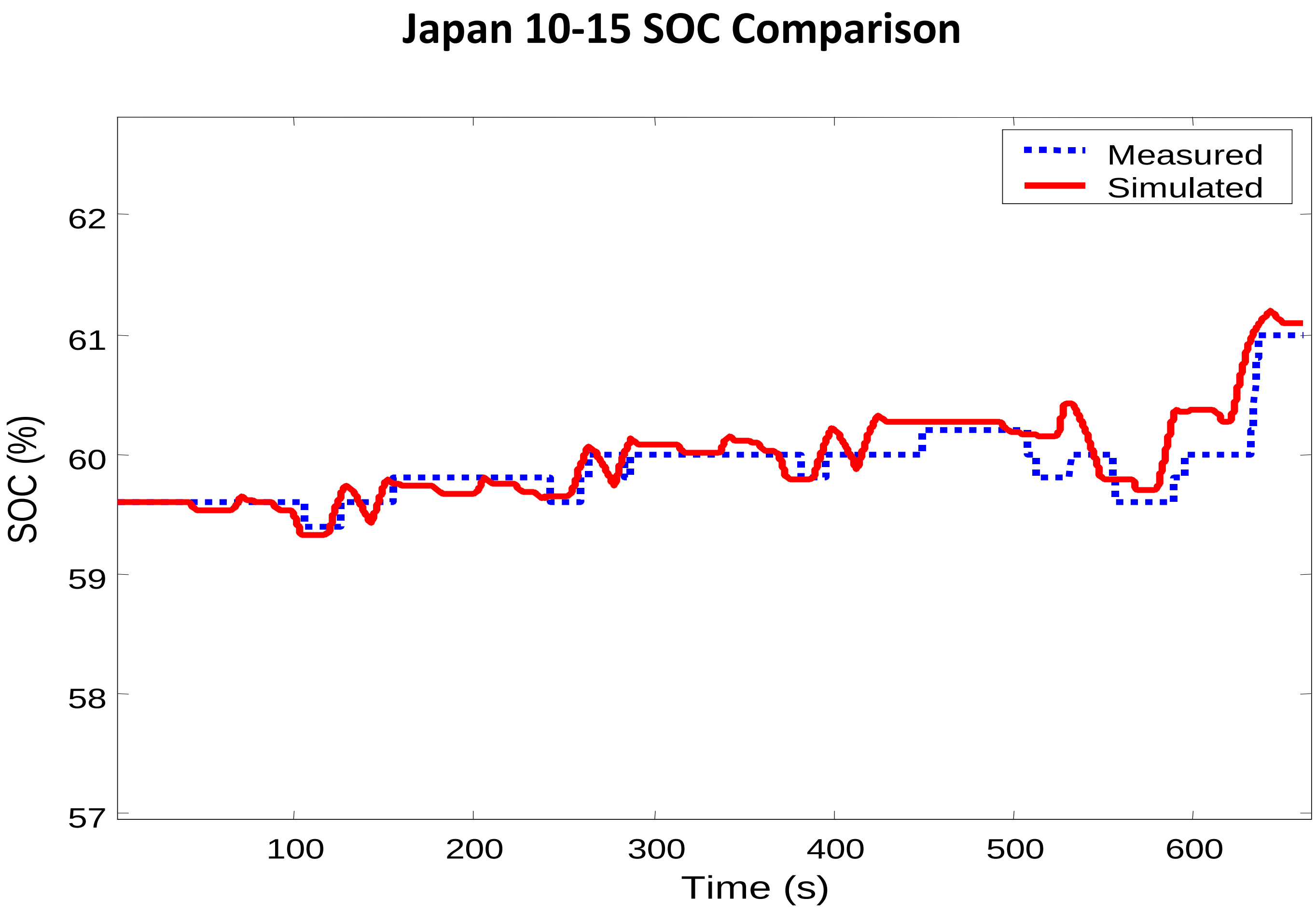
Honda Insight Validation



Japan 10-15



Honda Insight Validation



Honda Insight Validation Results

Cycle	Cons test mpg	Cons simul mpg	Diff in %	SOC init	SOCf test	SOCf simul	Diff in %
Japan 10-15	57.9	58.8	**1.5**	0.596	0.610	0.611	**0.4**
NEDC	60.6	60.2	**0.6**	0.600	0.602	0.583	**3.6**
HWFET	74.2	75.3	**1.4**	0.590	0.588	0.589	**0.2**
UDDS	58.3	57.8	**0.8**	0.728	0.706	0.720	**2.0**

Outline

- Validation Process
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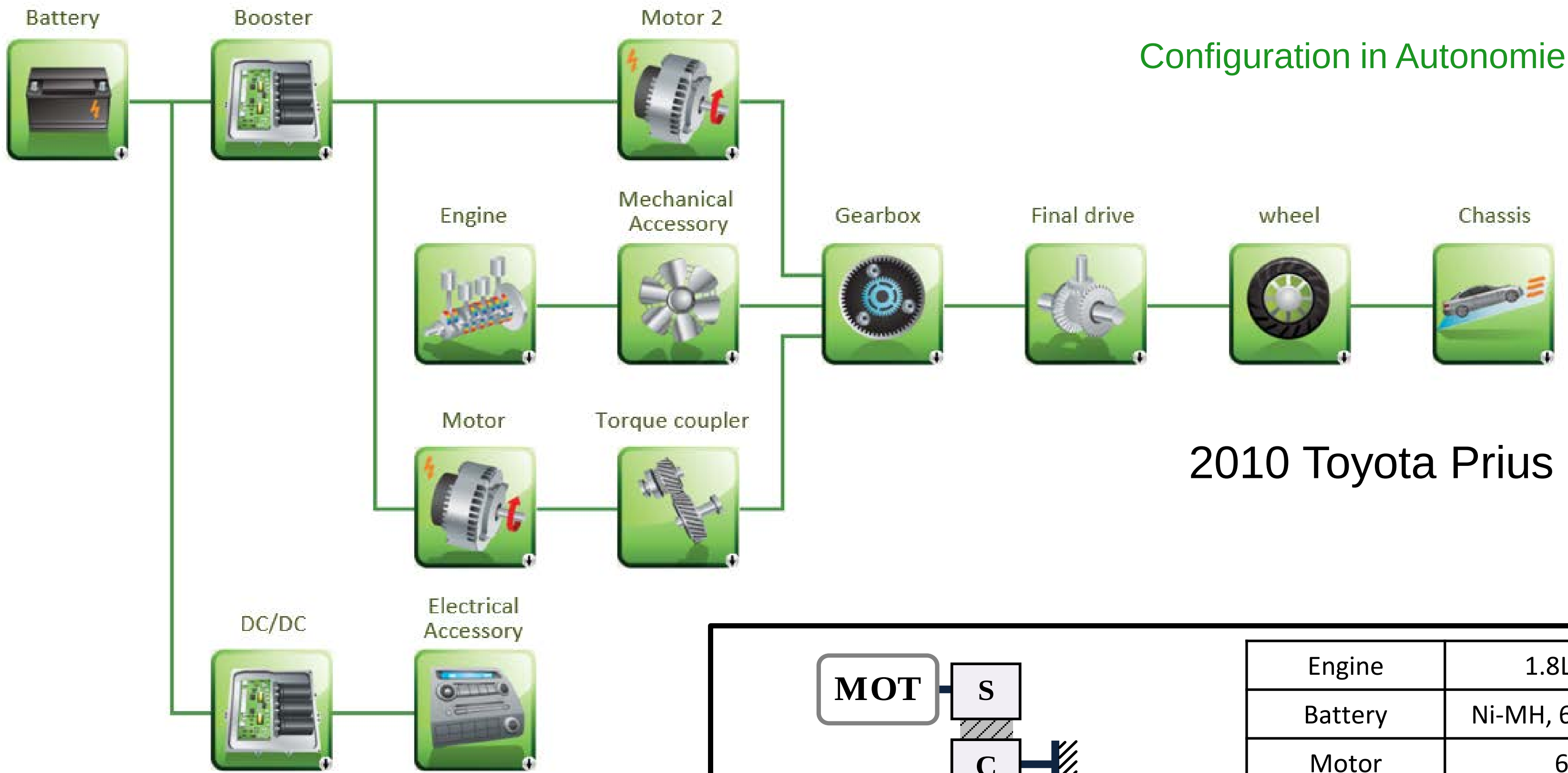
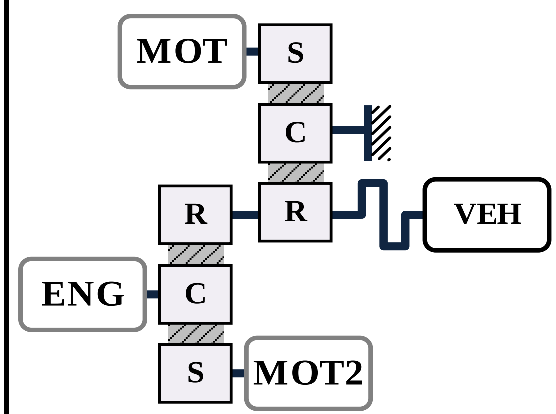
Toyota Prius 2010

2010 Toyota Prius
Vehicle Configuration



Configuration in Autonomie

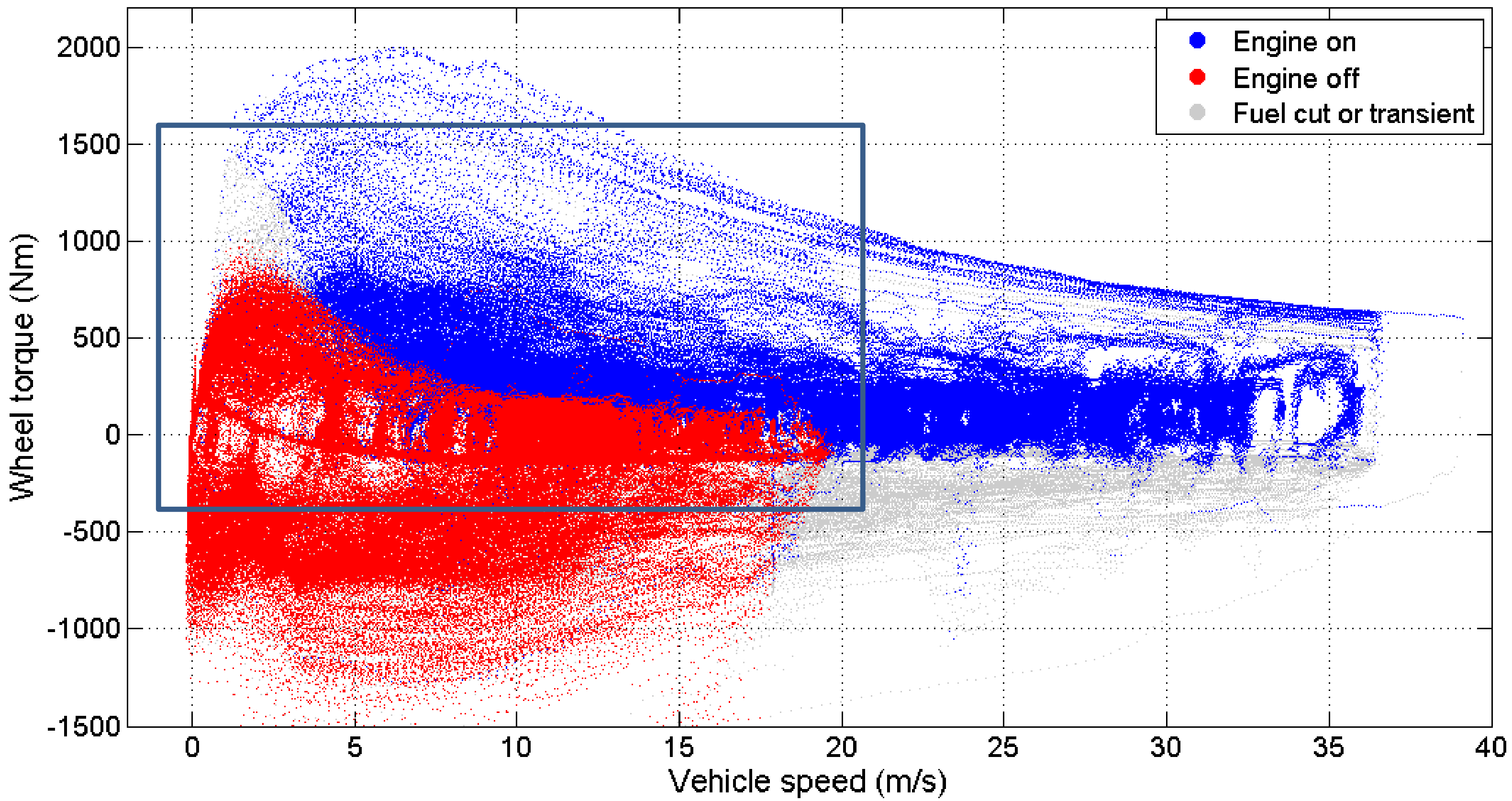
2010 Toyota Prius



Engine	1.8L, 73kW
Battery	Ni-MH, 6.5Ah, 27kW
Motor	60kW
Net power	100kW
Final drive	3.268
FE (EPA)	50 MPG (comb.), 51/48 MPG (city/hwy)
0-60mph	10.0 s

Supervisory Control Analysis
Mode Decision Control (Engine On/Off)

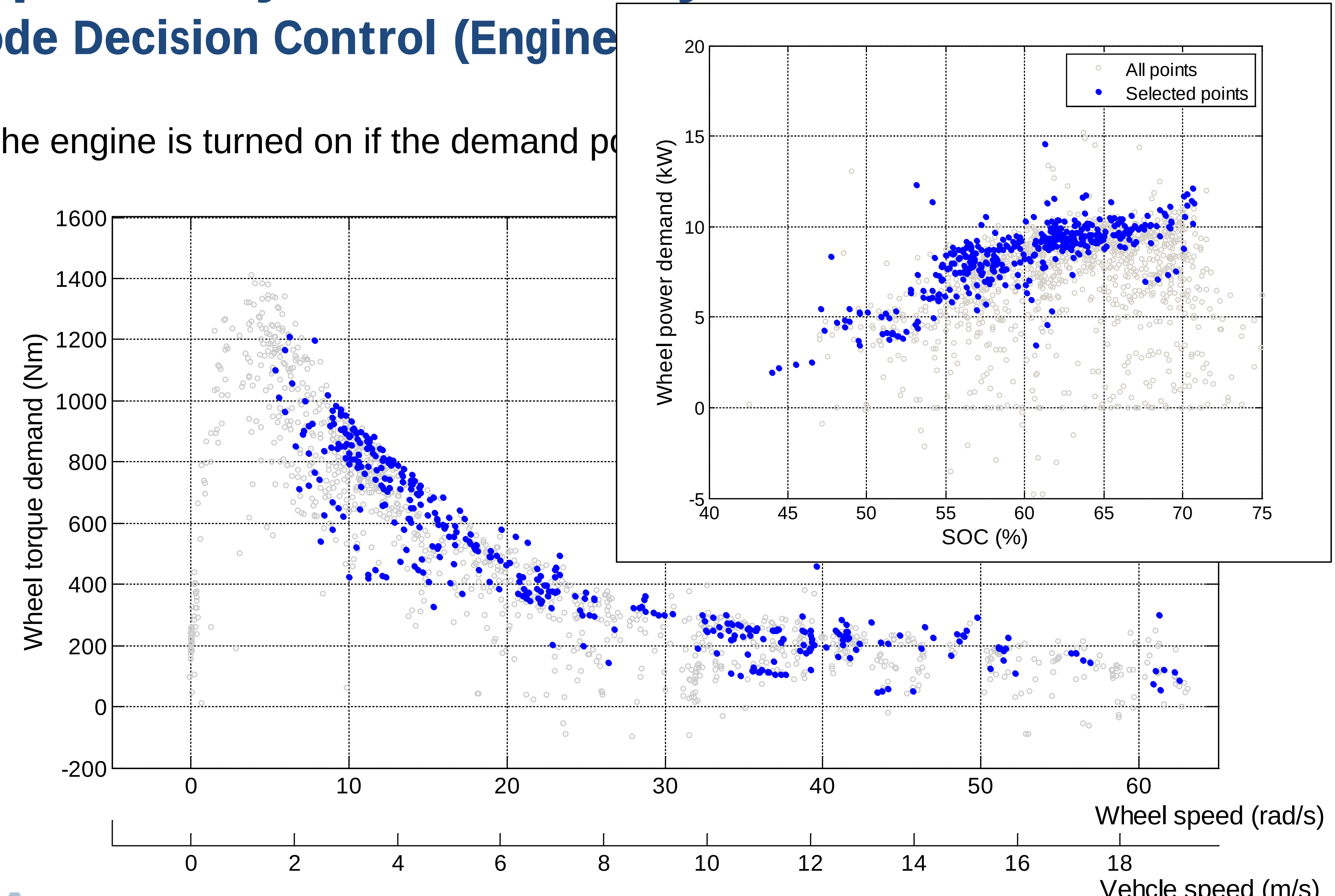
Motor usually provides the propulsion power at low power demand



Supervisory Control Analysis

Mode Decision Control (Engine

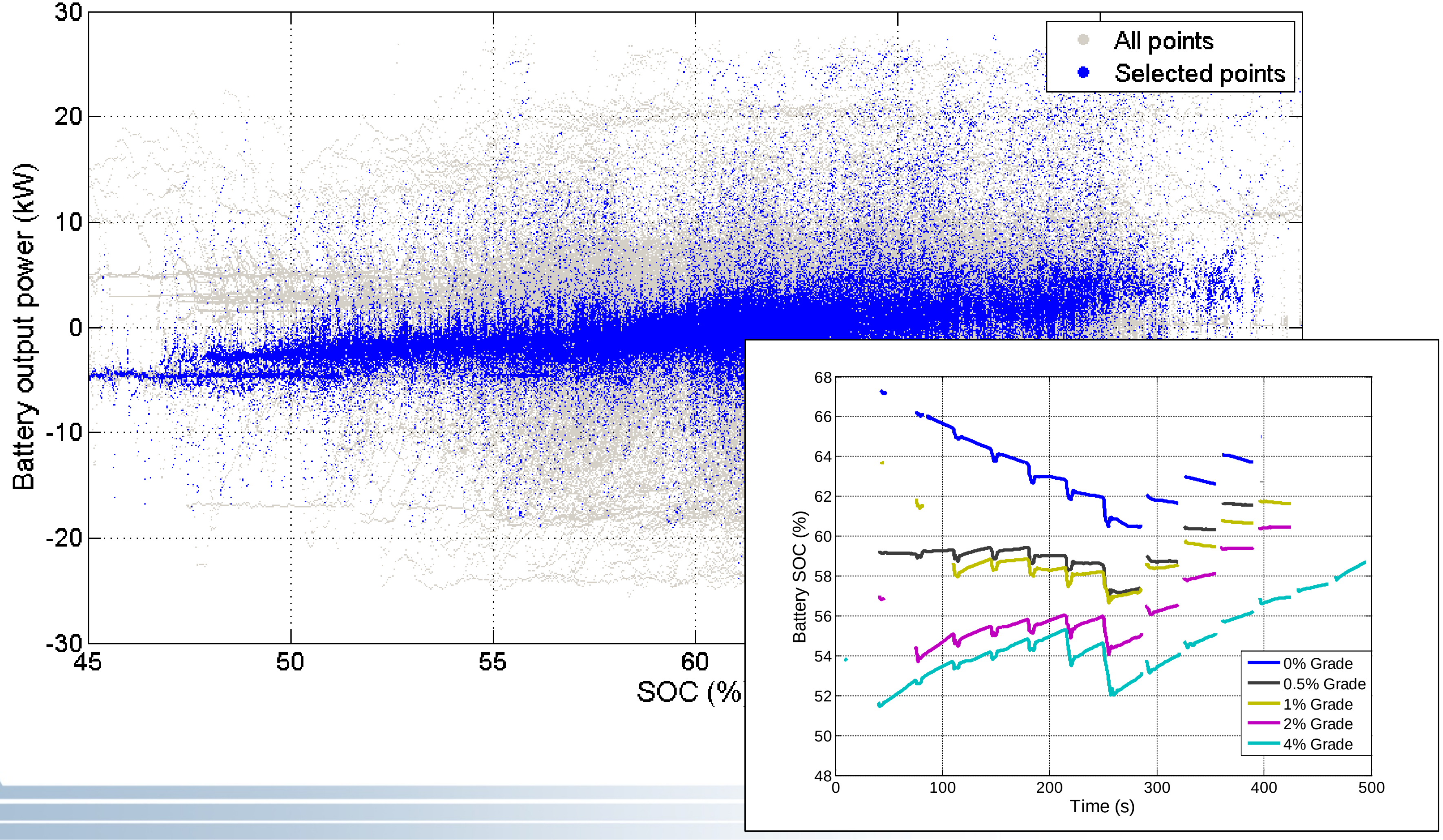
The engine is turned on if the demand p



Supervisory Control Analysis

Energy Management Strategy (SOC Balancing)

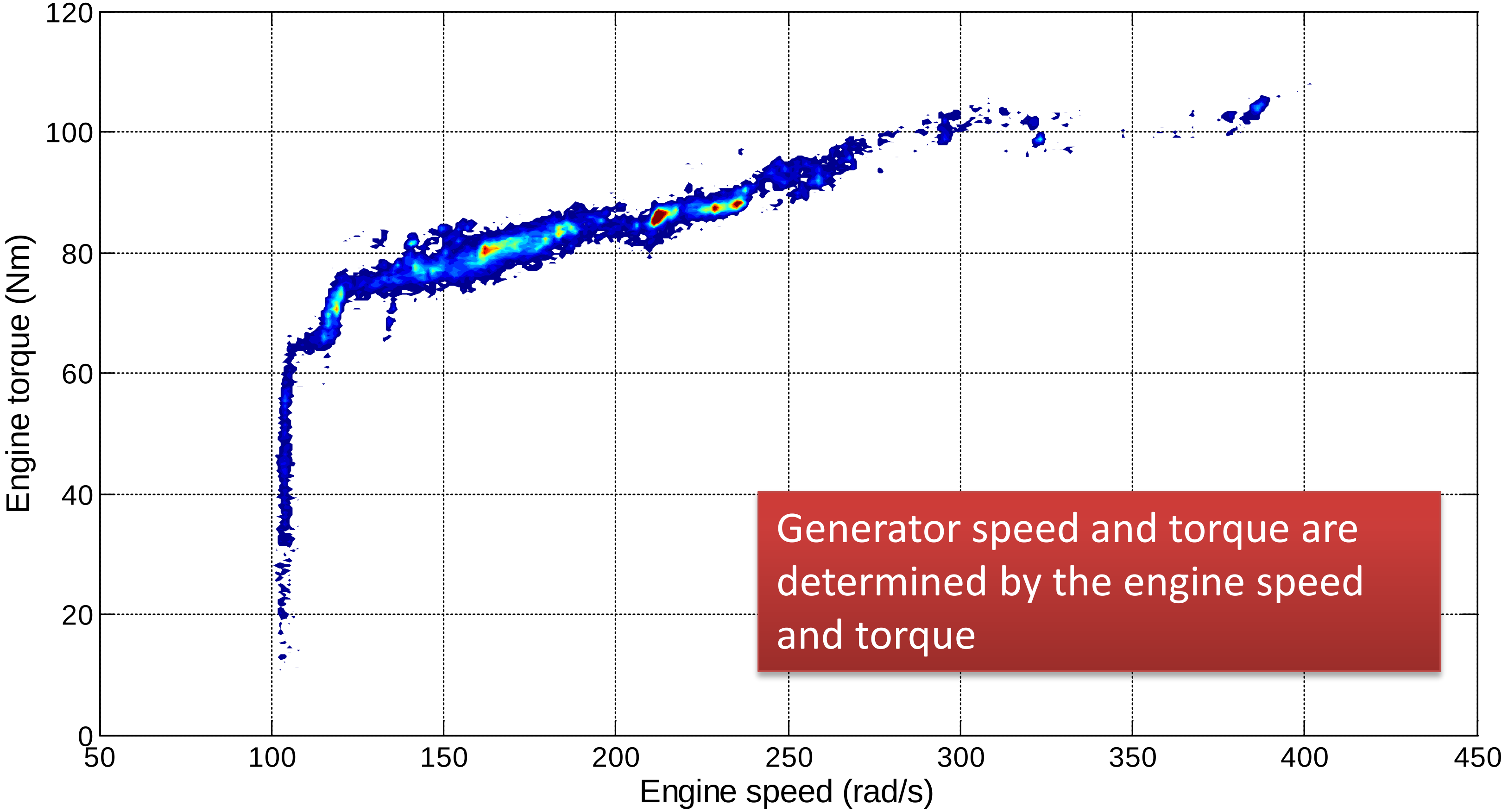
The engine is turned on if the demand power is higher than a given threshold power.



Supervisory Control Analysis

Powertrain Component Control (Engine Operating)

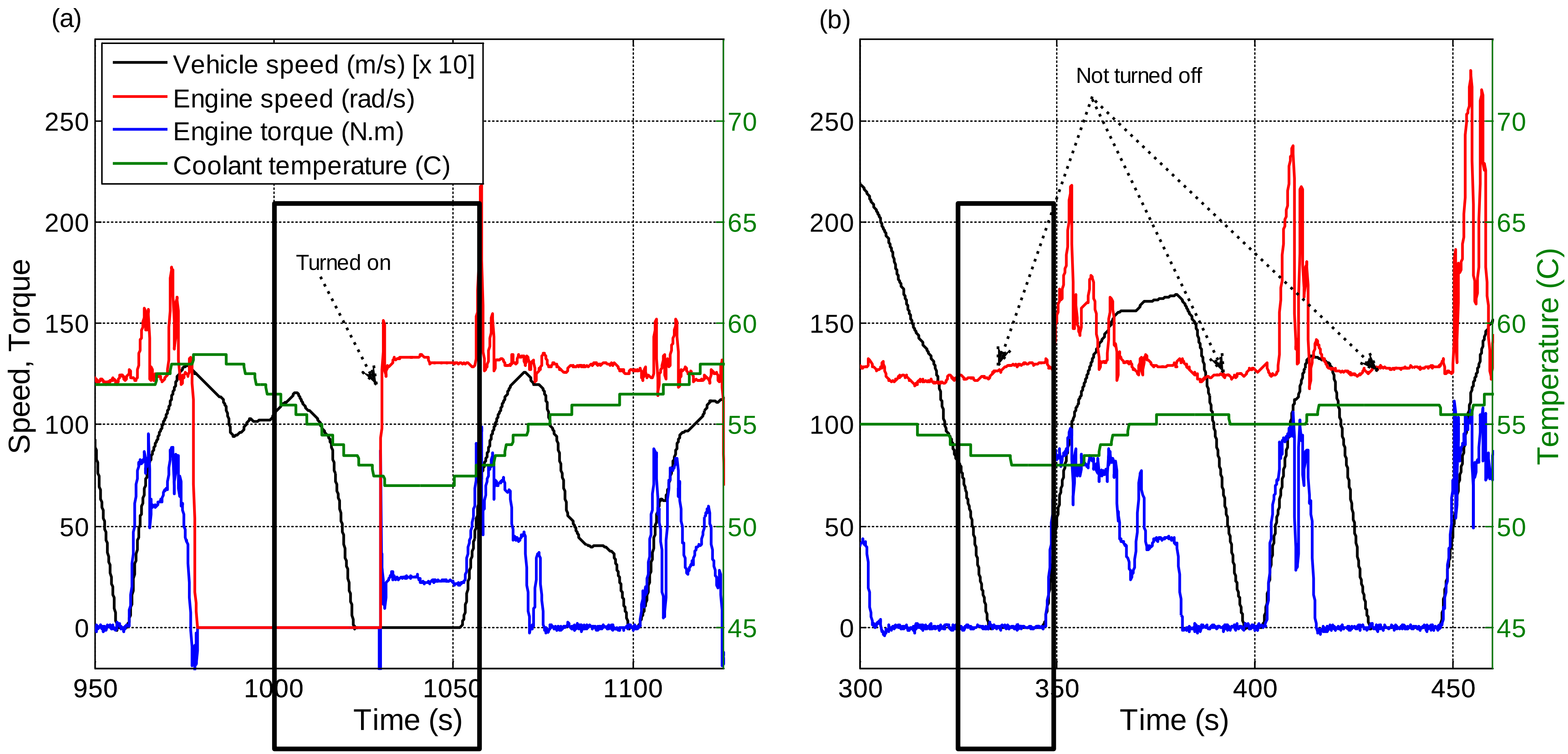
The engine torque is controlled according to the engine speed.



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.

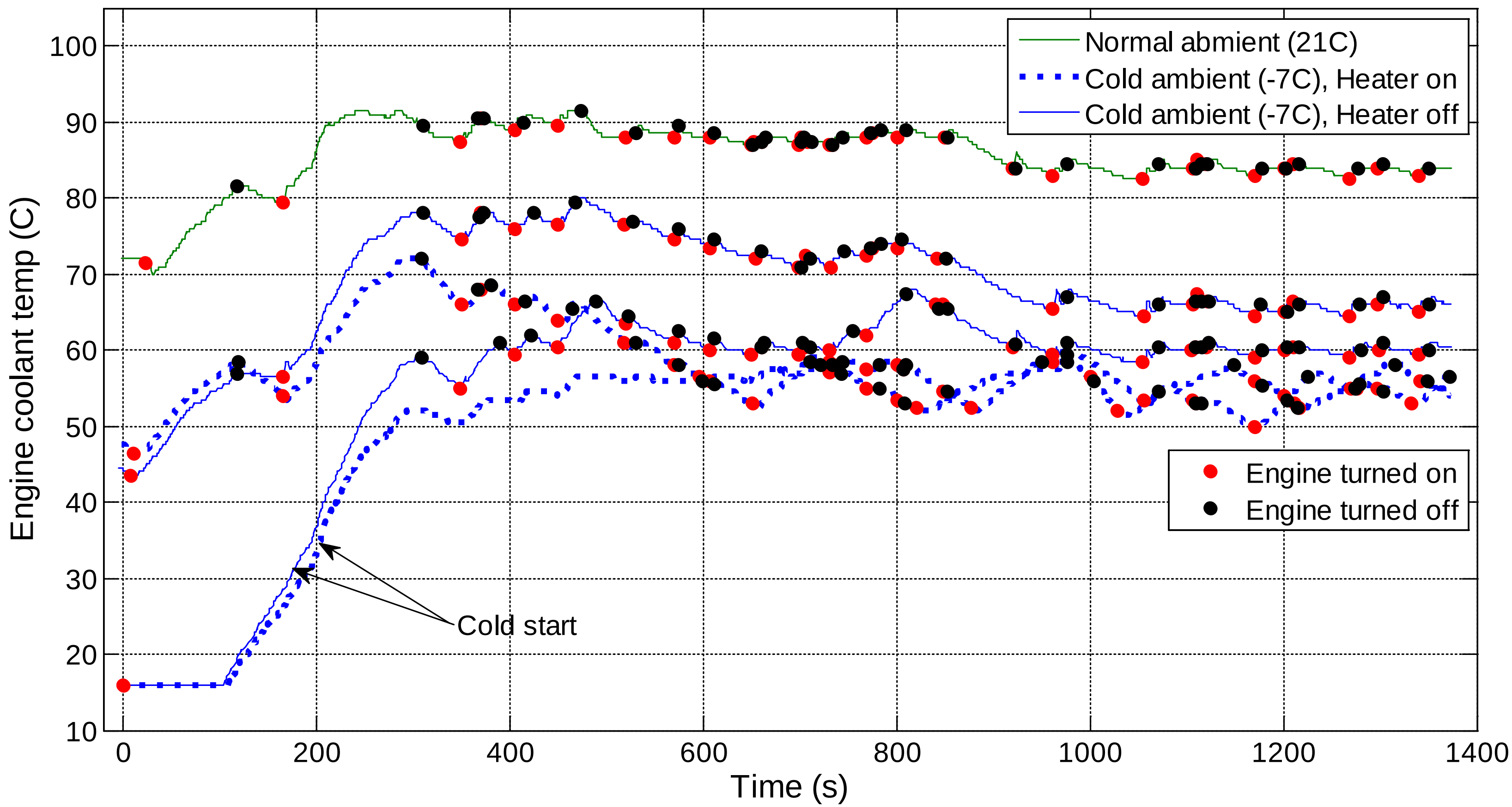


The engine is not turned off if the coolant temperature is low.

Impact of Thermal Condition on Control

Engine On/Off Is Changed By the Thermal Condition

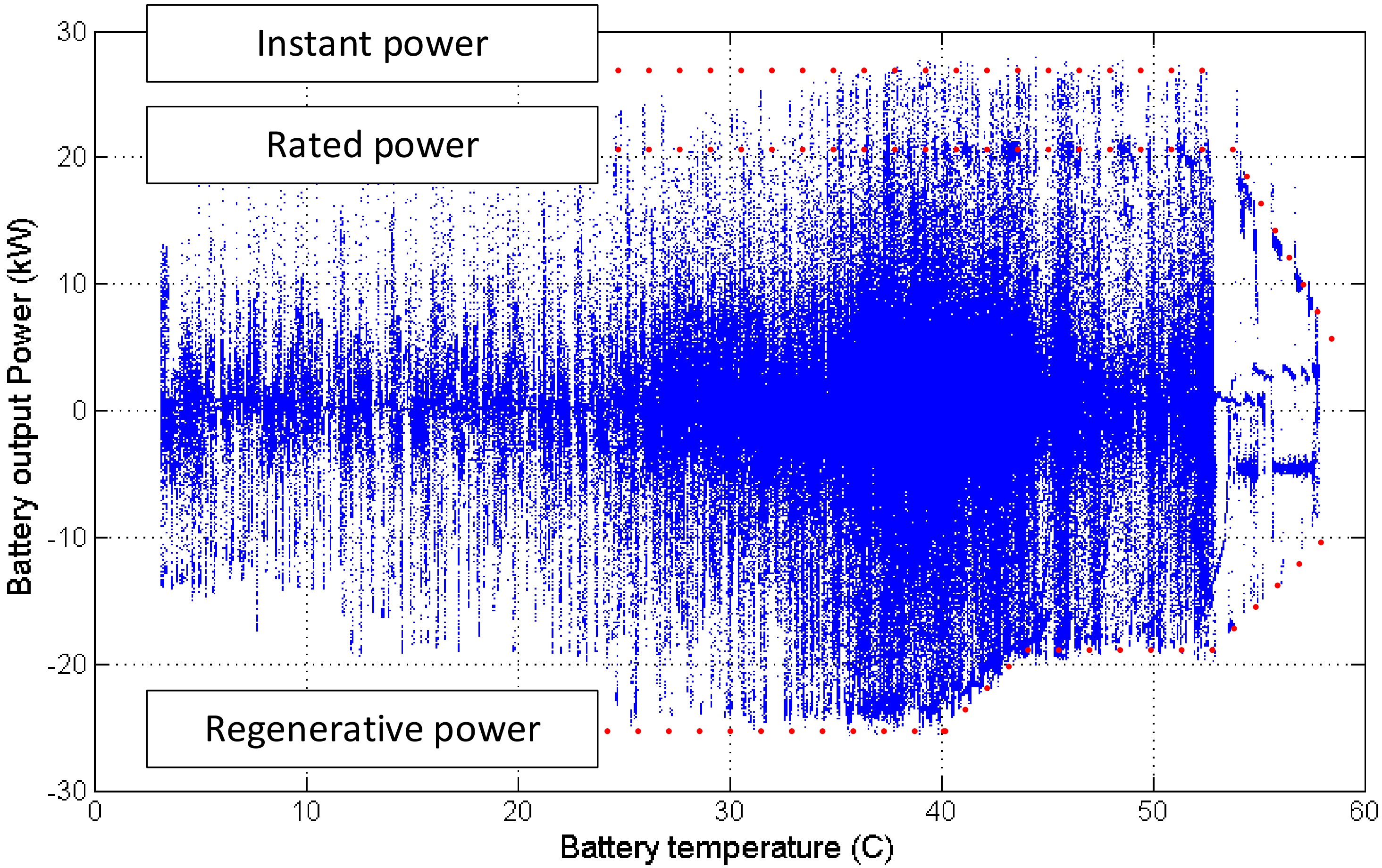
The engine coolant temperature is maintained above 53ºC.



Impact of Thermal Condition on Control

Battery Power Is Constrained by the Battery Temperature

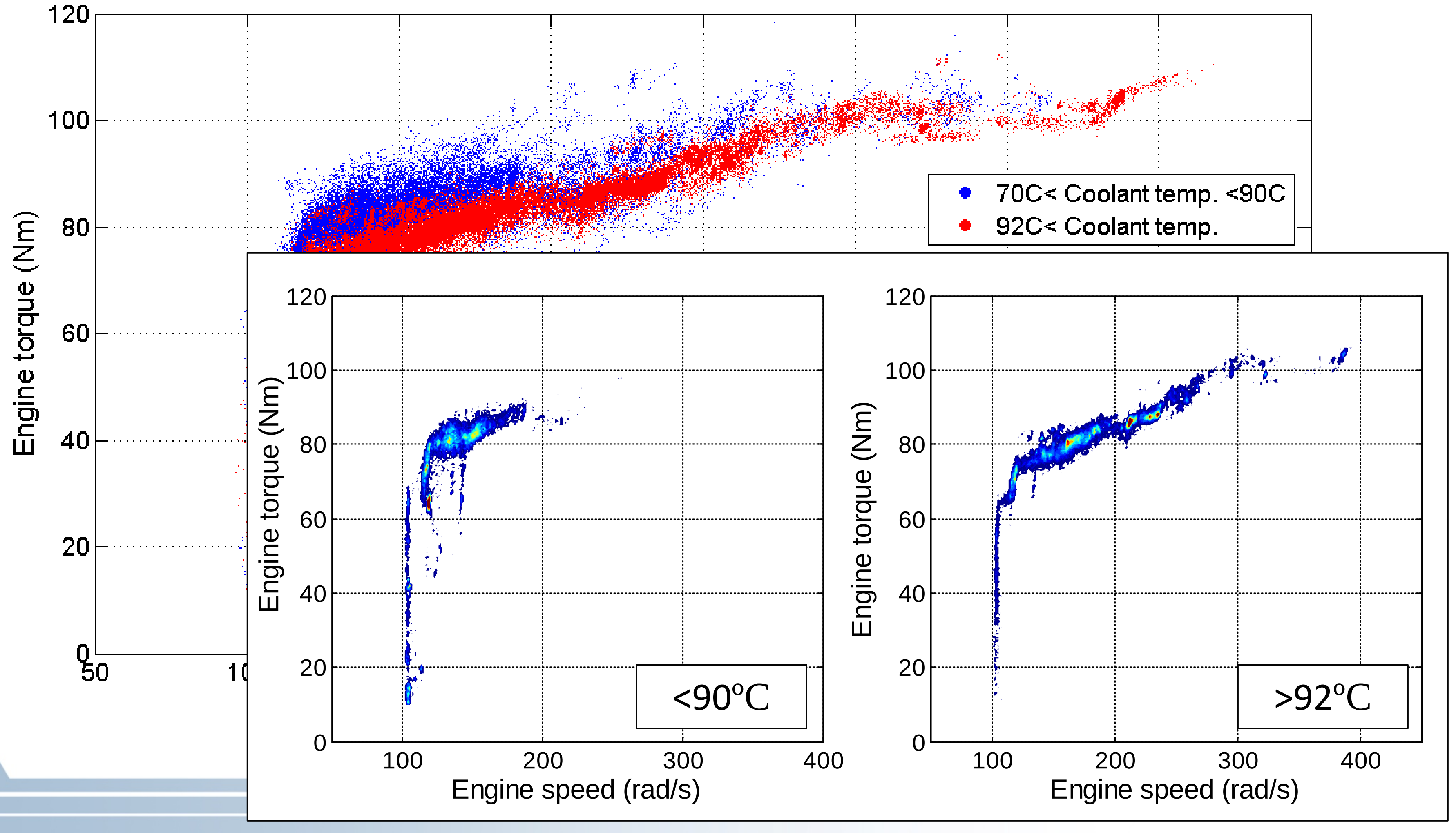
Maximum charging and discharging power are constrained by battery temperature.



Impact of Thermal Condition on Control

Engine Operating Target Changed

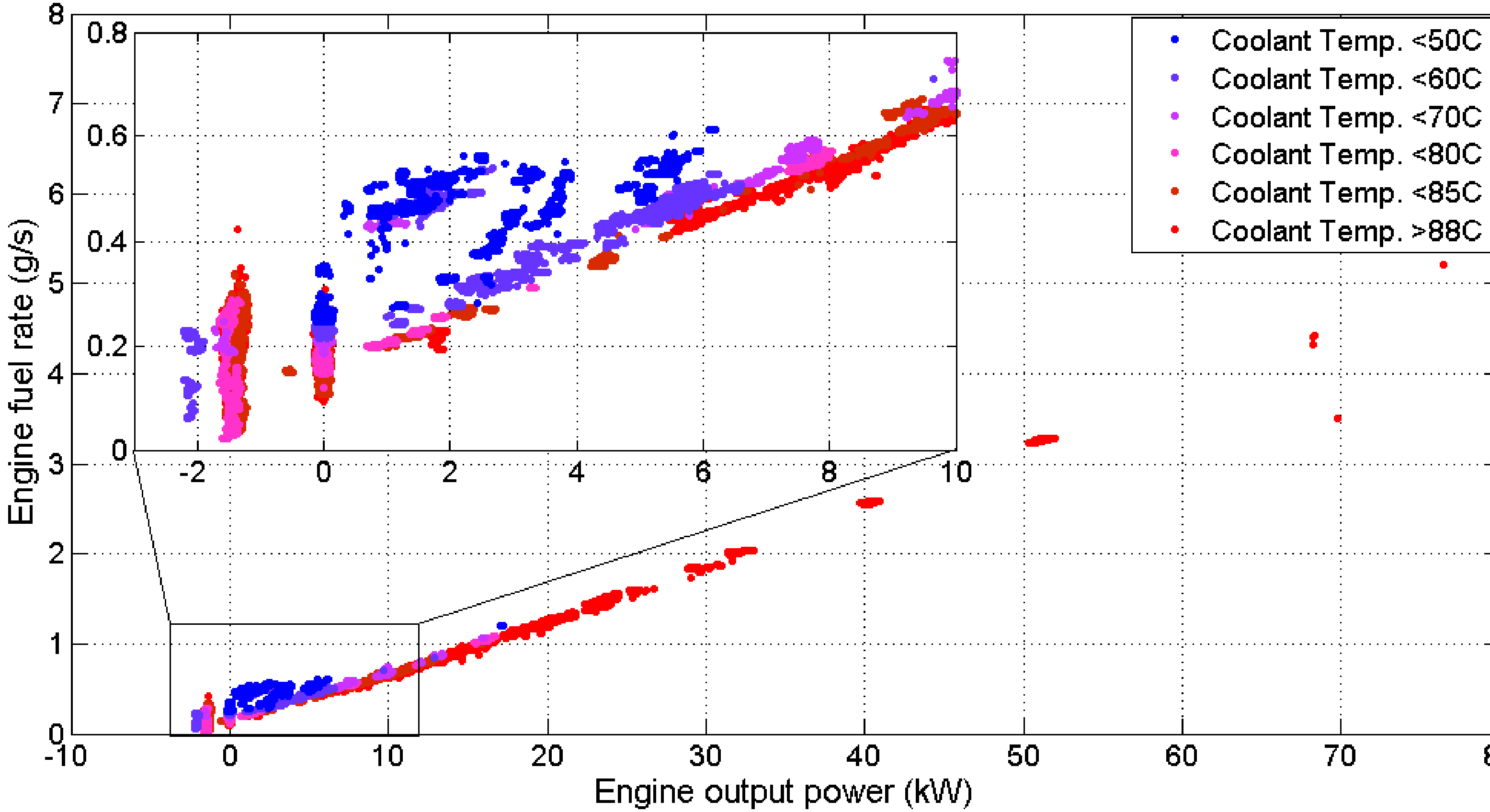
The engine tries to use higher torque if the coolant temperature is lower.



Thermal Impact on Component Performance

Engine Fuel Efficiency According to the Engine Temperature

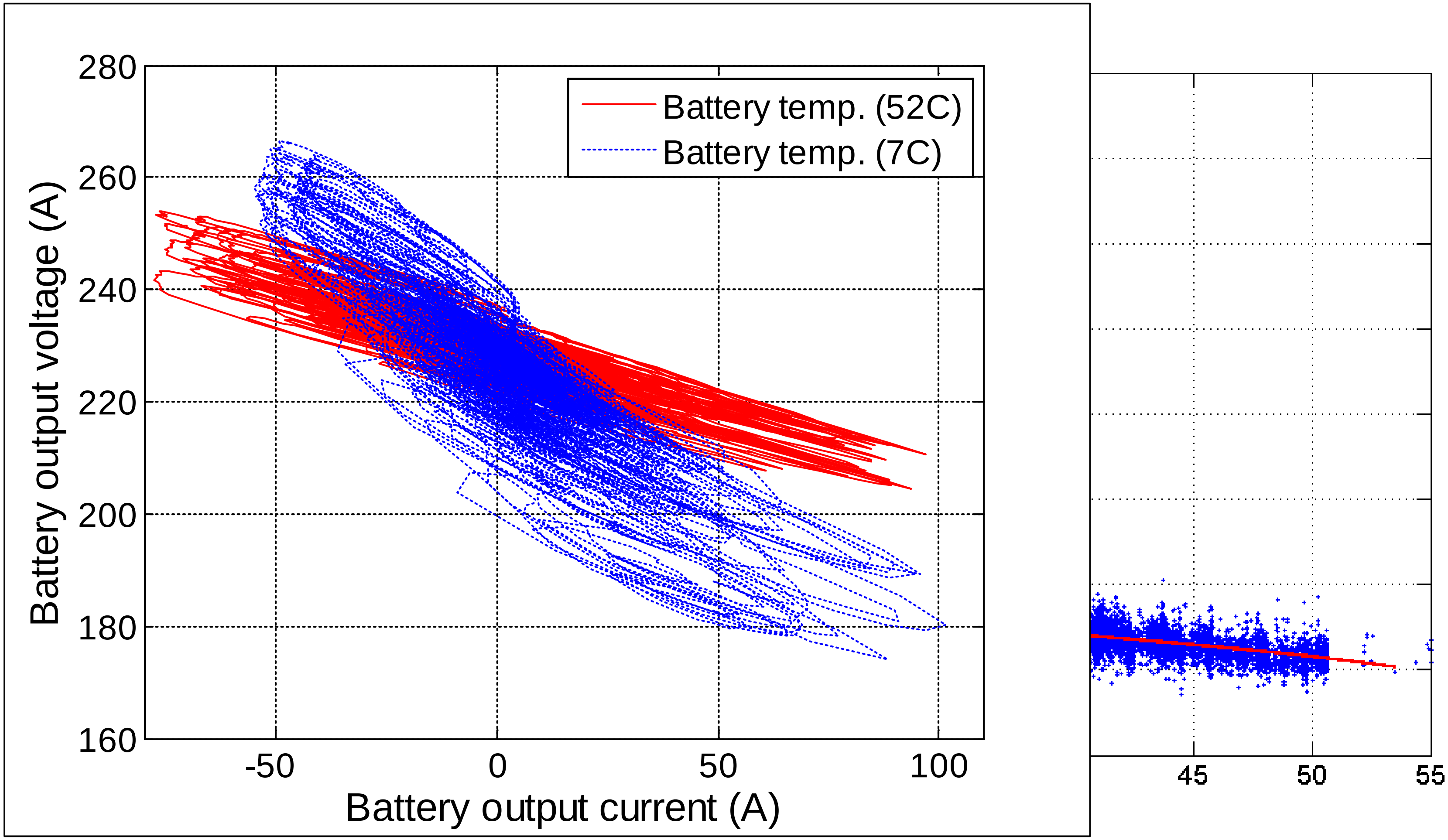
More fuel is consumed if the coolant temperature is lower.



Thermal Impact on Component Performance

Battery Efficiency According to the Battery Temperature

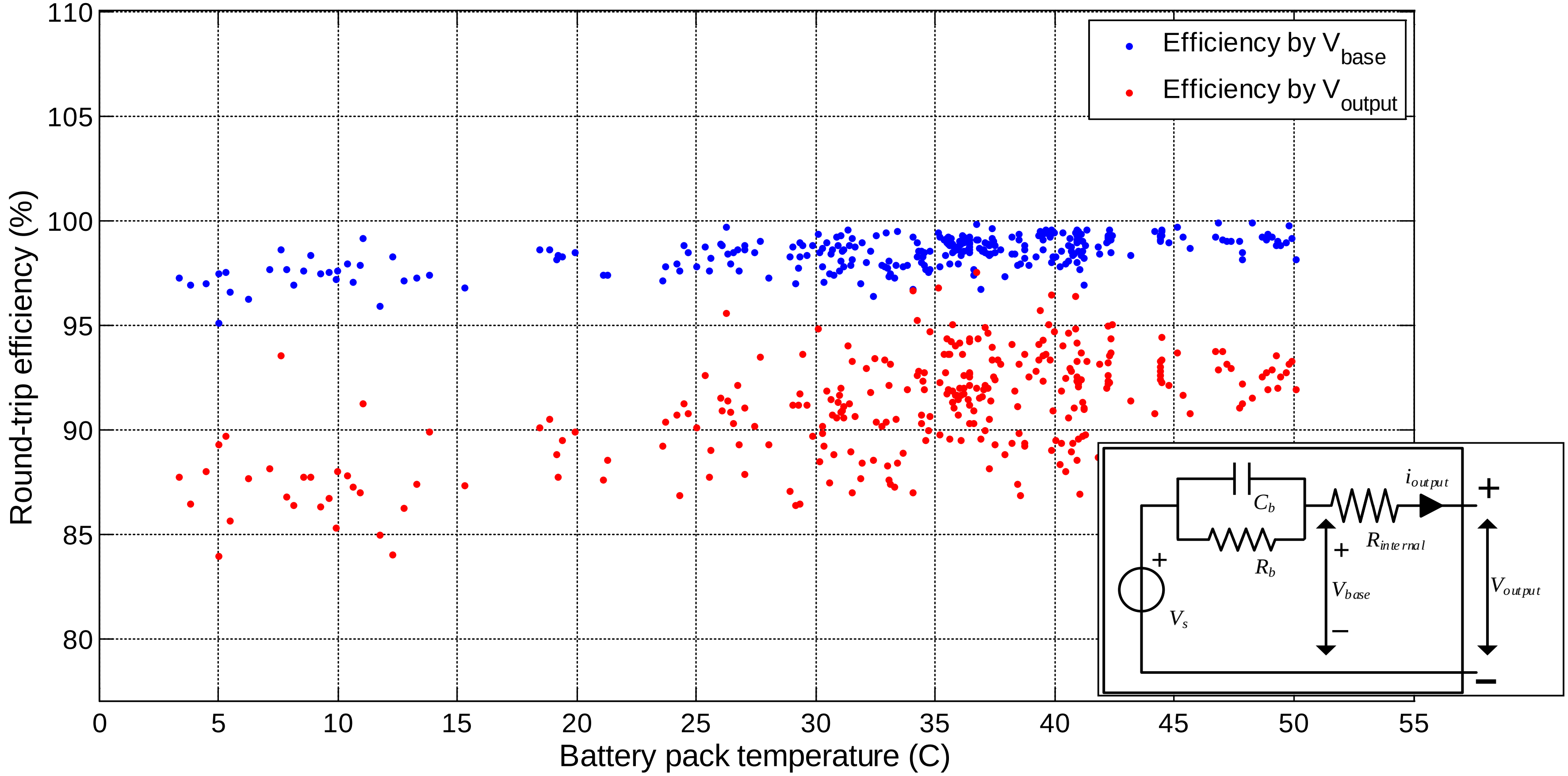
Internal resistance of the battery decreases as the temperature increases.



Thermal Impact on Component Performance

Round Trip Efficiency of the Battery

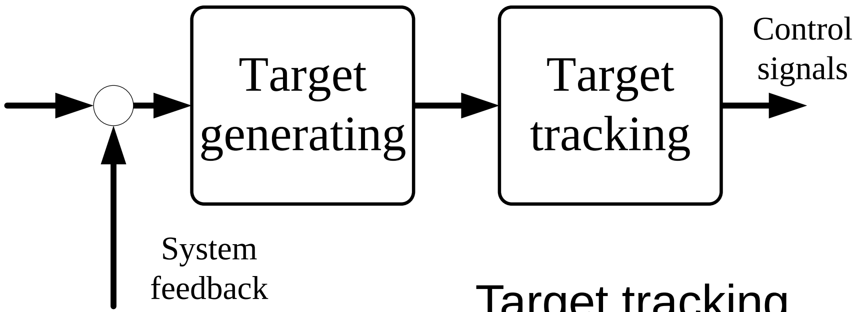
The loss is mostly caused by the Internal resistance.



Vehicle Model Development In Autonomie

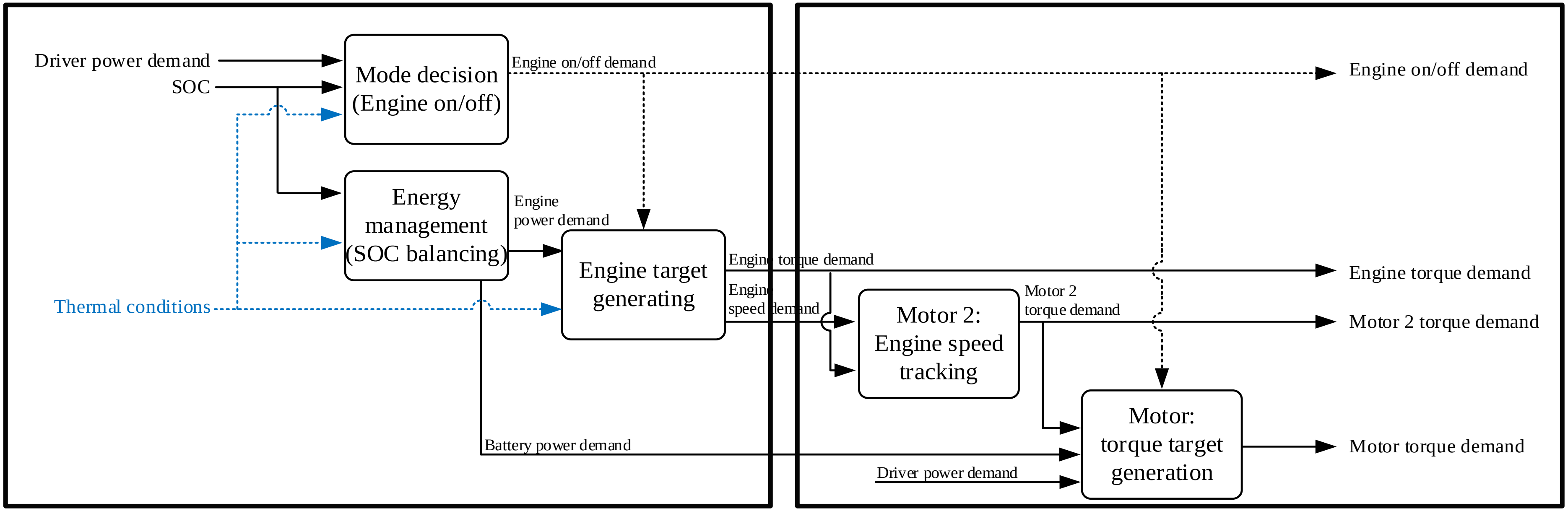
Control Development for the Thermal Model

Control concept based on the analyzed results



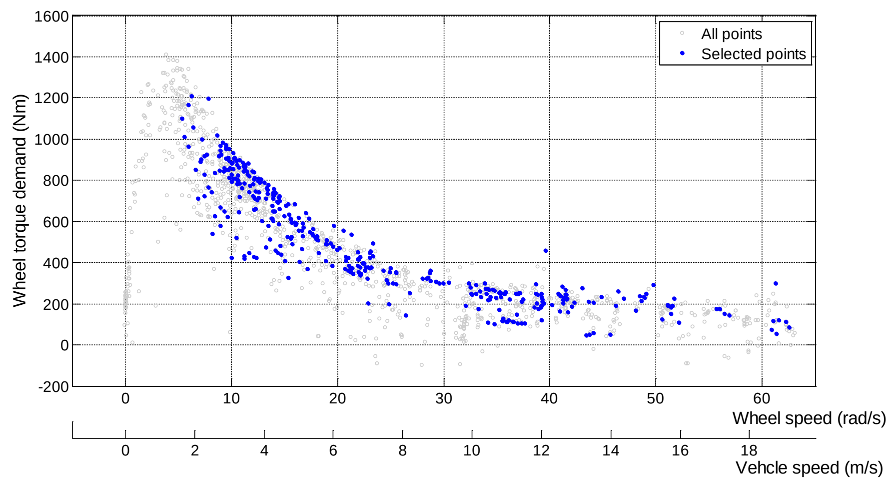
Target generating

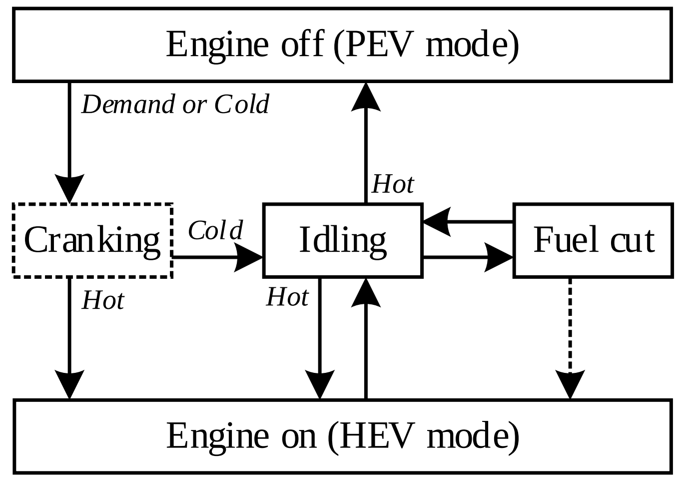
Target tracking

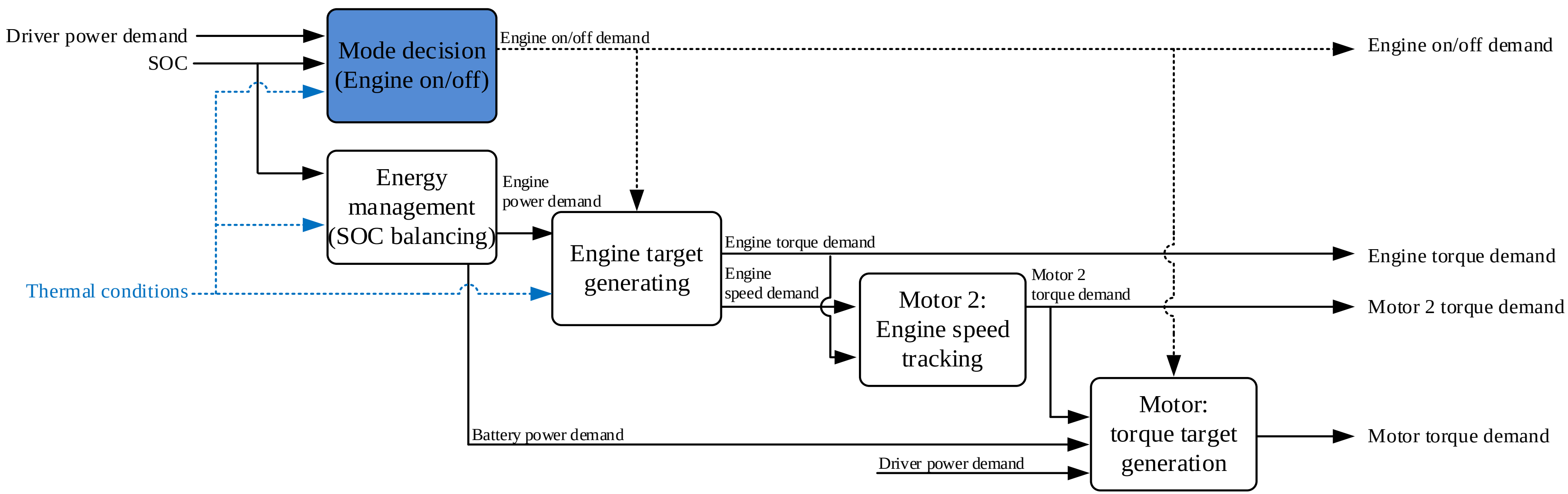


Vehicle Model Development In Autonomie

Control Development for the Thermal Model

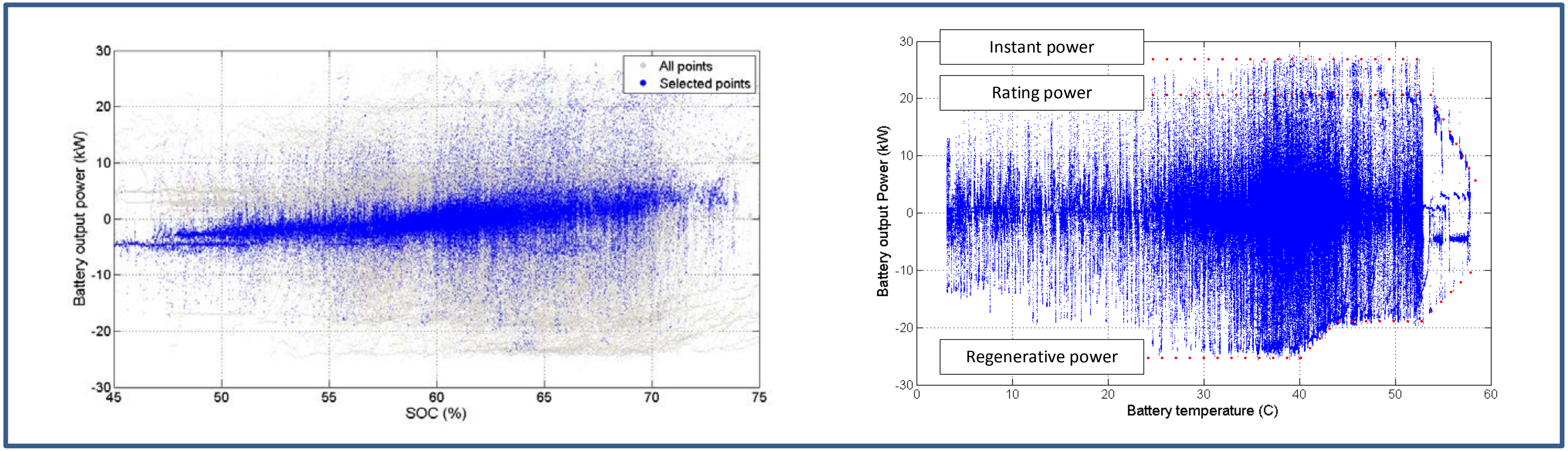


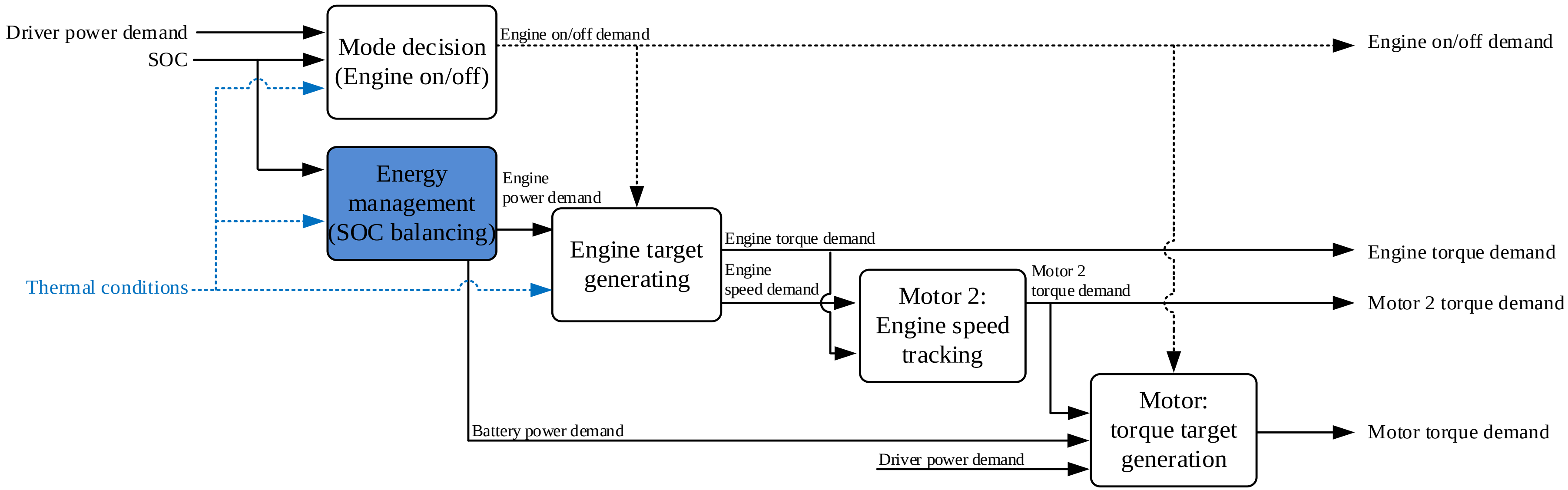




Vehicle Model Development In Autonomie

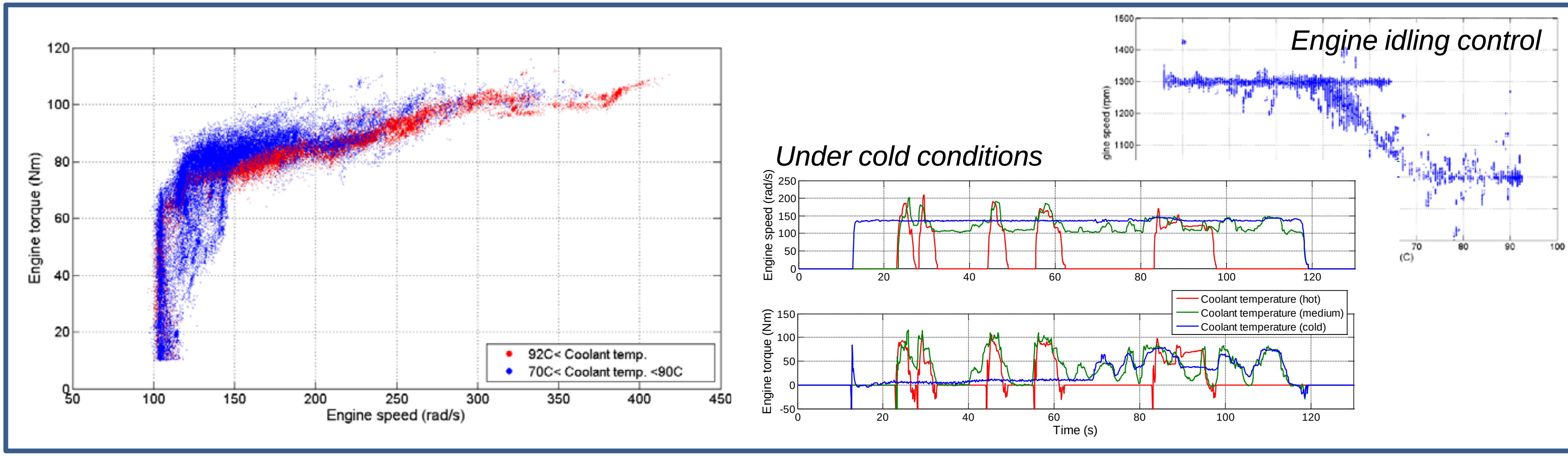
Control Development for the Thermal Model

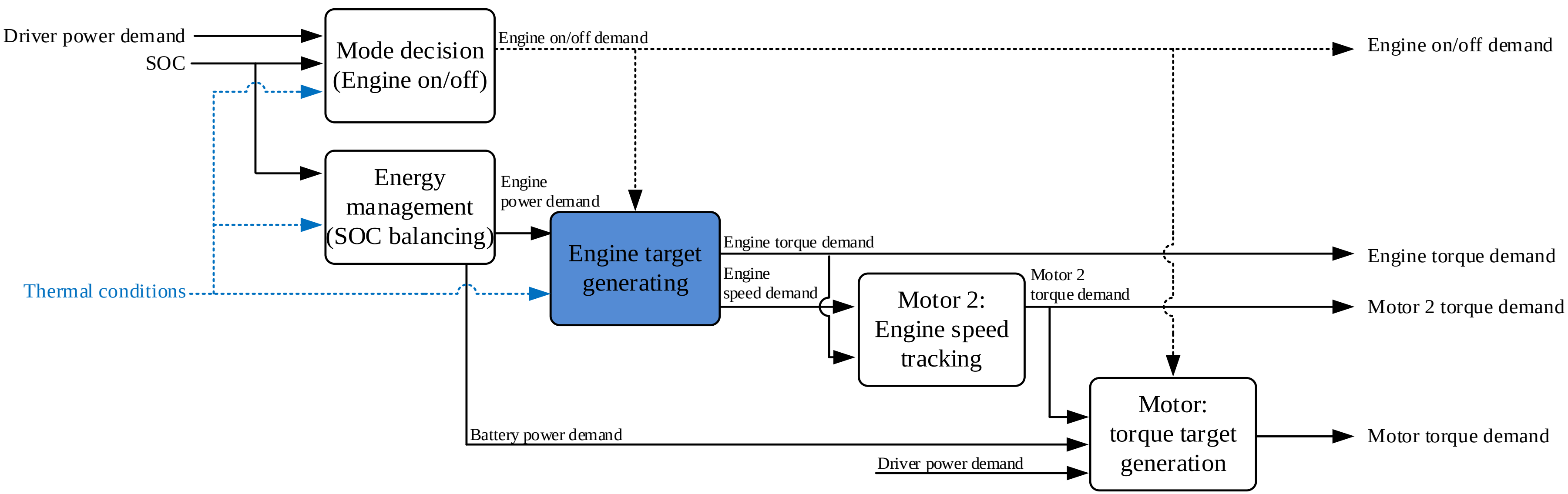




Vehicle Model Development In Autonomie

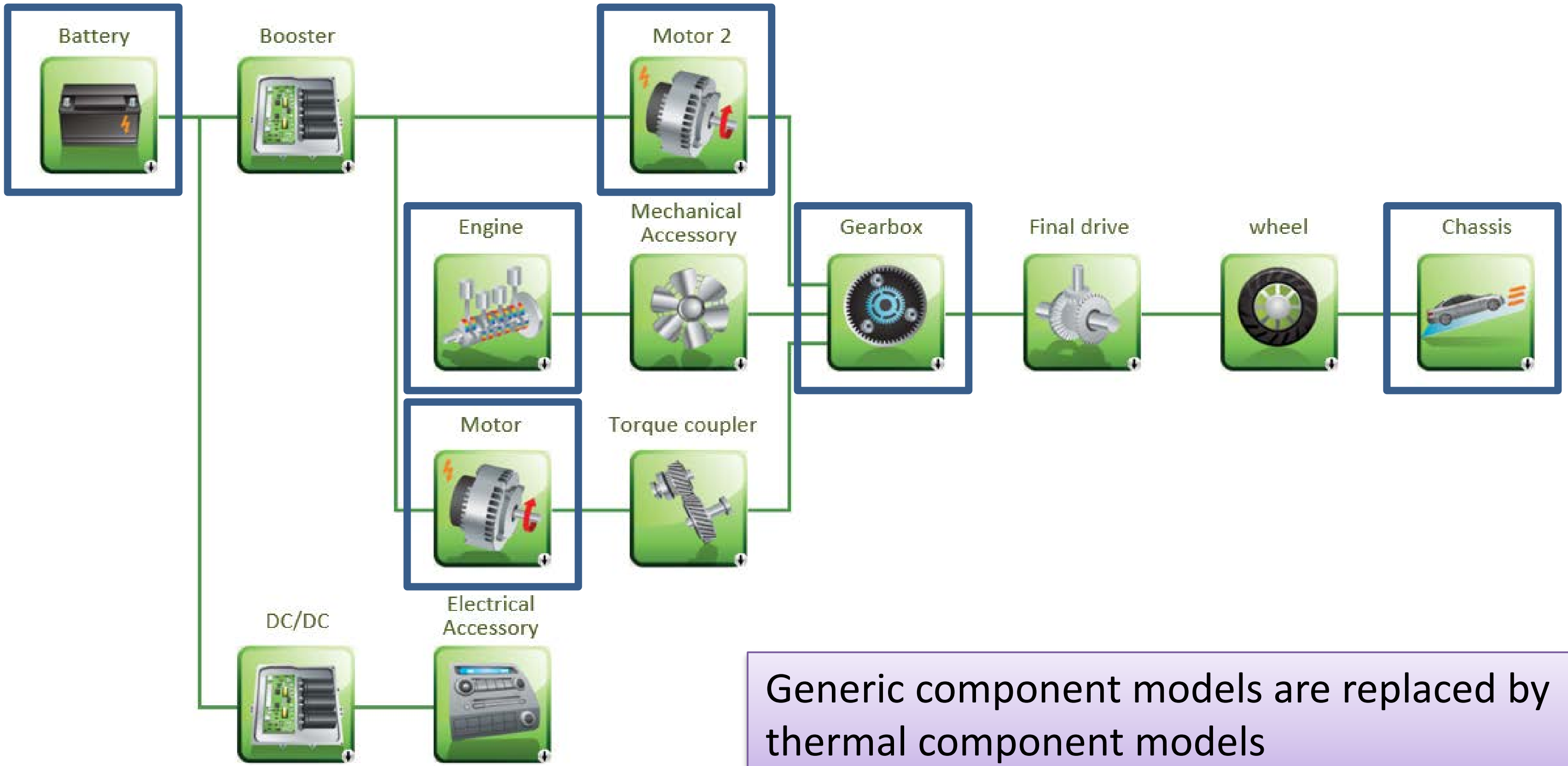
Control Development for the Thermal Model





Vehicle Model Development In Autonomie

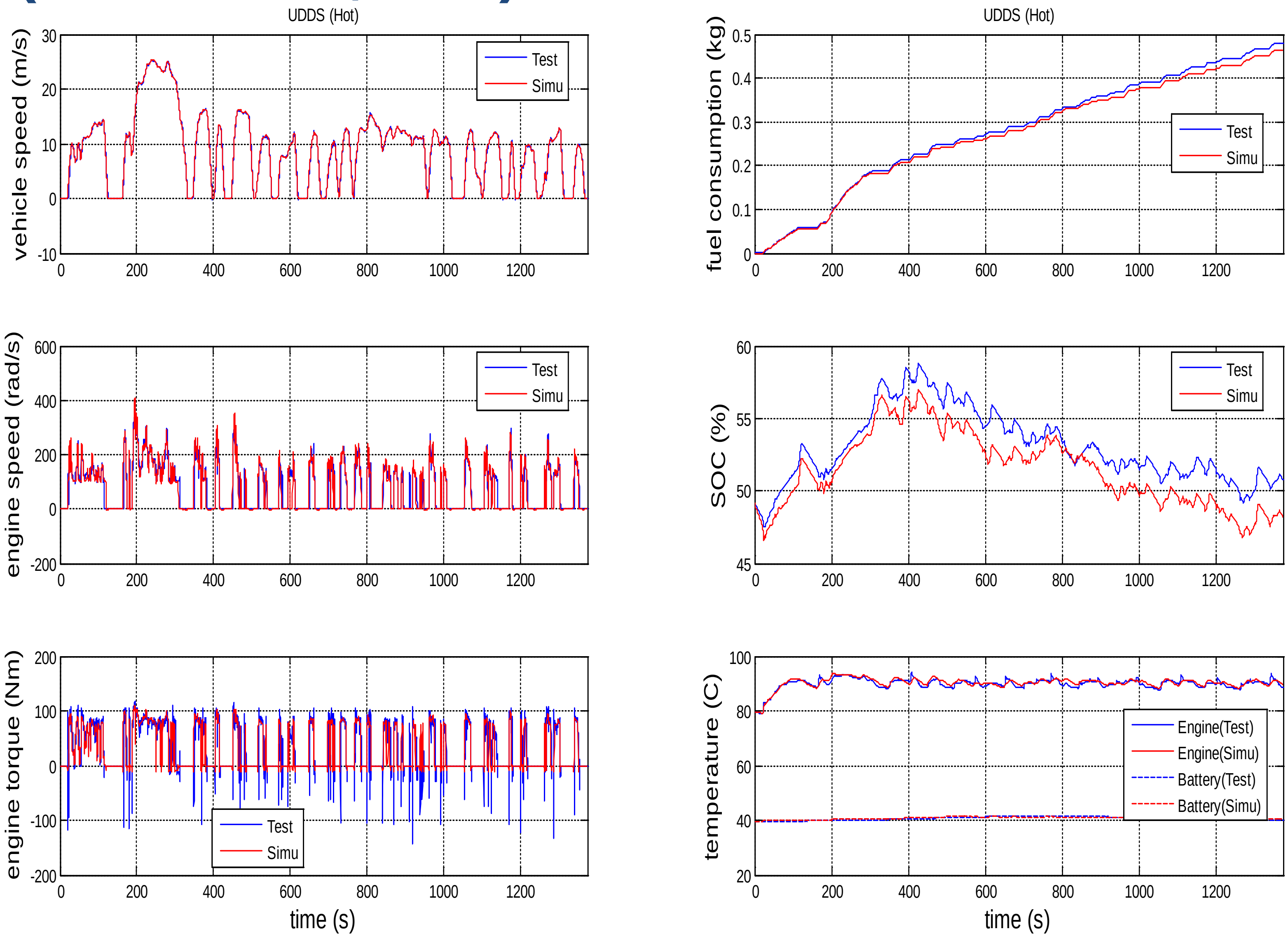
Integration of Thermal Models



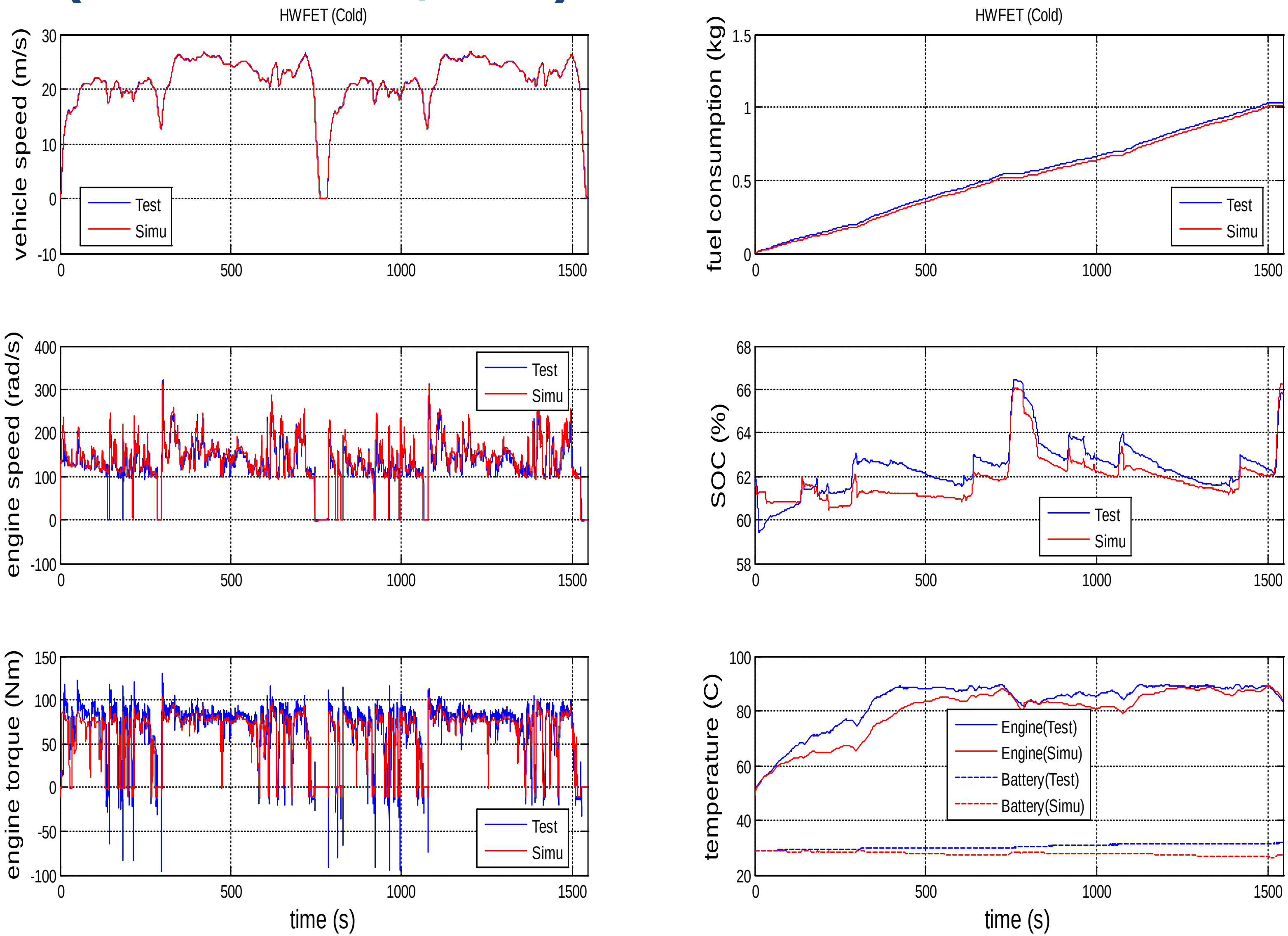
Generic component models are replaced by thermal component models

Simulation Results

UDDS (Hot Ambient, 35ºC)



Simulation Results
HWFET (Cold Ambient, -7ºC)

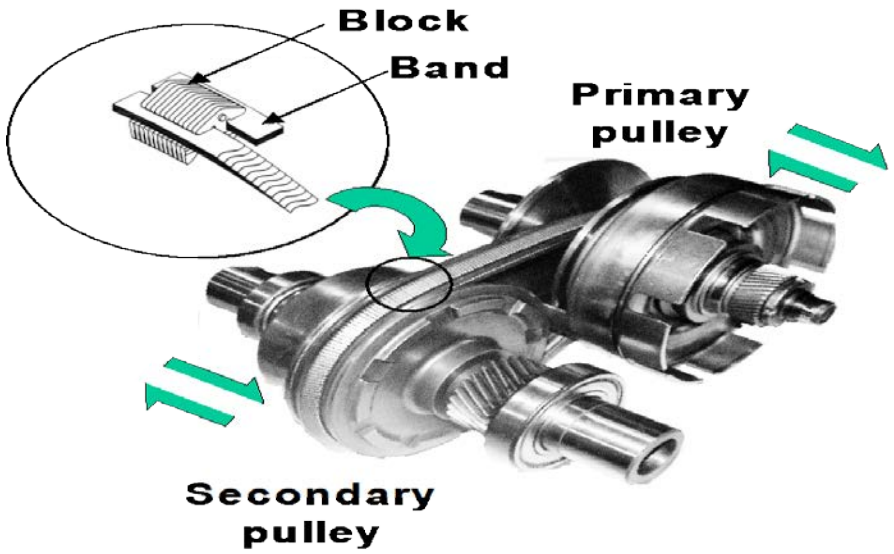


Prius HEV Thermal Model Validation under Different Ambient Temperature

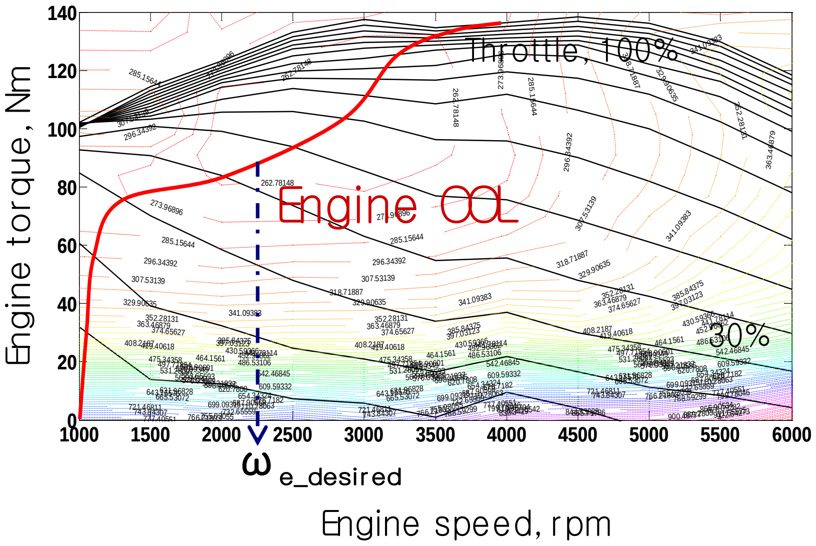
	Fuel Mass Consumed (kg)			Final SOC		
	test	simu	Difference(%)	test	Simu	ΔSOC
UDDS(Normal)	0.300	0.303	1.2	56.9	55.8	-1.1
UDDS(Cold)	0.523	0.543	3.8	65.7	68.4	2.7
UDDS(Hot)	0.478	0.462	-3.3	50.8	48.2	-2.6
HWFET(Normal)	0.914	0.915	0.1	65.8	66.6	0.8
HWFET(Cold)	1.035	1.012	-2.2	65.8	66.2	0.4
HWFET(Hot)	1.089	1.104	1.4	64.6	64.3	-0.3

Nissan HEV CVT

Metal V belt CVT



<Structure of Metal V belt CVT >

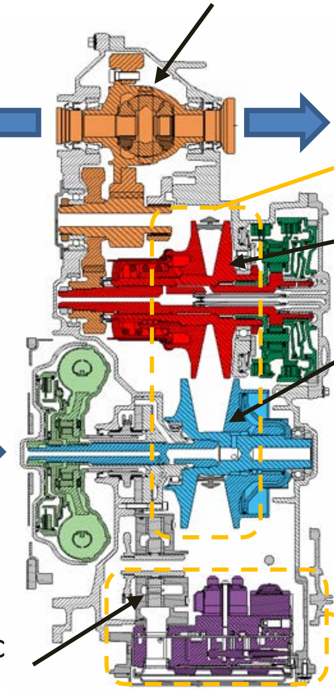


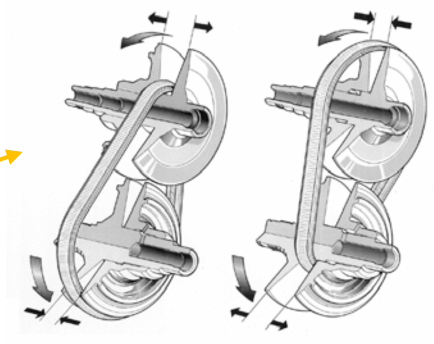
<Engine OOL>

- 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

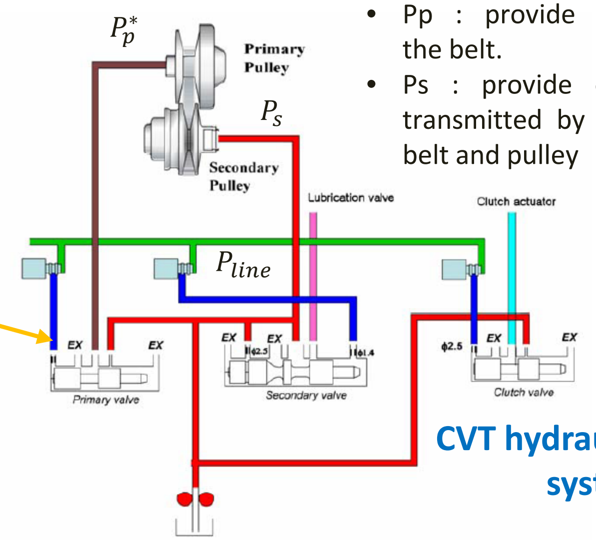
Variator working principles and lay-out





High ratio **Low ratio (OD)**

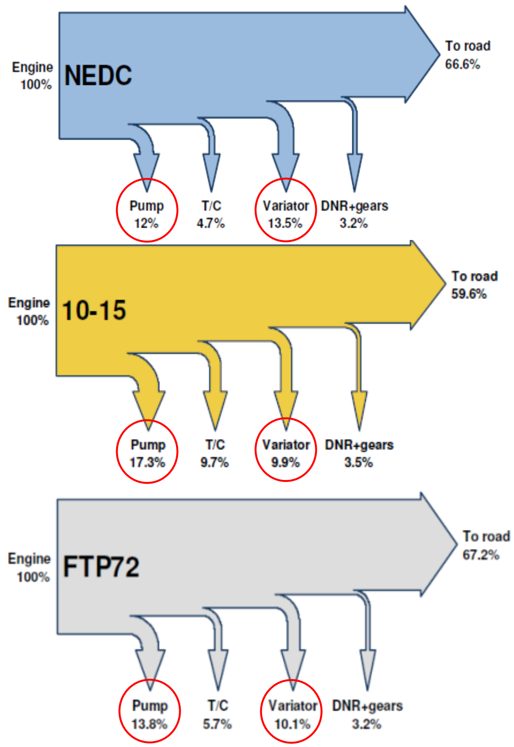
- Pp : provide ratio adjustment of the belt.
- Ps : provide clamping. Torque is transmitted by the friction between belt and pulley



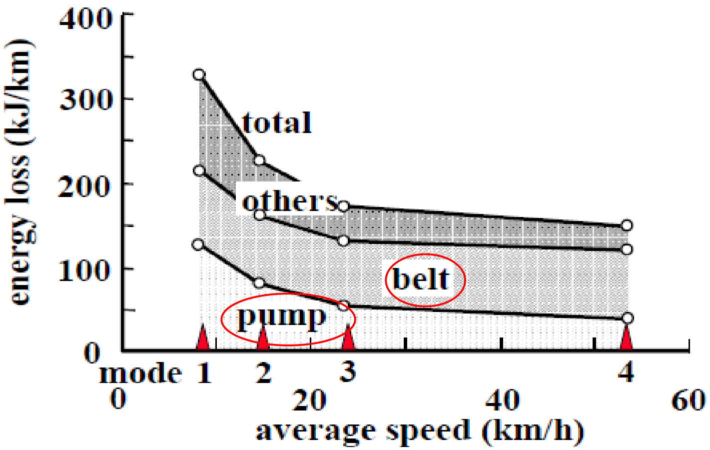
CVT hydraulic control system

Hydraulic pump loss and mechanical loss (variator belt & pulley loss)

Vehicle energy loss with CVT according to driving cycles*



CVT loss**

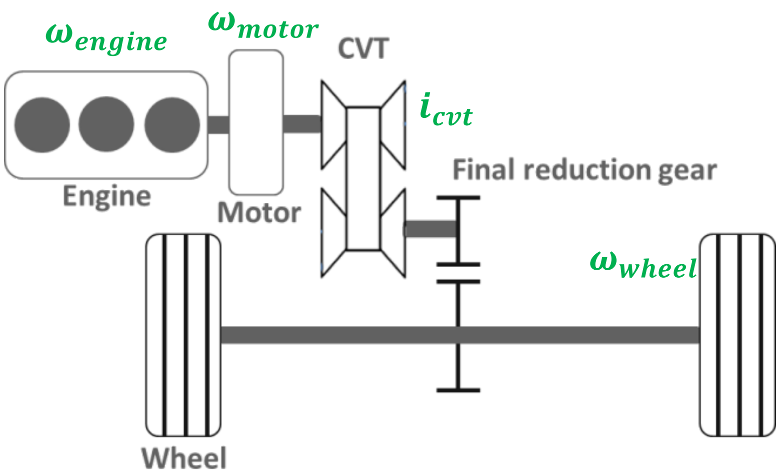


- Hydraulic pump loss : major part in the total loss at low vehicle speeds
- Mechanical loss : major part in the total loss at high vehicle speeds

*V. Francis, "Fuel consumption potential of the pushbelt "CVT", FISITA World Automotive Congress, 2006
**Tohru Ide, "Effect of Belt Loss and Oil Pump Loss on the Fuel Economy of a Vehicle with a Metal V-Belt CVT", FISITA World Automotive Congress, 2000

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

$$\omega_{engine} = \omega_{motor}$$

$$\omega_{motor} = i_{cvt} \times \omega_{wheel}$$

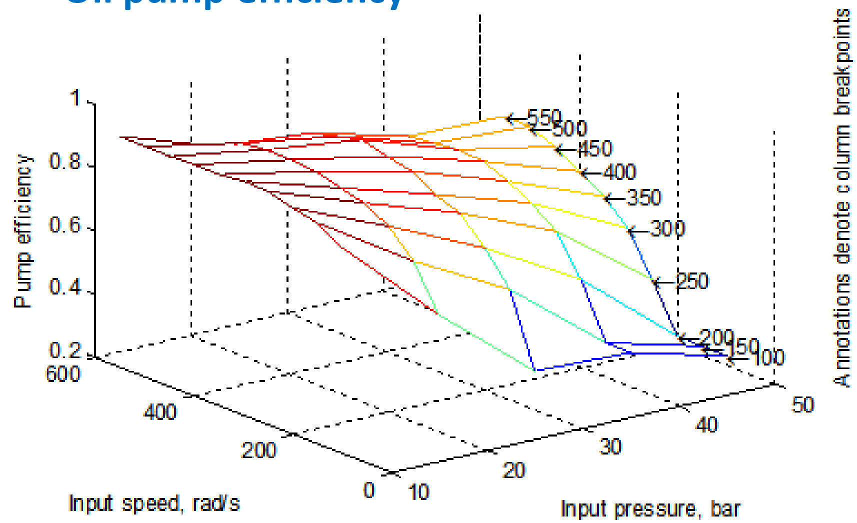
< Vehicle specifications >

Engine	Displacement	1500 cc
	Torque	172 Nm @ 5500 rpm
	Power	82 kW @ 5500 rpm
Motor	Max. power/ torque	17 kW/106 Nm
	Max. speed	9500 rpm
Battery	Number of cells	40
	Nominal cell voltage	3.6 V
	Rated pack energy	0.675 kWh
TM	CVT ratio	3.172–0.529:1
	Final drive ratio	3.94:1
Vehicle	Weight	1295 kg
	Tire radius	0.381 m

Oil pump efficiency depends on the line pressure and input speed

- Oil pump efficiency map from experiment is used

Oil pump efficiency*



$$P_{pump,loss} = P_{line} D_{pump} \omega_{pump} / \eta_{pump}$$

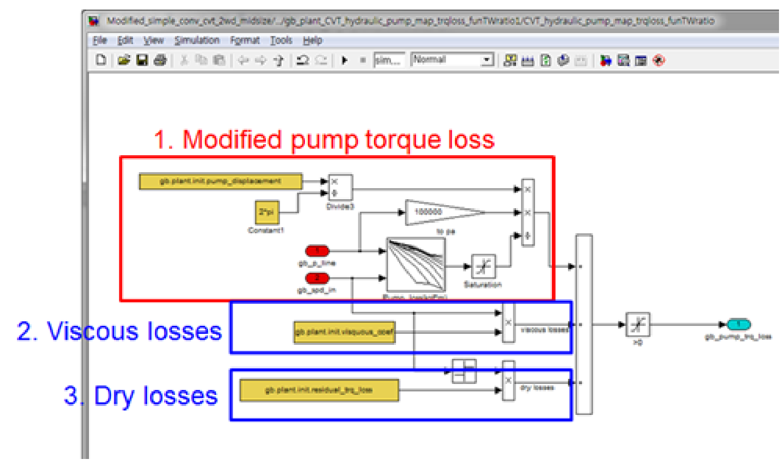
$$\rightarrow T_{pump,loss} = P_{line} D_{pump} / \eta_{pump}$$

- $\eta_{pump} = f(i_{cvt}, P_{line})$

  $i_{cvt} (= \omega_p / \omega_s)$: CVT ratio

P_{line} : line pressure
D_{pump} : pump displacement
ω_{pump} : pump speed
η_{pump} : oil pump efficiency

Pump loss model

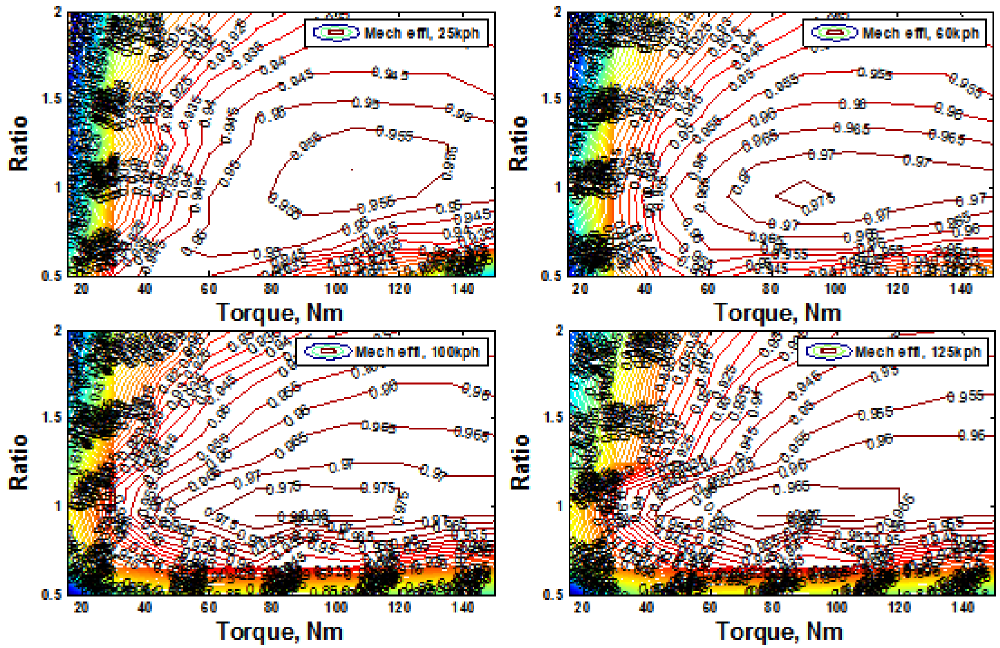


*W. Ryu "A Study on Metal Belt CVT Control for System Efficiency Improvement", Dissertation of Sungkyunkwan University, 2006

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

- Mechanical loss model

CVT mechanical efficiency*



- $\eta_{mech} = f(i_{cvt}, T_t, V_v)$

  $1/i_{cvt} (= \omega_s / \omega_p)$: speed ratio

  T_t : turbine torque

  V_v : vehicle speed

- $\eta_{mech} = (T_{in} - T_{mech.loss}) / T_{in}$

  $\rightarrow T_{mech.loss} = (1 - \eta_{mech}) T_{in}$

  $T_{in} = T_{engine} - T_{pump.loss}$

* Bas Vroemen, “Component Control for The Zero Inertia Powertrain”, Dissertation of Technische Universiteit Eindhoven, 2001

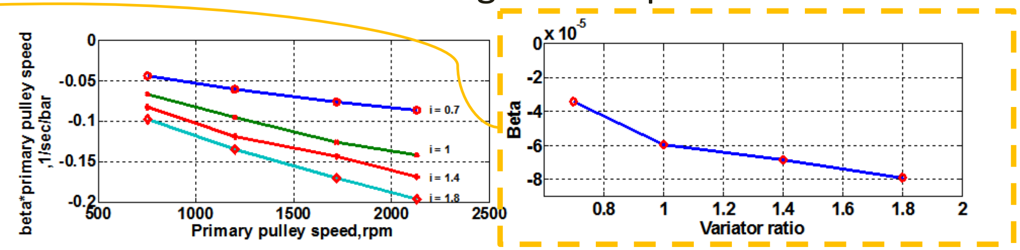
Mechanical losses depend on the speed ratio, input torque and vehicle speed

- CVT shift dynamics model

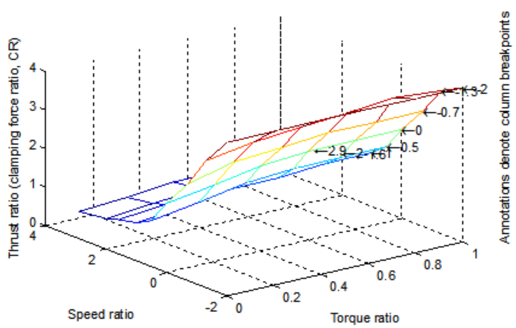
$$\frac{di}{dt} = \beta(i)\cdot\omega_p \cdot (P_p - P_p^*)$$

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

Ide's formula using SKKU experiments



FpFs map*



- $$FpFs = \frac{F_p}{F_s} = f(i_{cvt}, T_r)$$

$FpFs$: thrust ratio

F_p : primary clamping force

F_s : secondary clamping force

i_{cvt} : CVT ratio

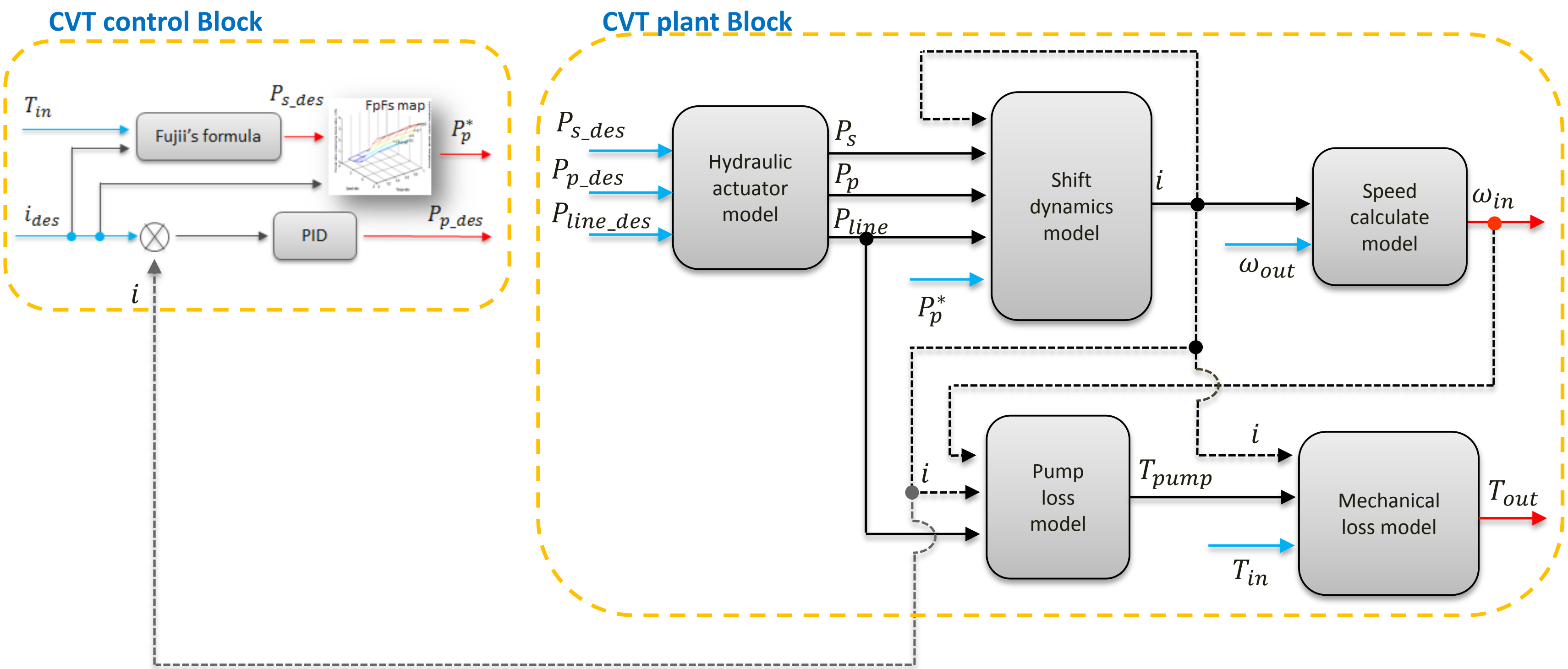
$T_r = T_{in}/T_{max}$: torque ratio

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

*T. Ide, A. Udagawa and R. Kataoka, "Simulation Approach to the Effect of the Ratio Changing Speed of a Metal V-Belt CVT on the Vehicle Response", Vehicle System Dynamics, 24: 4, 377 — 388, 1995
**J. Park "A Study on Shift Control Algorithm for a 2 stage CVT", Dissertation of Sungkyunkwan University, 2012

Overall New CVT Model

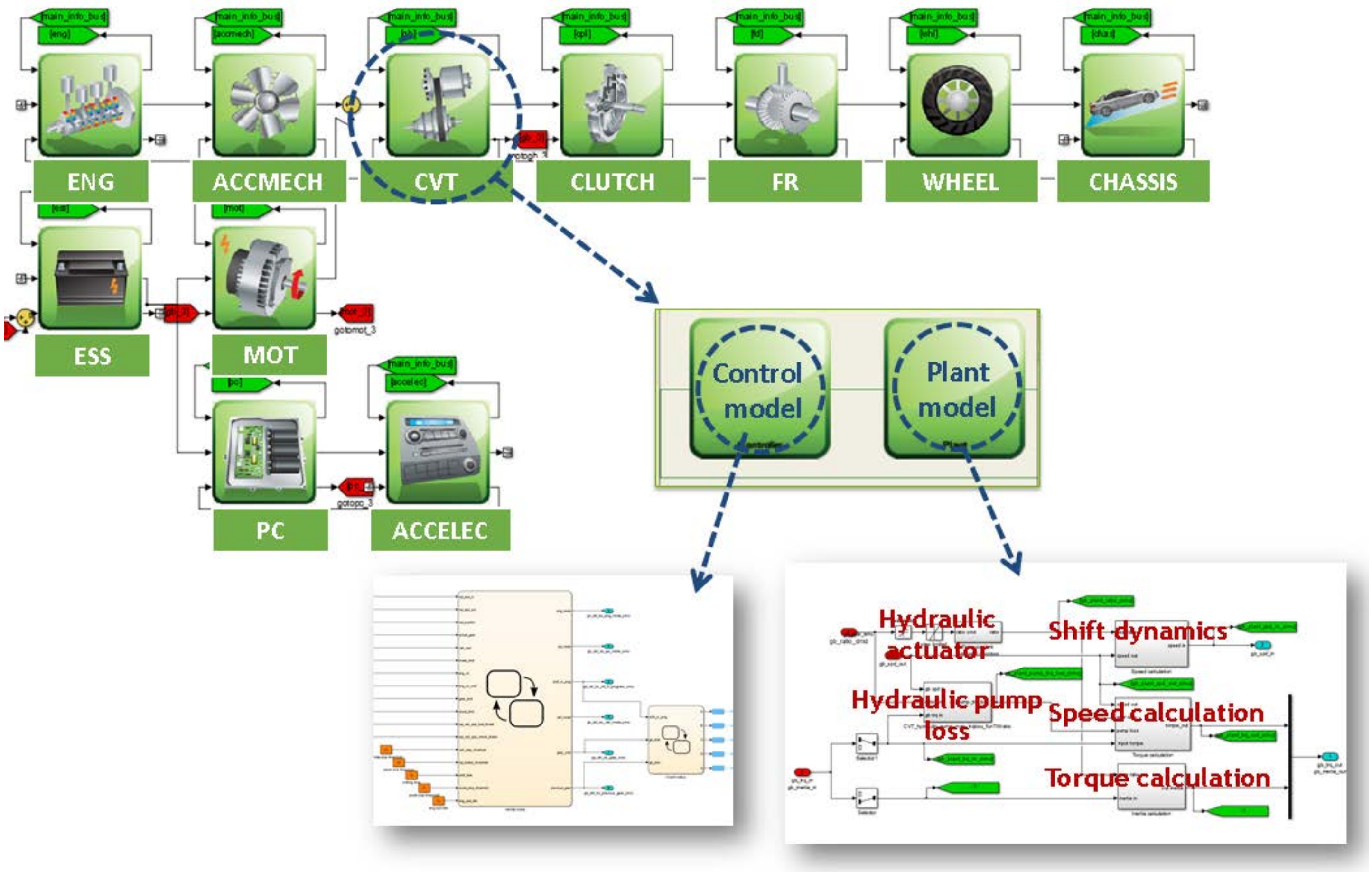
- The each pressure are determined to control the demanded CVT ratio



CVT system block diagram

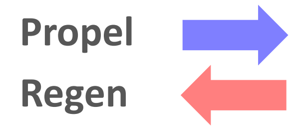
Development of vehicle performance simulator

- The component and models developed in this study are integrated into Autonomie

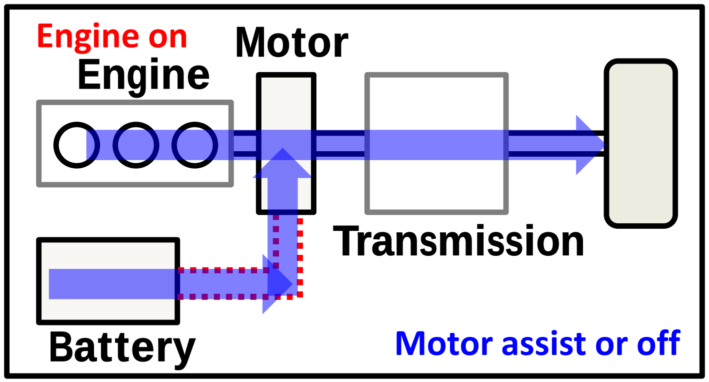


Driving Mode Control Analysis

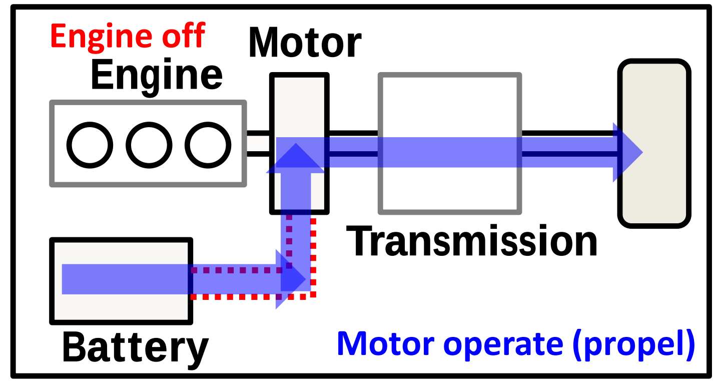
- In the target HEV, the engine is a main power source and the motor assists the engine according to the vehicle operating conditions



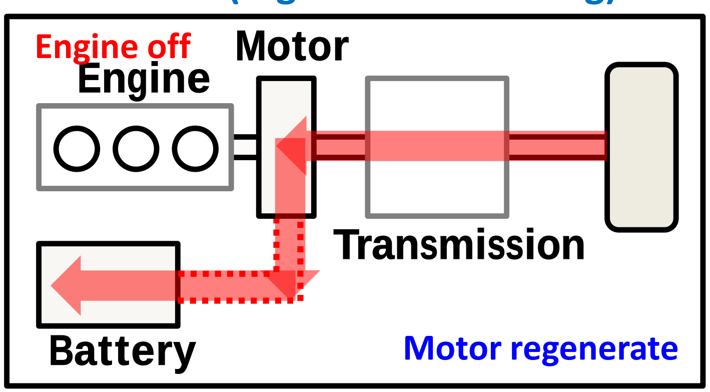
Acceleration



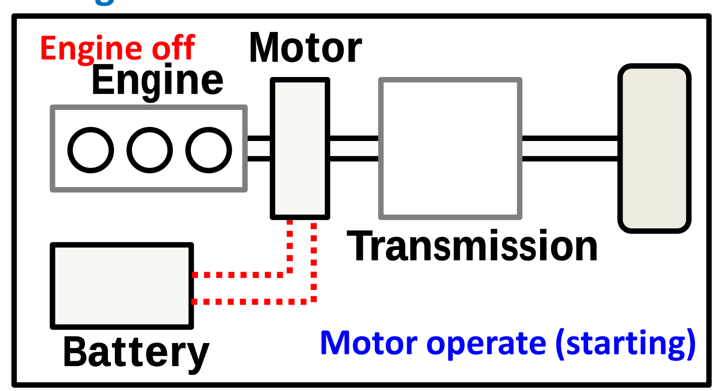
Cruising



Deceleration(regenerative braking)



Idling

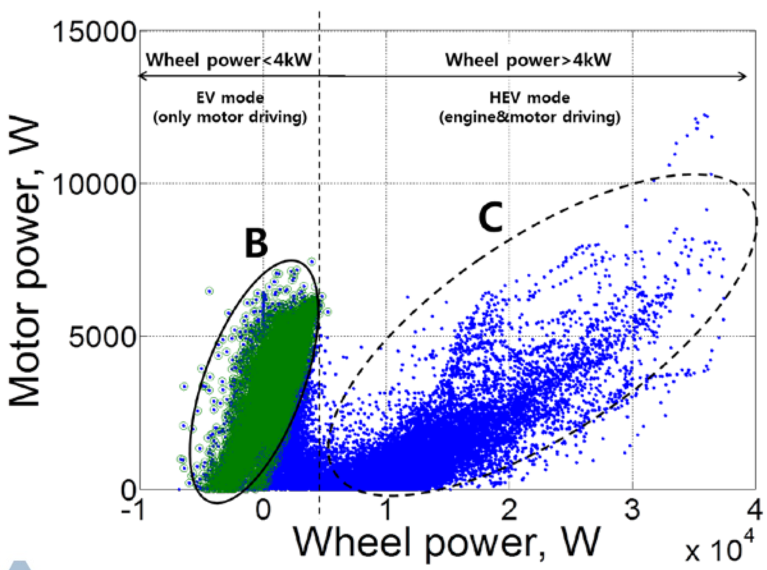


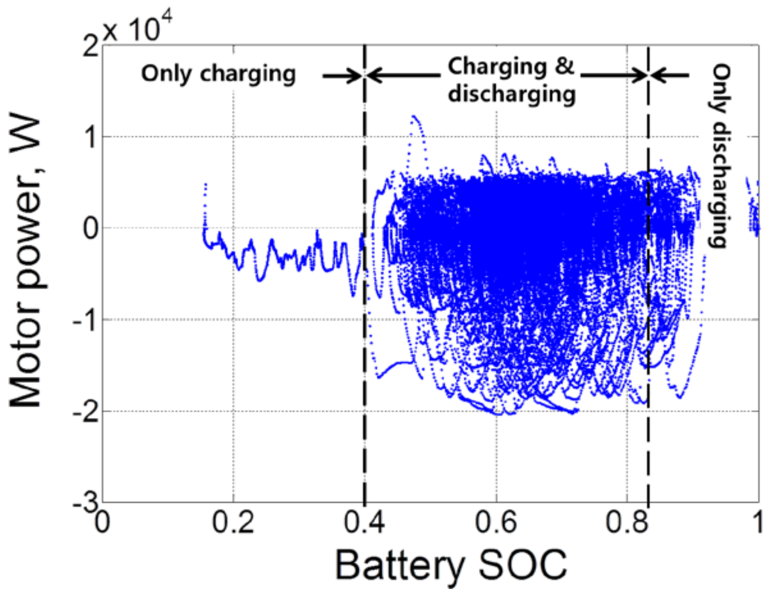
Driving Mode Control Analysis

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

Mode	Operating Conditions
EV mode	Low-speed cruise/ low power
Engine mode	Slow acceleration/ high-speed cruise
HEV mode	Start-up/ aggressive acceleration

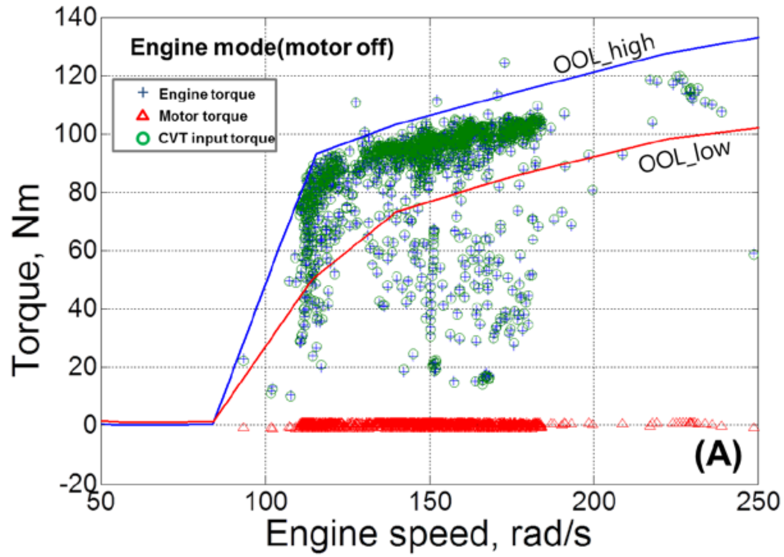
Driving mode control analysis in EV mode



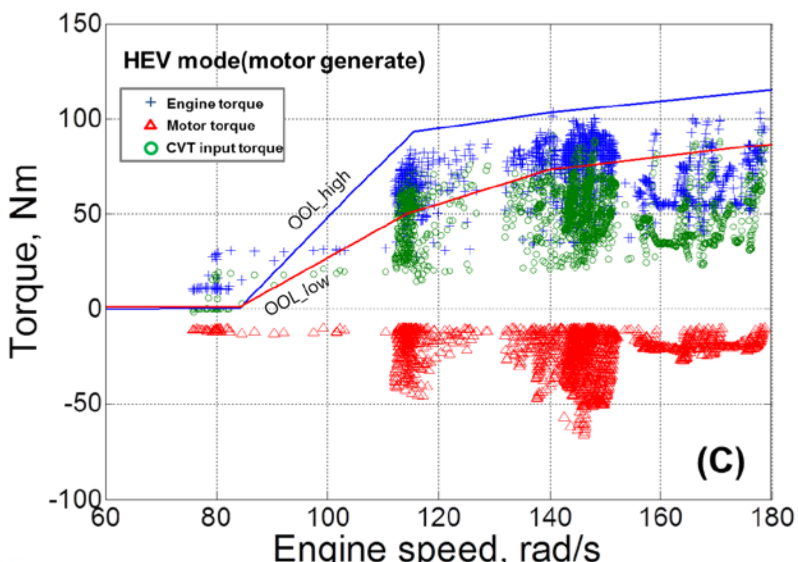


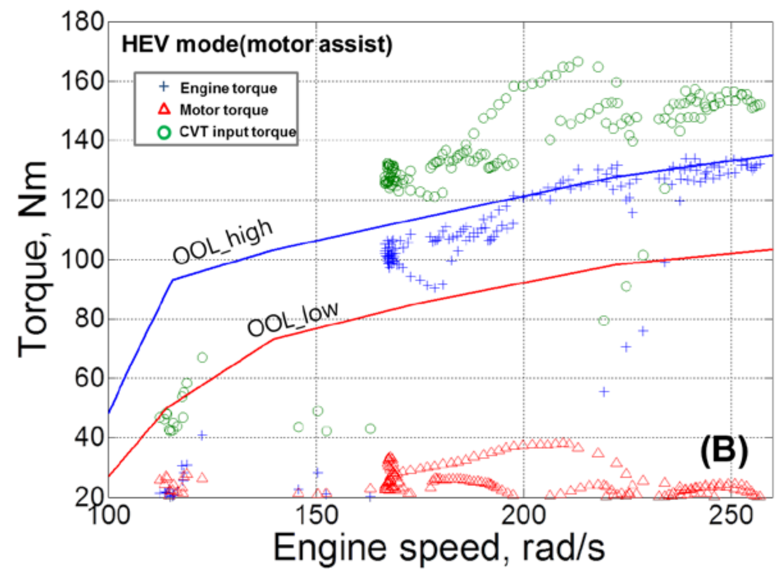
Driving Mode Control Analysis

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

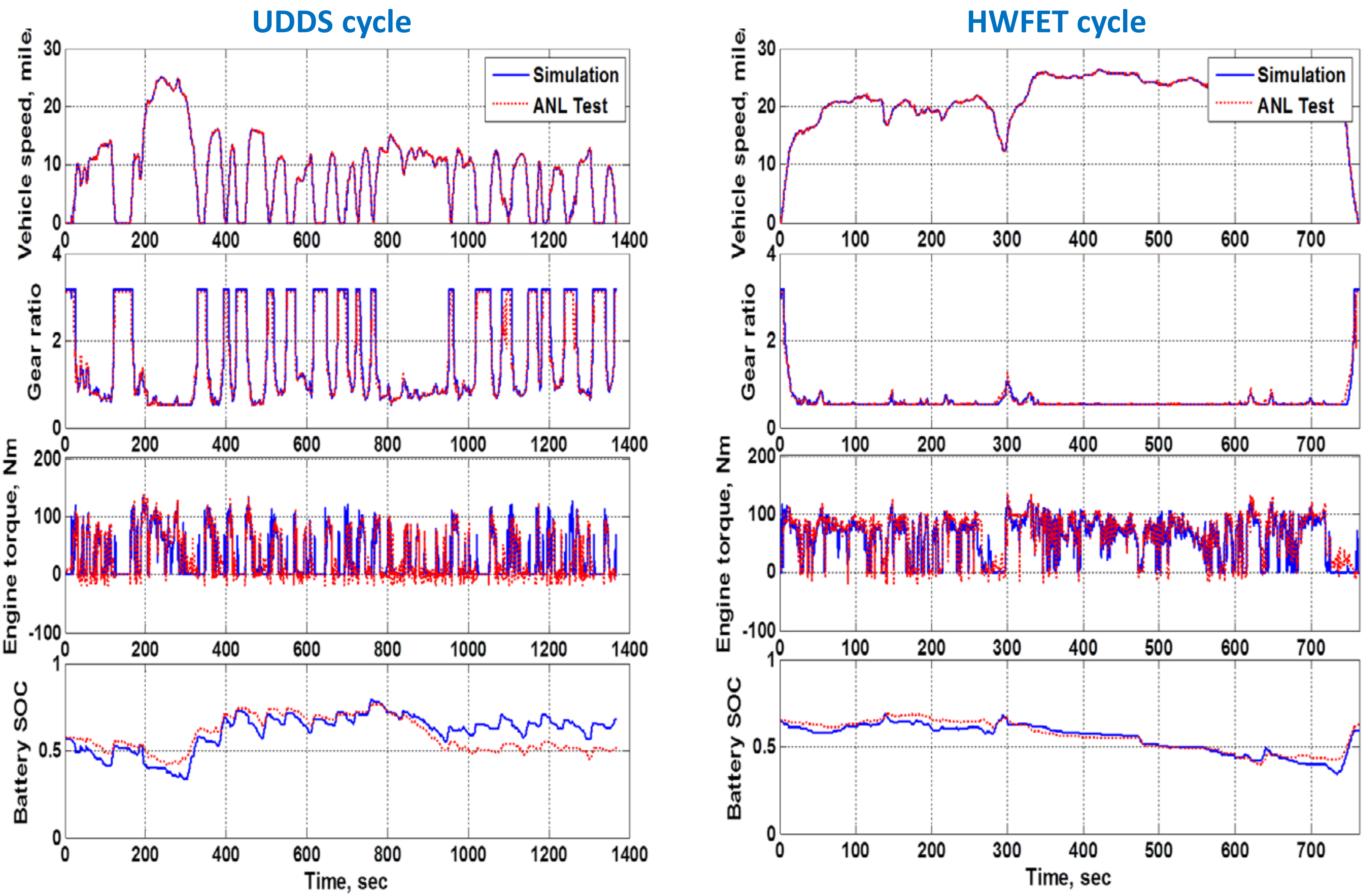


Driving mode control analysis in HEV mode





Results



UDDS cycle
HWFET cycle
Simulation
ANL Test
Vehicle speed, mile
Gear ratio
Engine torque, Nm
Battery SOC
Time, sec

Validation Results

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

$$NCCP = \frac{\max[R_{xy}(\tau)]}{\max[R_{xx}(\tau), R_{yy}(\tau)]} \qquad R_{xy}(\tau) = \lim_{\tau \to \infty} \frac{1}{T} \int_0^{\tau} x(t) \cdot y(t-\tau) dt$$

NCCP values for UDDS and HWFET cycles

Cycle	Vehicle Speed	Gear Ratio	Engine Torque	Battery SOC
HWFET	0.99	0.98	0.90	0.97
UDDS	0.99	0.93	0.90	0.96

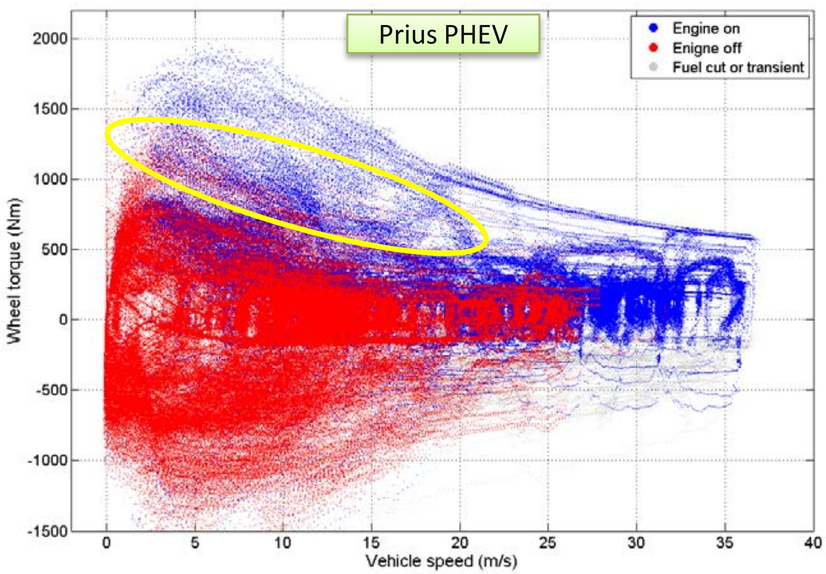
Outline

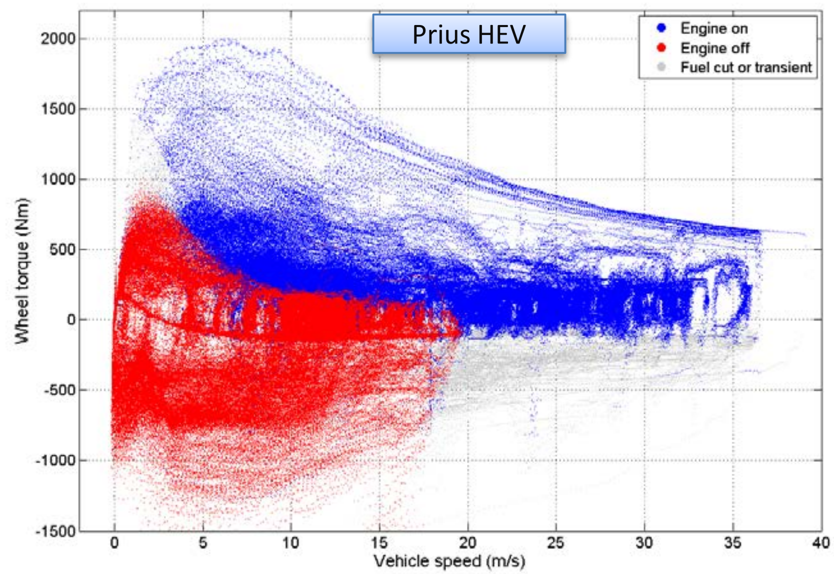
- Validation Process
- Component Model Development and Validation
- Vehicle Validation Examples
  - Conventional Vehicles
  - Mild Hybrids
  - Full Hybrids
  - Plug-in Hybrids (Blended)
  - E-REV PHEV
  - BEV
- Thermal Model Validation Overview

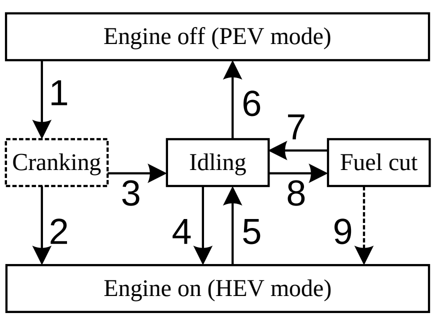
Prius PHEV

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





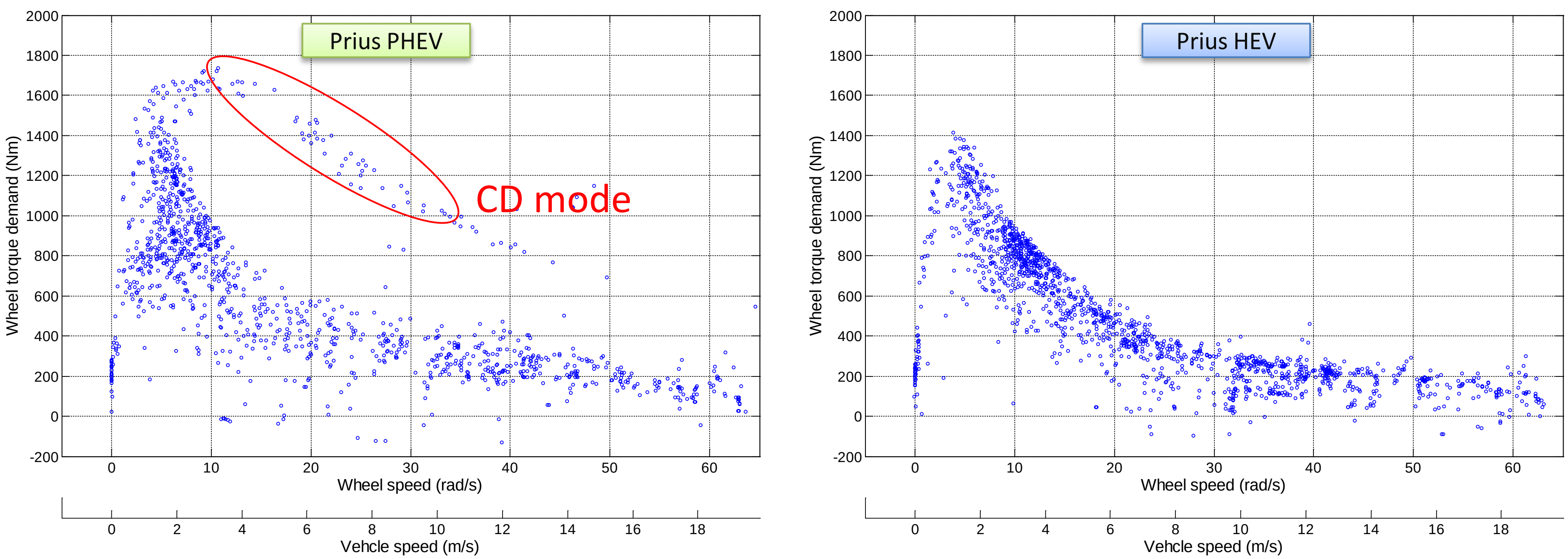


Engine operation mode of Prius PHEV is the same as HEV

	Engine Speed	Fueling
Engine off	0	Off
Cranking	Accelerating	Ready to fuel
Idling	Idle speed	Idling
Fuel cut	Idle speed	Off
Engine on	Controlled	Controlled

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

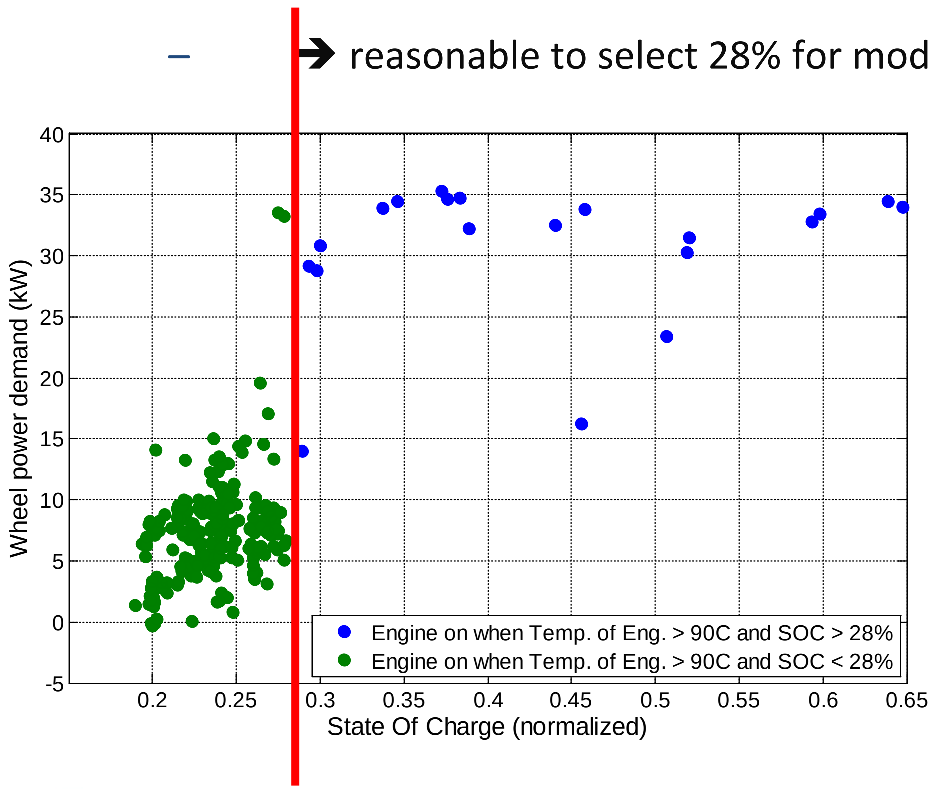


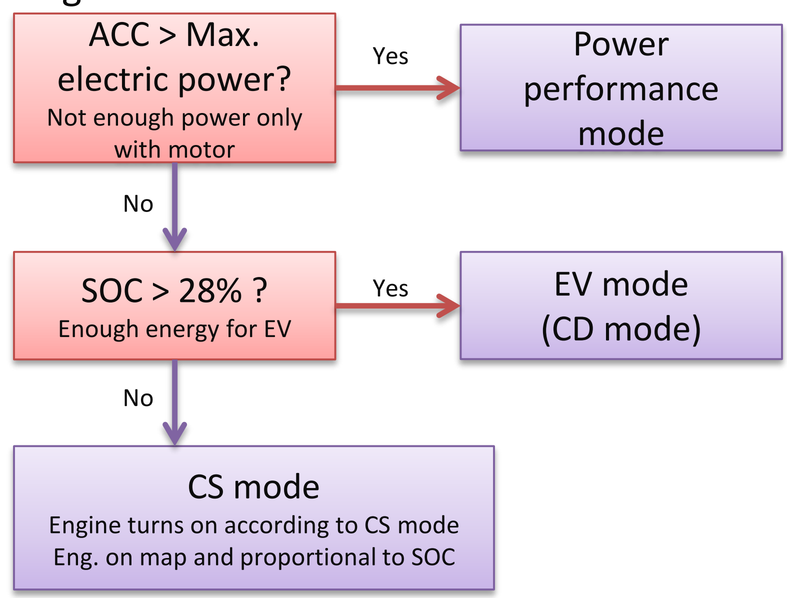
The on/off strategy in CS mode looks similar to the strategy of HEV

- More EV driving in PHEV
- Change of driving pattern (CD to CS)

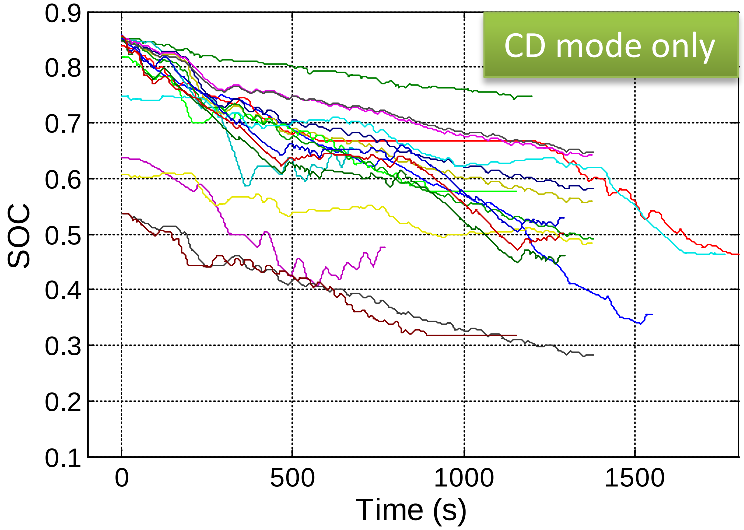
Mode Control: CD or CS modes Can Be Determined by Engine On Points and SOC

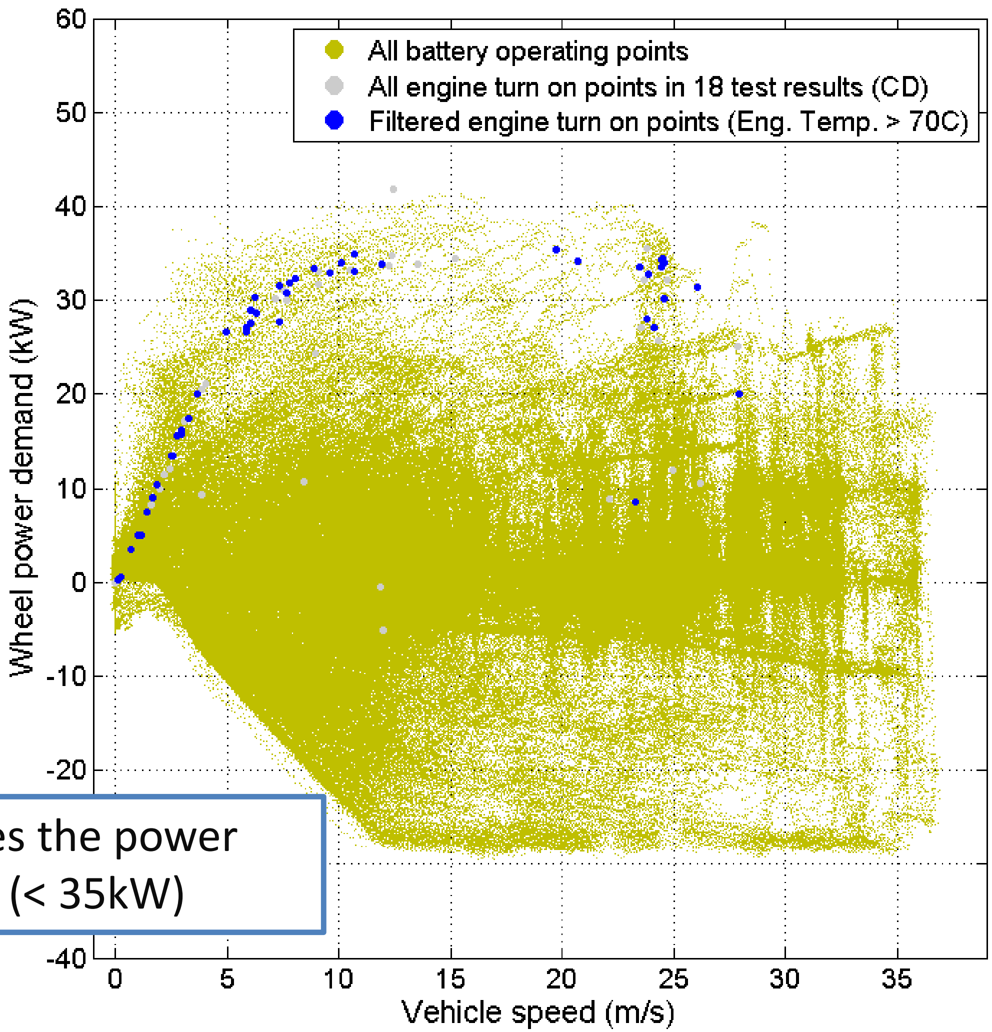
- Driving mode change
  - Analysis of driving mode according to engine turn on point change
  - When SOC is over 28% engine is turned on in higher power demand (30kW) than under 28% (under 15kW)
  - → reasonable to select 28% for mode change between CD mode to CS mode





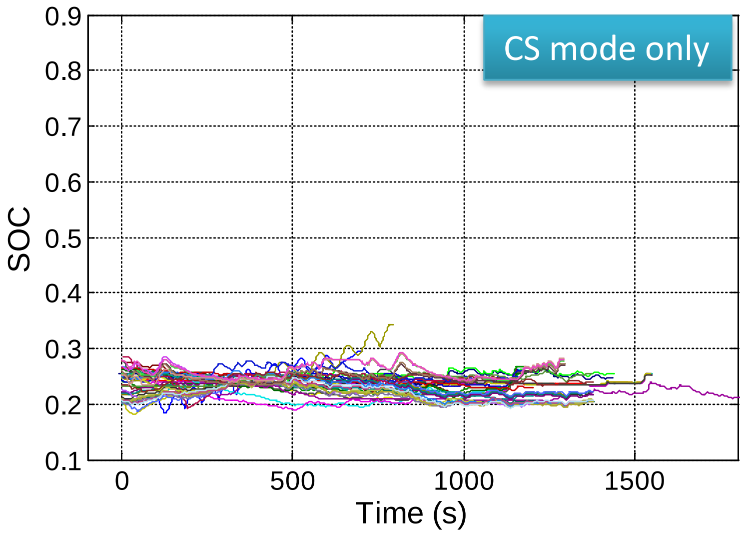
Mode Control: Engine Is Turned On If Battery Cannot Provide All Power Required In CD Mode

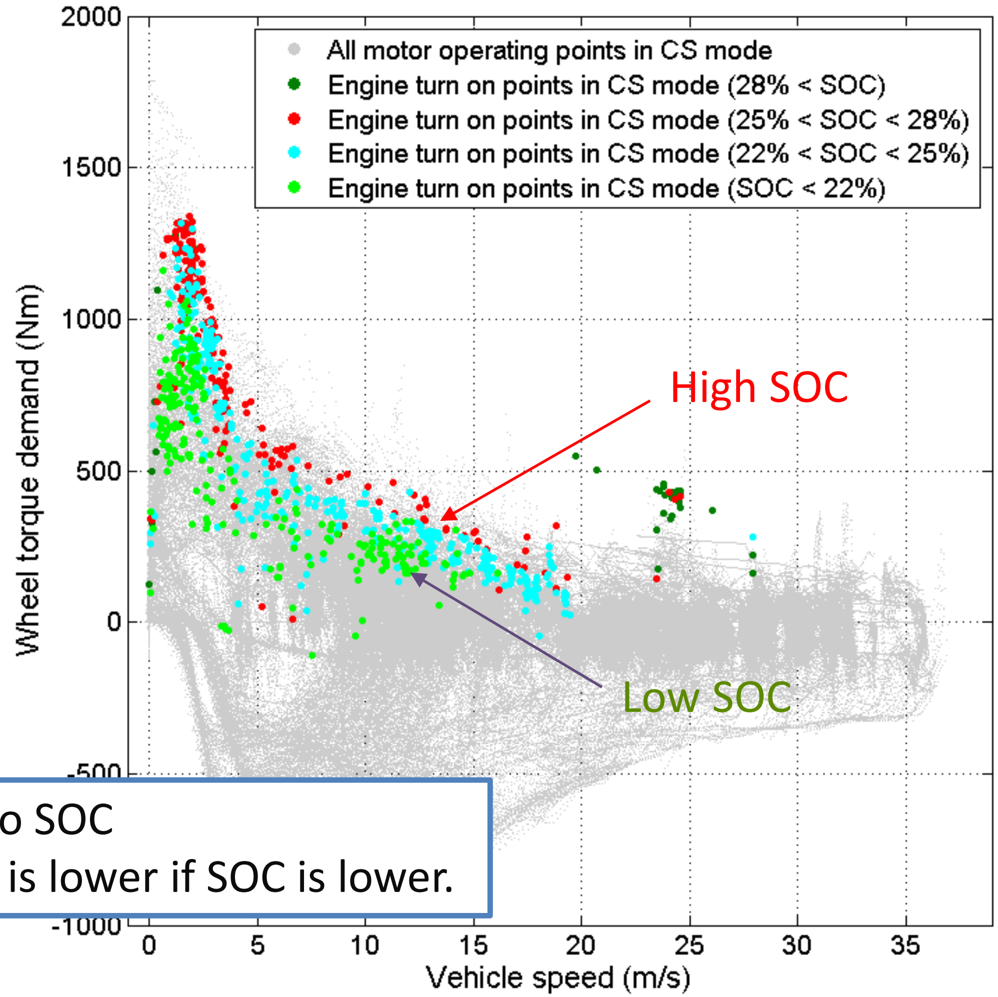




Engine turn on when the vehicle requires the power exceed battery maximum output power (< 35kW)

Mode Control: Engine Is Turned ON If Demand Torque Exceeds a Threshold Line In CS Mode

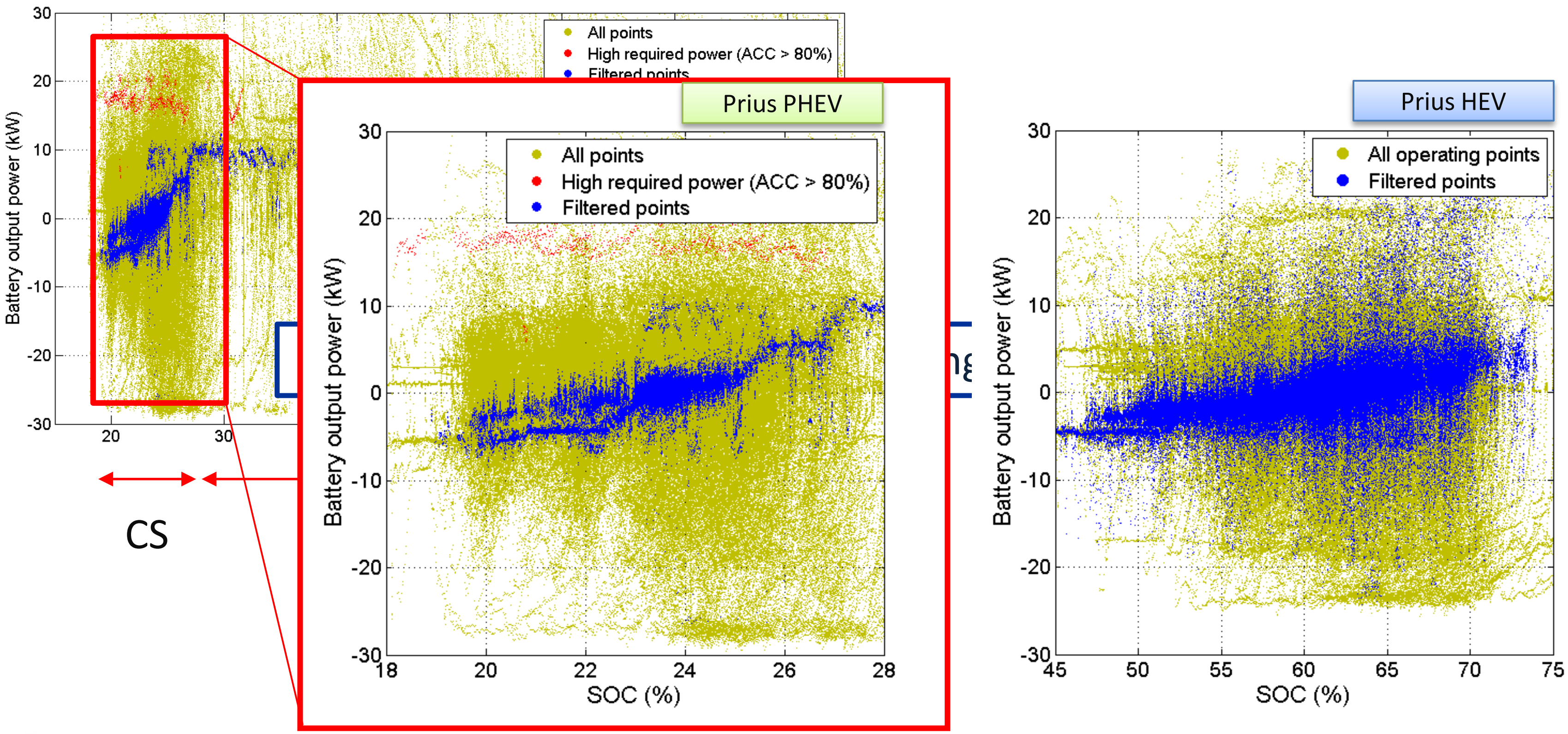




Threshold line is changed according to SOC
We can say that the threshold power is lower if SOC is lower.

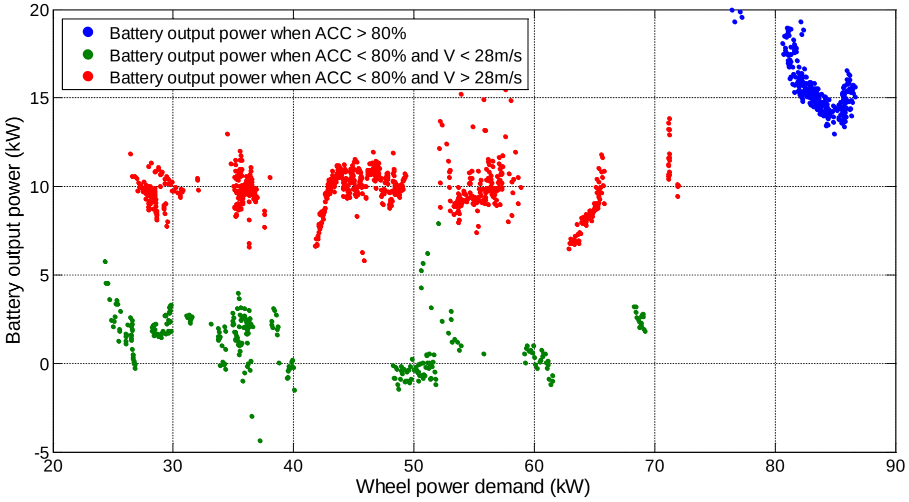
Energy Management Strategy: SOC Balancing Strategy Is The Same As the HEV Strategy In CS mode

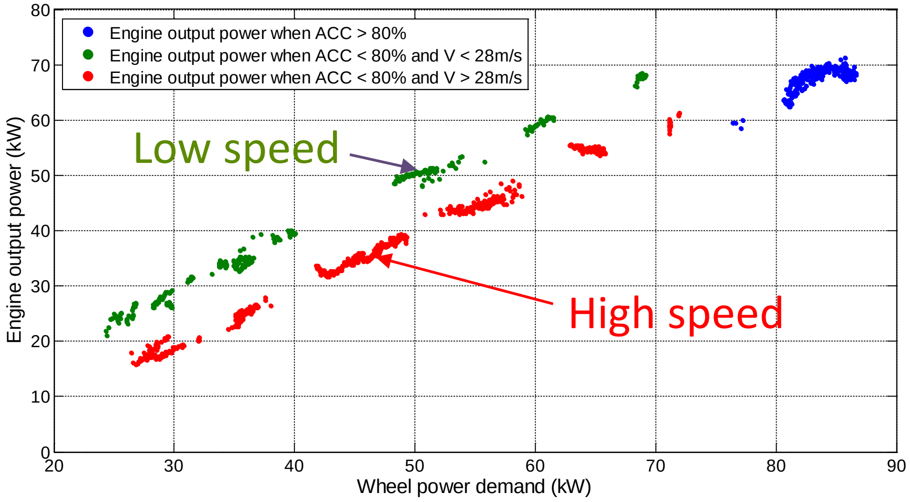
- SOC Balancing Strategy
  - ACC pedal > 80% ➔ engine and battery working together
  - CS mode: Battery power is proportional to SOC (the same as HEV)
  - CD mode: output power of the battery is 0kW to 10kW



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)



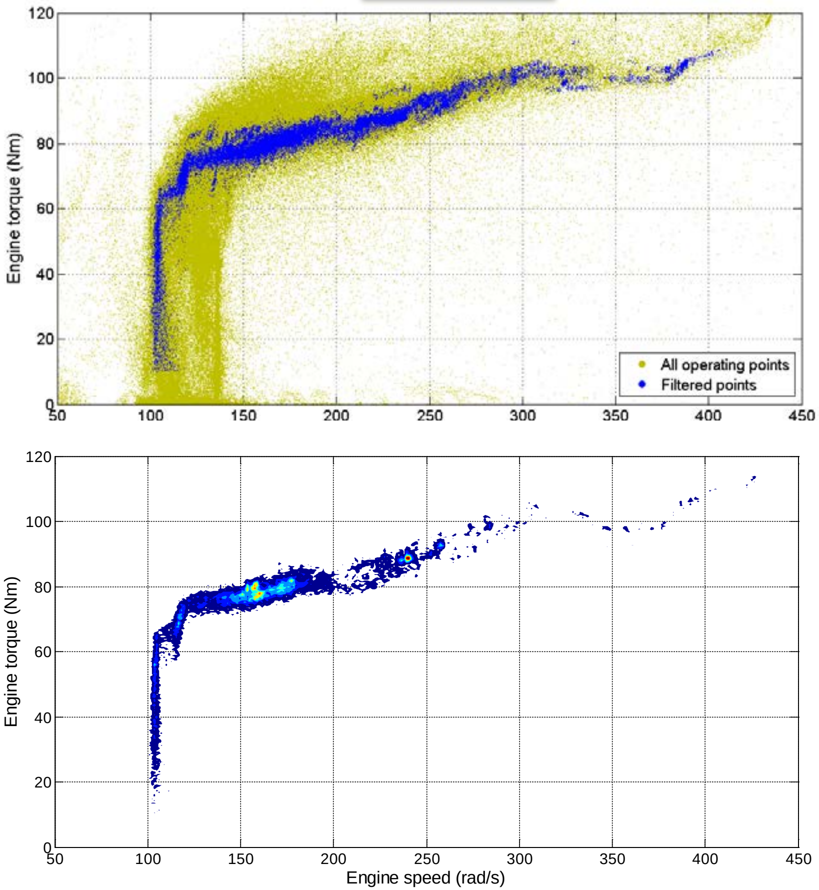


In CD mode, the engine is basically not used. However, the engine is mostly turned on for highway driving, so this special control concept is necessary for highway driving.

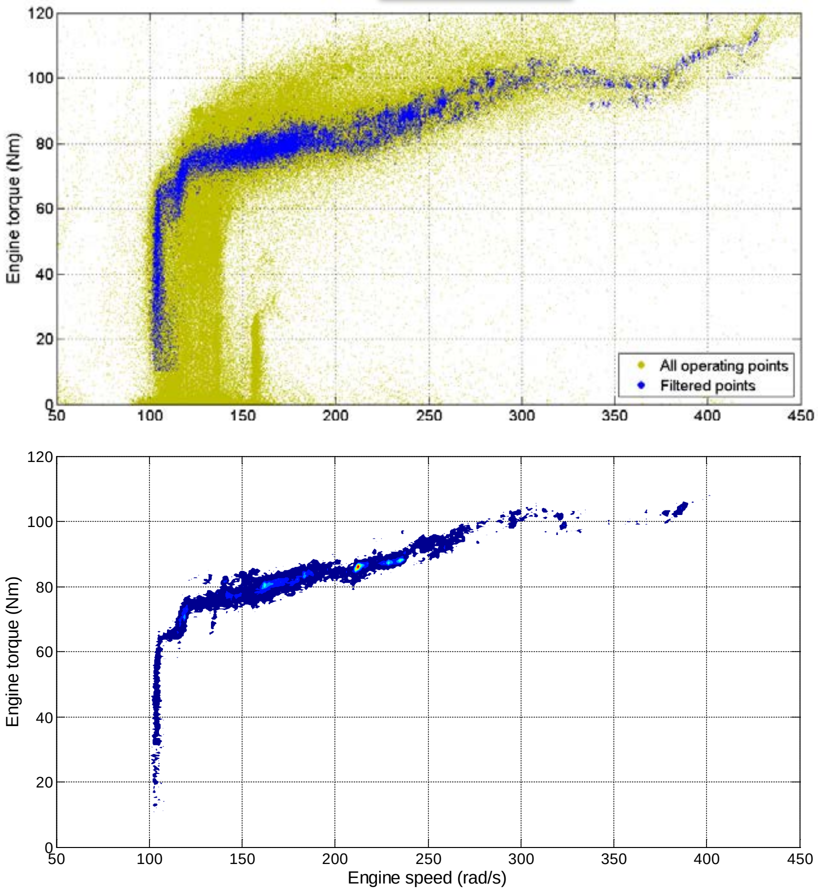
Component Operation Control: Engine Target Is The Same As The Engine Target of HEV

- Engine is operated followed by a specific line
- No difference between CD and CS mode

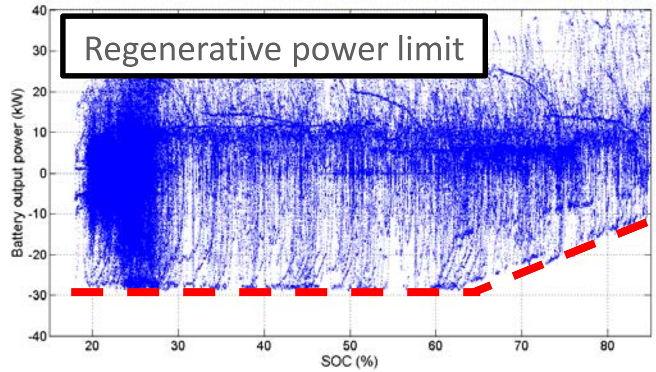
Prius PHEV



Prius HEV

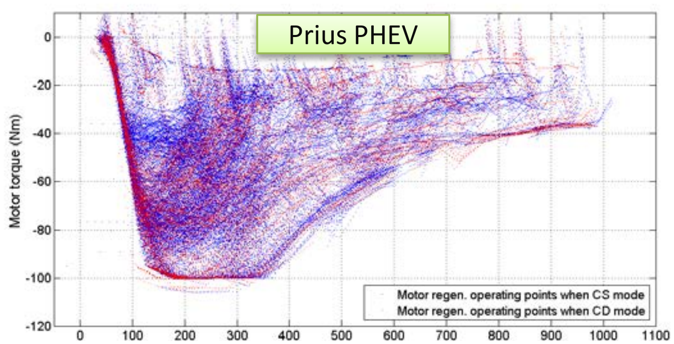


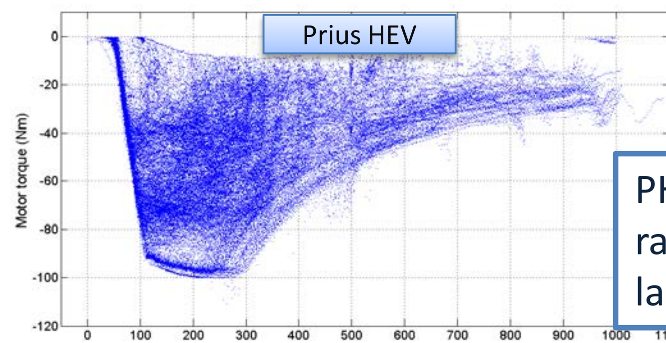
PHEV Has Similar Regenerative Performance Than Prius HEV



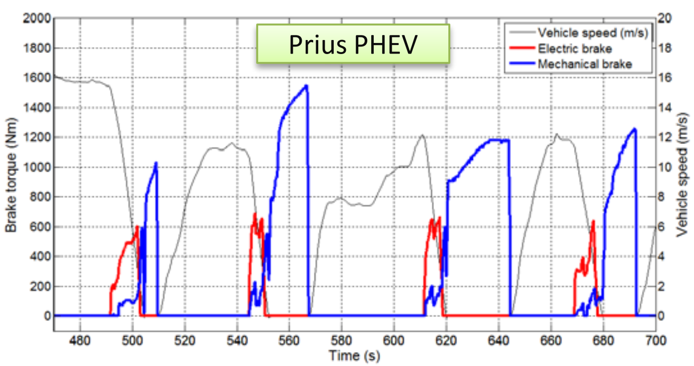
The battery in PHEV is constrained by SOC. (not observed in HEV due to SOC range)

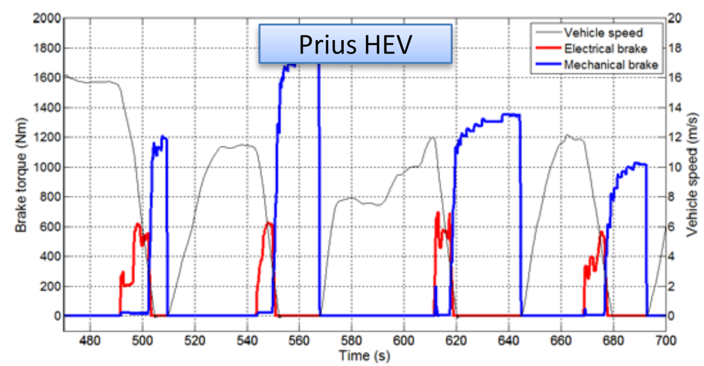
Instead, constraint by temperature in PHEV is not observed because the temperature is really well controlled





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



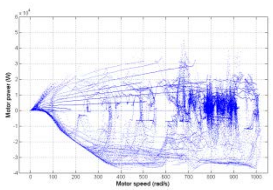


Summary of Operation

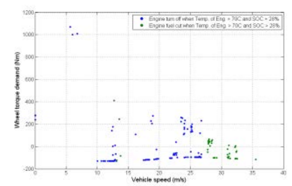
- Summary (at normal temperature)

CD mode

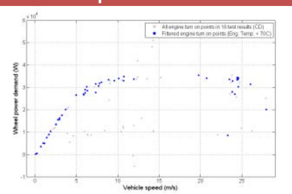
Engine off (EV)



Brake signal & Vehicle speed < 28m/s



Required power > Max. electric power



Engine on

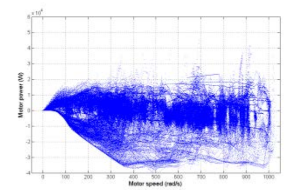
- Vehicle speed < 28m/s
  - Engine only mode ➔ ($P_{bat} = 0$)
- Vehicle speed > 28m/s
  - Battery supporting mode ➔ ($P_{bat} = 10kW$)

SOC < 28% (CD mode → CS mode)

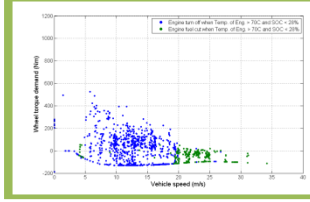
SOC > 30% (CS mode → CD mode)

CS mode

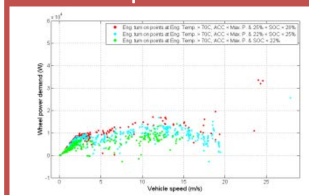
Engine off (EV)



Brake signal & Vehicle speed < 20m/s

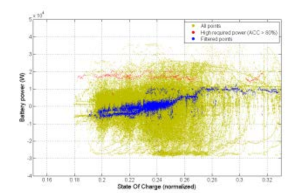


Engine turn on map: vehicle speed and SOC



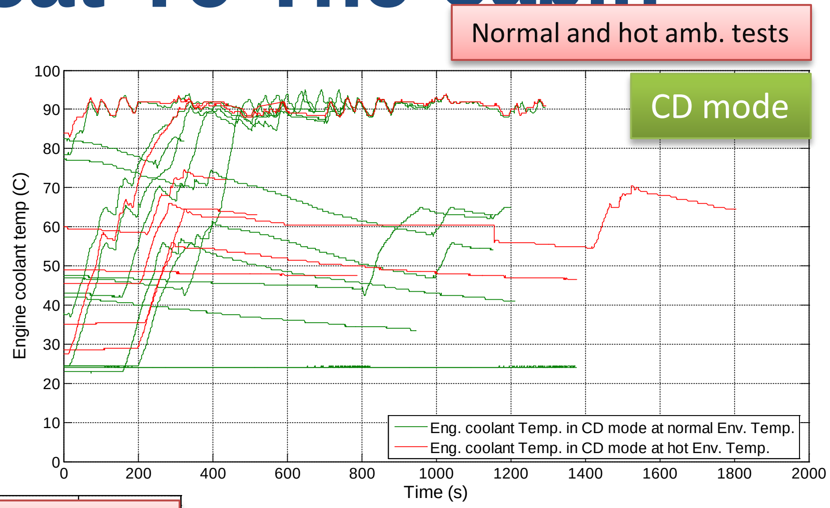
Engine on

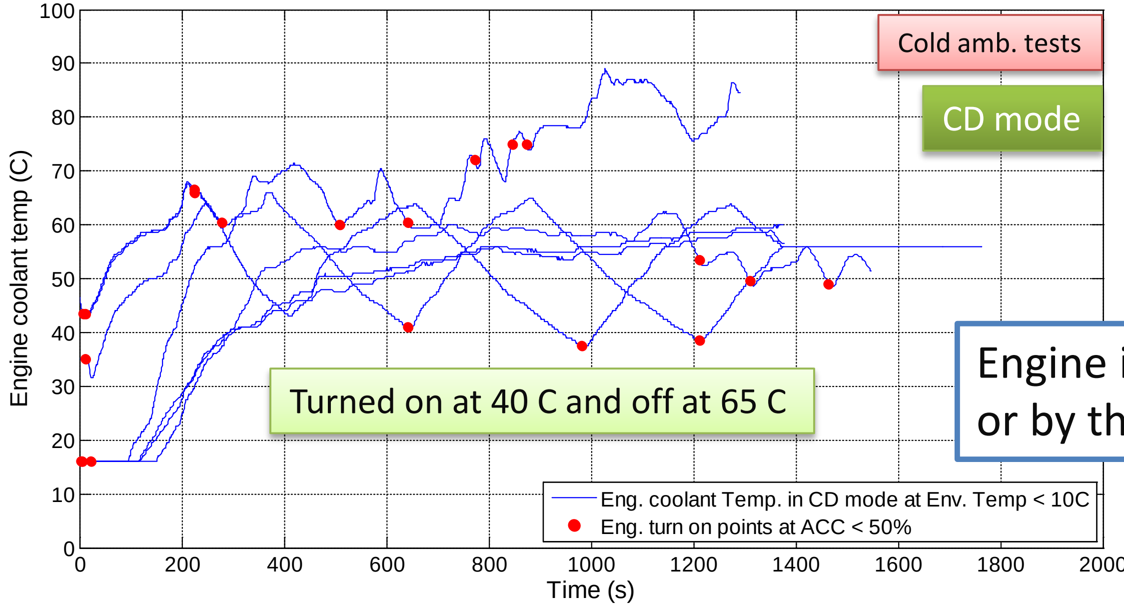
- Battery output power is proportional to SOC



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)

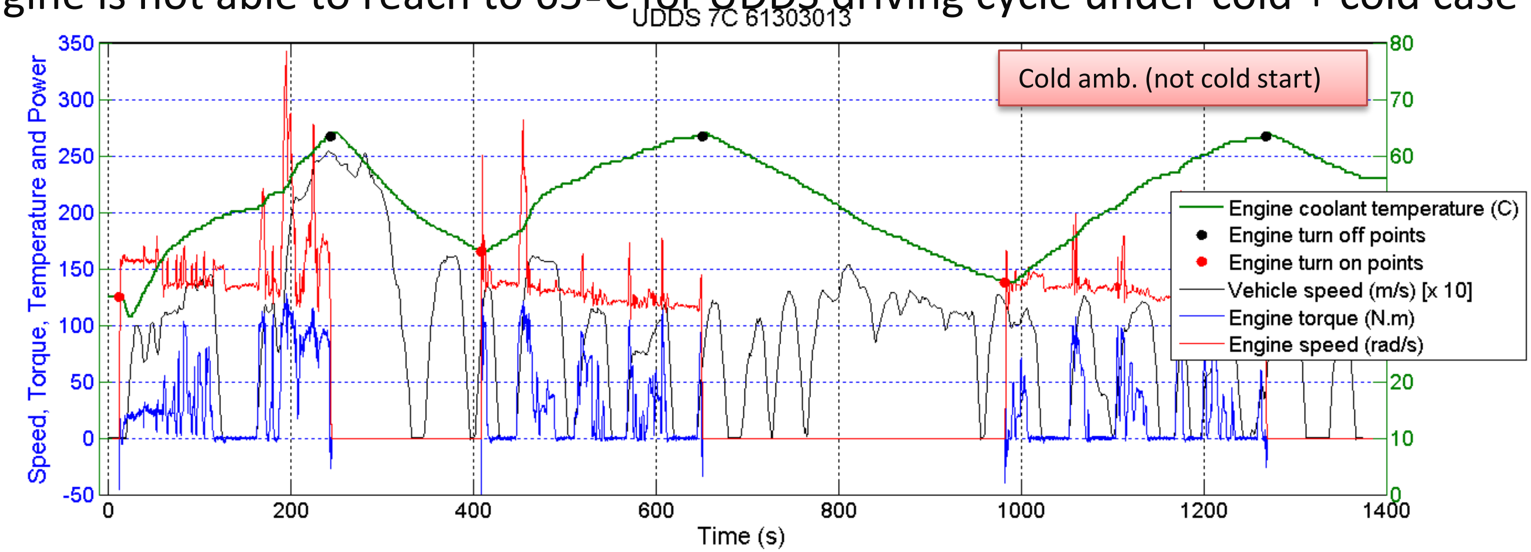


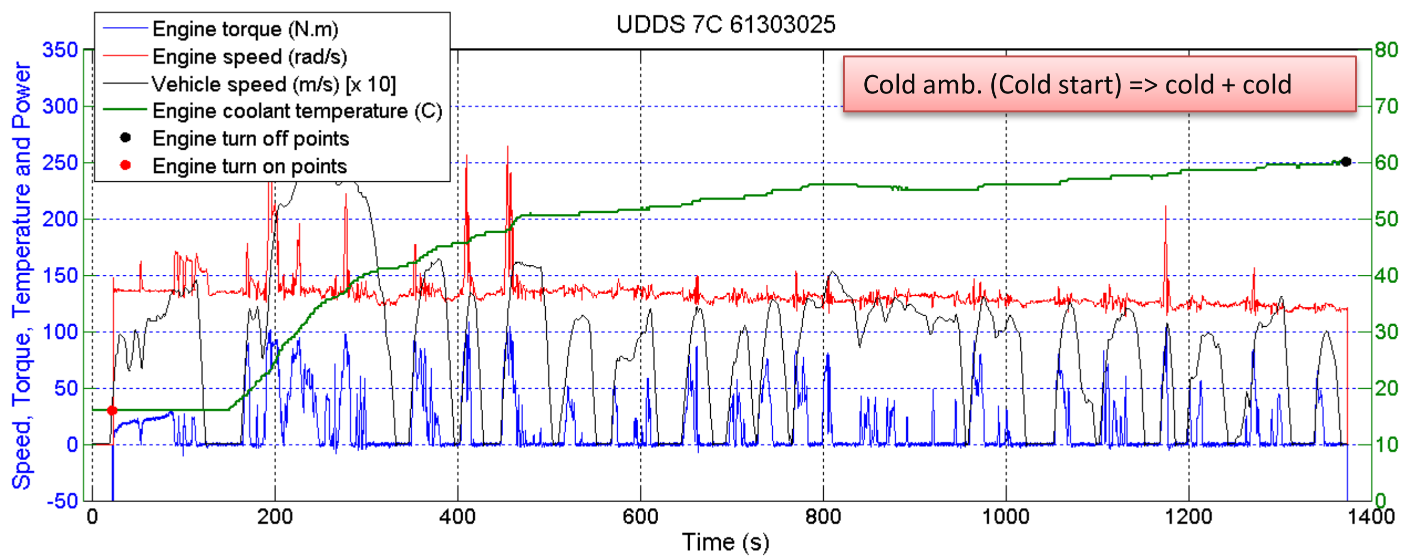


Engine is turned by the demand power or by the temperature condition.

In Cold Start Case, The Engine Is Turned On All The Time On UDDS Driving Cycle Even In CD Mode

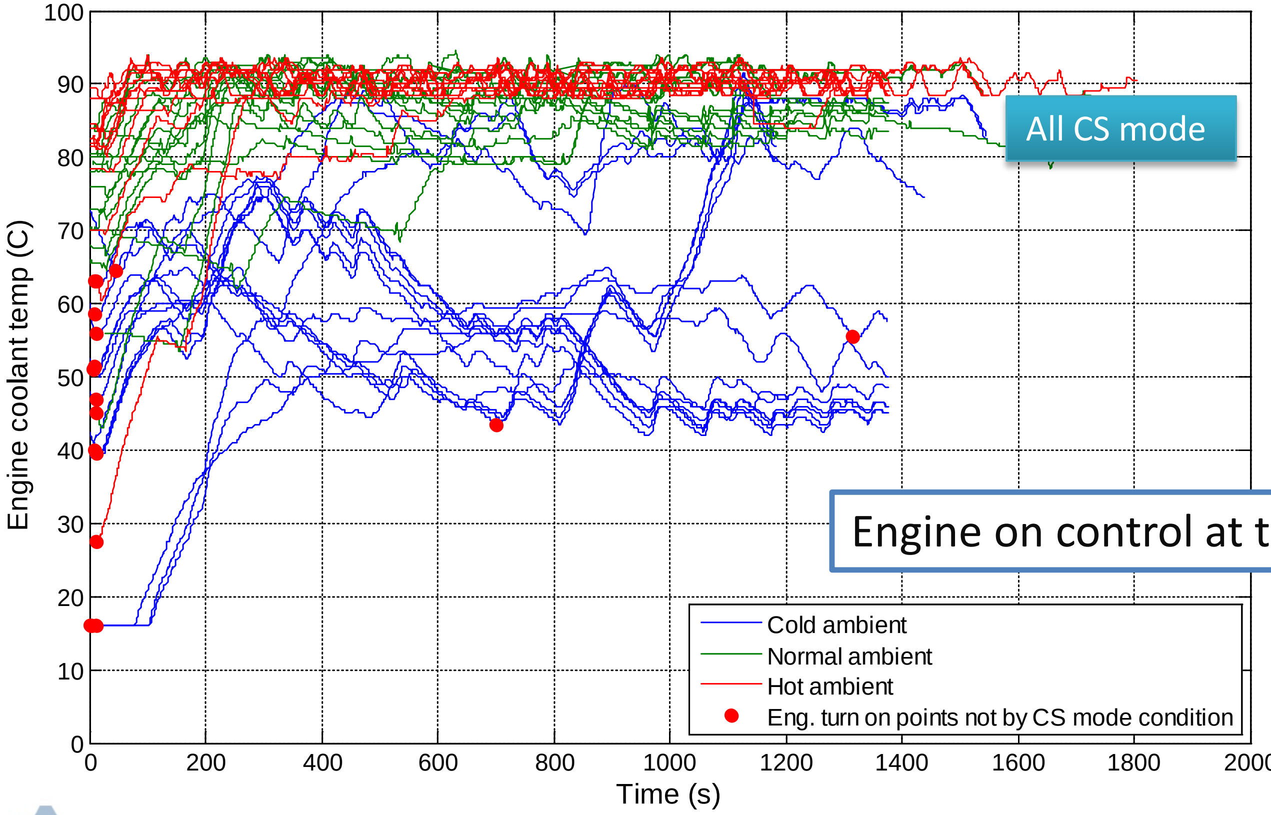
- Engine is not able to reach to 65ºC for UDDS driving cycle under cold + cold case





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)

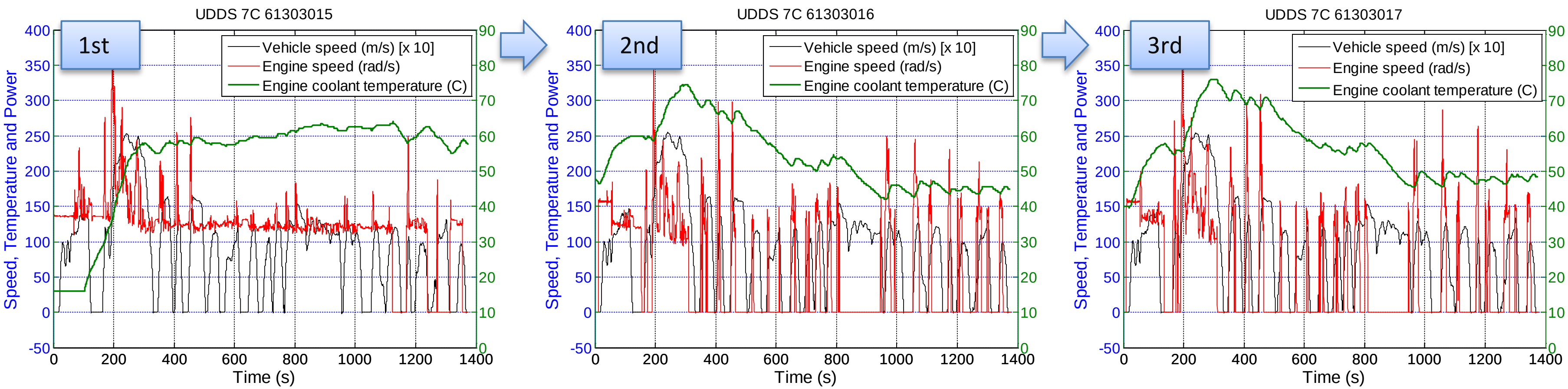


Engine on control at the launch of the vehicle

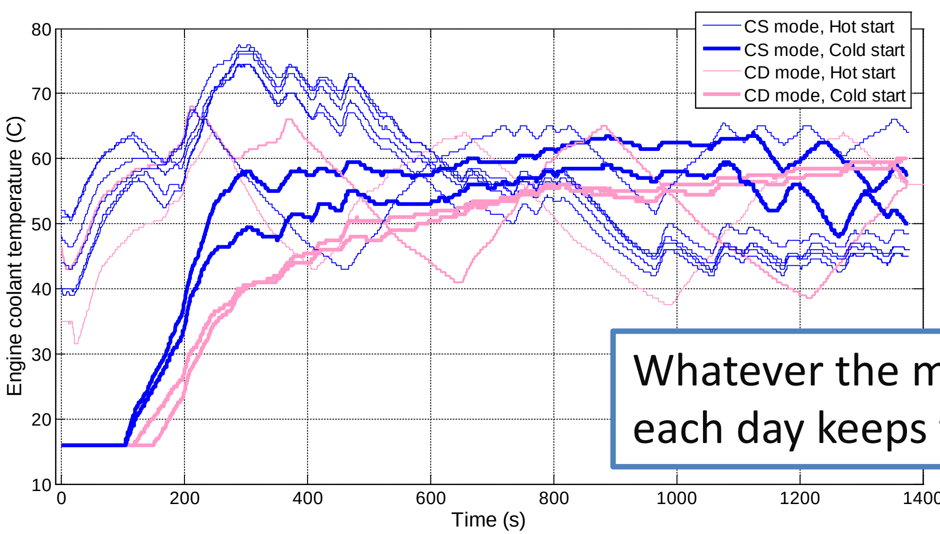
Points selected when the engine is turned on without demand torque.

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)



2nd and 3rd look similar.

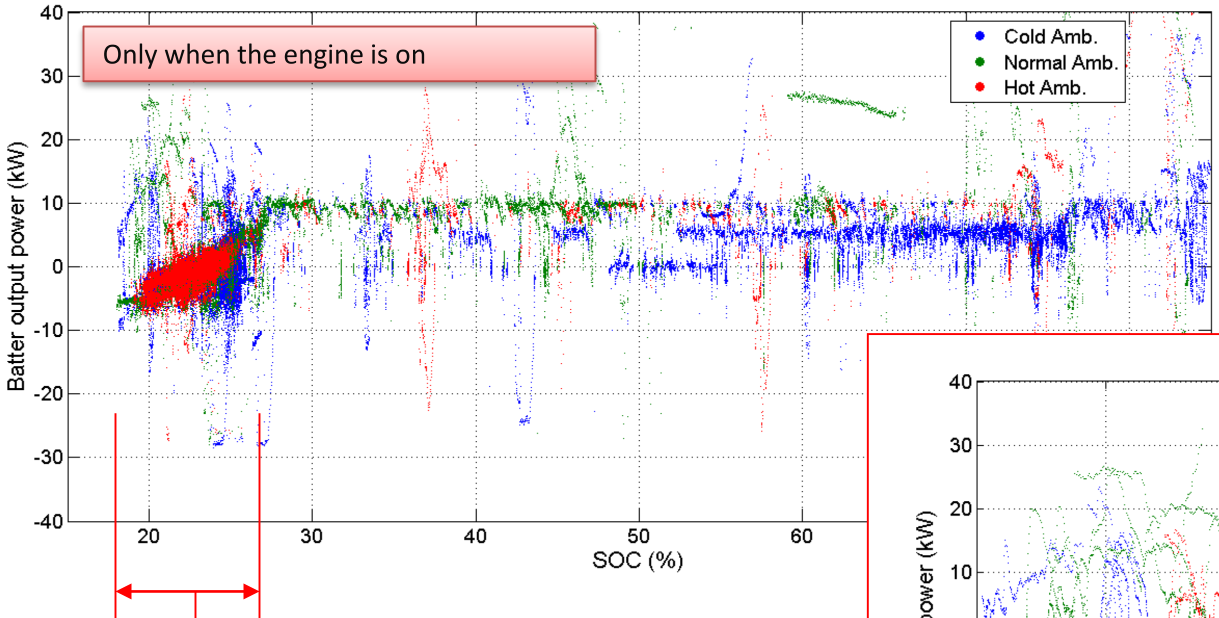


The coolant temperature cannot reach to 65°C under cold start

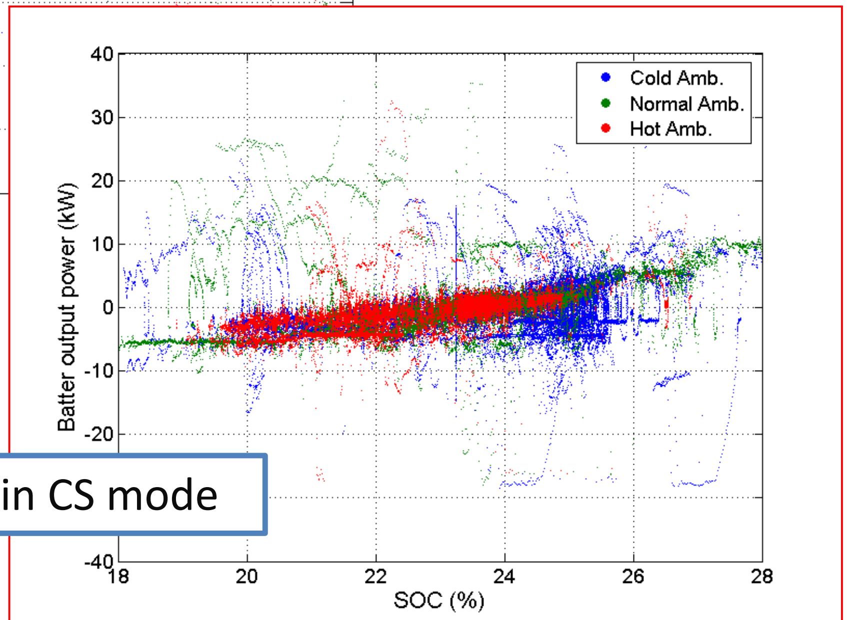
Whatever the mode is CS or CD, the first UDDS test of each day keeps the engine on under the cold ambient.

There Is No Significant Impact(s) On Energy Management Strategy For SOC Balancing

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



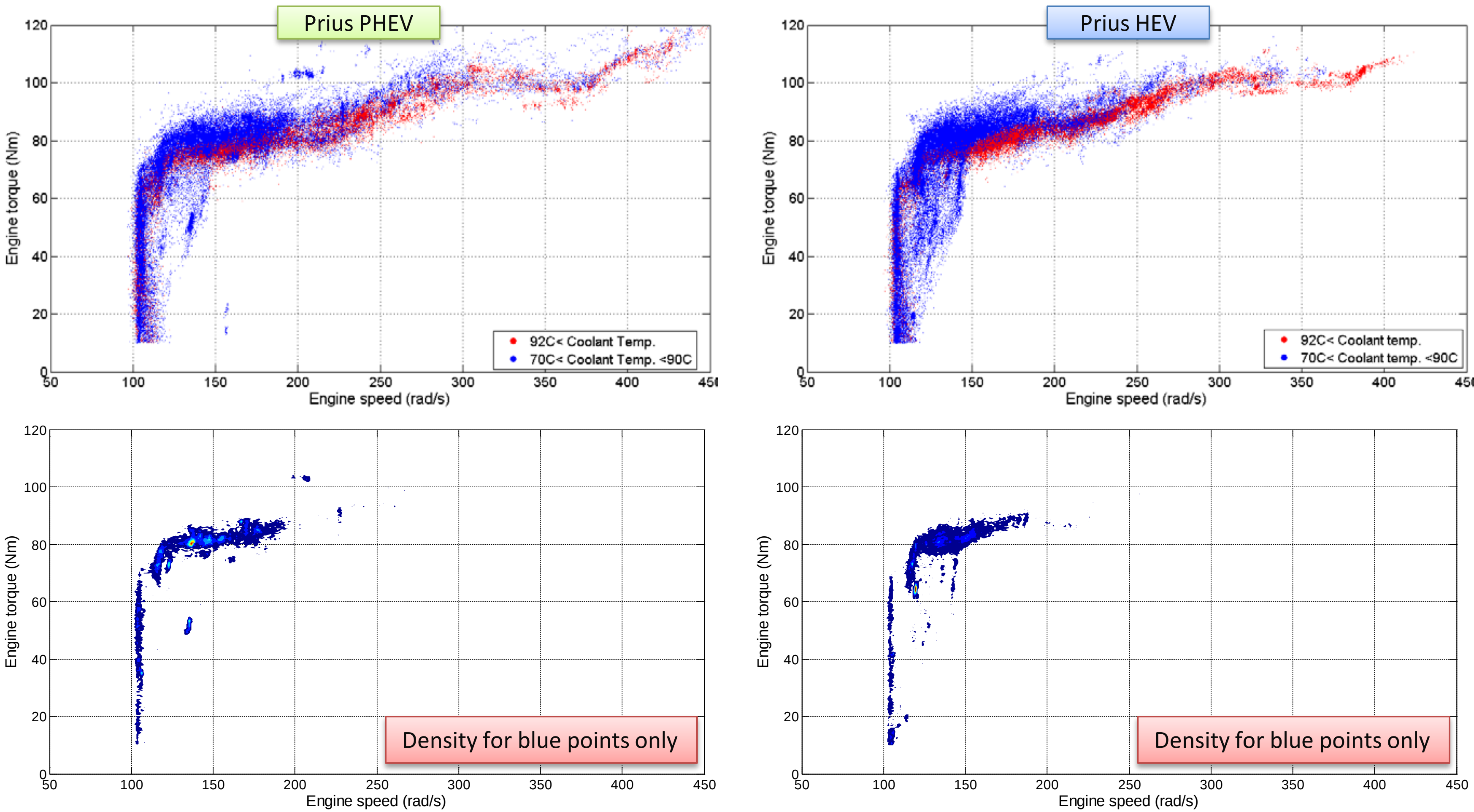
CS mode



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

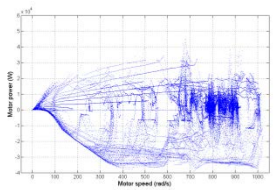
- In low coolant temperature ➔ engine torque is controlled in higher range than normal



Summary of Operation with Thermal Condition

CD mode

Engine off (EV)

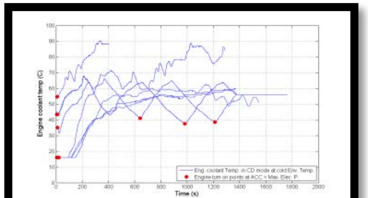


Brake signal & Vehicle speed < 28m/s
AND
Engine coolant Temp. > 65C (Heater on)

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)

Required power > Max. electric power
OR
Heater on & Engine coolant Temp. < 40C
OR
Cold start: Heater on & (Engine coolant Temp. < 65C

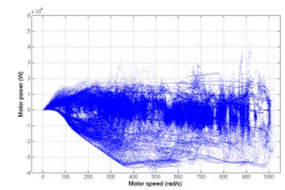


SOC < 28%

SOC > 30%

CS mode

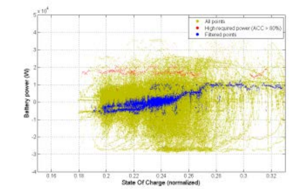
Engine off (EV)



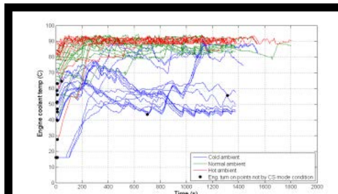
Brake signal & Vehicle speed < 20m/s

Engine on

- Battery output power is proportional to SOC



Engine turn on map: vehicle speed and SOC
OR
(Engine coolant Temp. < 40C)
OR
Cold start: Engine coolant Temp. < 65C



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 accessary power applied depending on the temperature and driving cycles

	CD: FE discrepancy (%) (SOC difference)		CS: FE discrepancy (%) (SOC difference)	
	UDDS	HWFET	UDDS	HWFET
22C	- (0.7%)*	- (-0.8%)*	0.25 (-0.6%)	0.37 (-0.5%)
35C	- (-0.15%)*	- (-1.95%)*	3.20 (0.4%)	1.17 (0.1%)
-7C	2.02 (-2%)	0.04 (1.25%)	3.92 (-0.6%)	3.76 (0.5%)

*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 accessary power applied depending on the temperature and driving cycles

Cycle name	Ambient Temperature	Driving mode	Fuel consumption (g)			ΔSOC (%)			Final SOC (%)		
			Test	Simulation	diff.(%)	Test	Simulation	diff.(%)	Test	Sim.	diff.
UDDS	22C	CD	0	0	-	**-28.95**	**-29.64**	**2.4%**	55.87	55.18	-0.69
		CS	**286.5**	**287.1**	**0.2%**	-0.58	+0.01	-	21.64	22.23	0.59
	35C	CD	67.1	52.4	-	**-35.90**	**-35.76**	**-0.4%**	49.27	49.41	0.14
		CS	**405.4**	**392.8**	**-3.1%**	-0.01	-0.46	-	20.88	20.43	-0.45
	-7C	CD	450.3	459.2	2.0%	-21.03	-19.06	-	64.16	66.13	1.97
		CS	**357.1**	**371.4**	**4.0%**	-5.10	-4.46	-	20.27	20.91	0.64
HWFET	22C	CD	0	0	-	**-45.22**	**-44.41**	**-1.8%**	39.99	40.8	0.81
		CS	442.3	443.9	**0.4%**	+0.05	+0.58	-	25.29	25.82	0.53
	35C	CD	0	0	-	**-54.68**	**-52.73**	**-3.6%**	30.65	32.6	1.95
		CS	**521.3**	**527.4**	**1.2%**	+0.51	+0.36	-	25.36	25.21	-0.15
	-7C	CD	413.9	413.7	0.0%	-22.2	-23.45	-	63.47	62.22	-1.25
		CS	**497.1**	**516.5**	**3.9%**	-1.77	-2.30	-	26.16	25.63	-0.53

2015-01-1157

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.

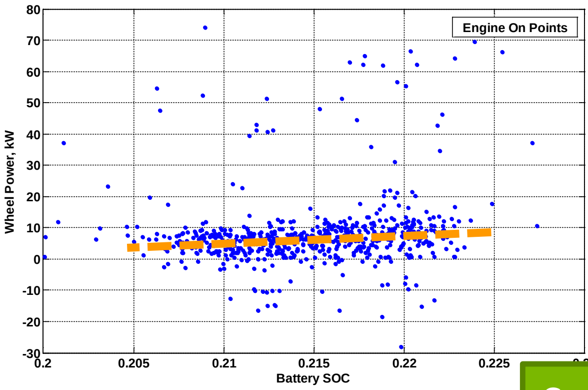
Outline

- 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

GM Volt 2012

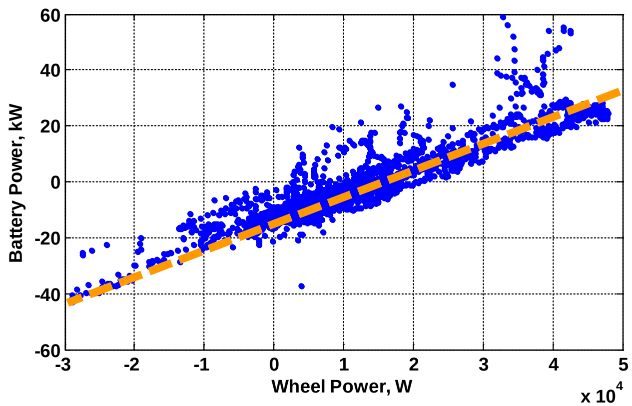
Test Data Analysis for Control Model
- Energy management strategy analysis

- SOC balancing during charge sustaining



Strategy 1.

SOC is too low → Engine is turned on at low power (→HEV mode)

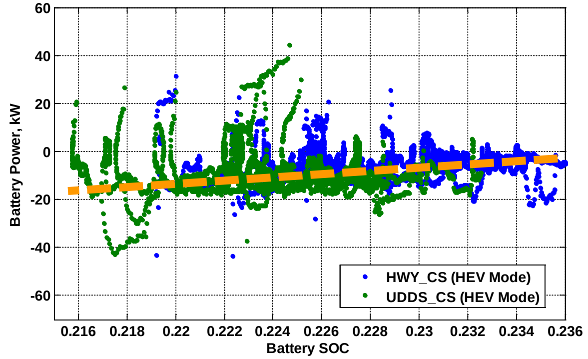


Strategy 2.

Compute battery power demand as a function of wheel power demand

Strategy 3.

In normal level, compute battery power demand for SOC regulation

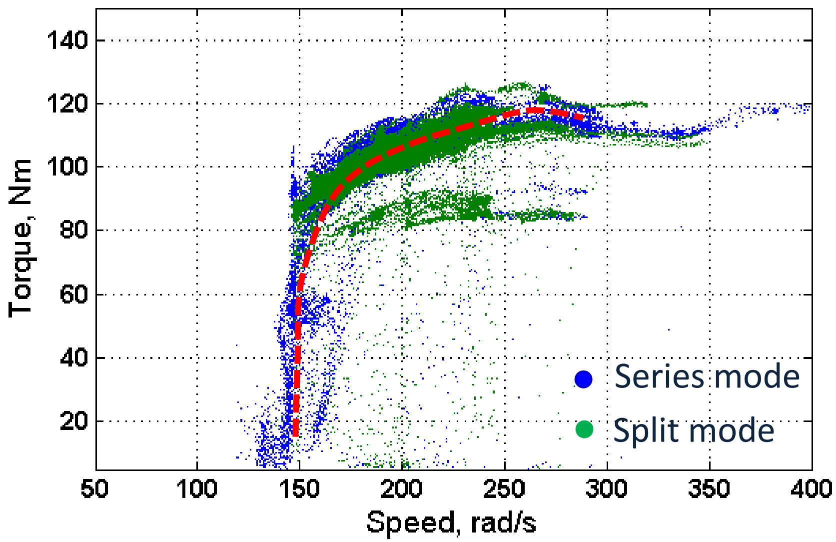


Test Data Analysis for Control Model

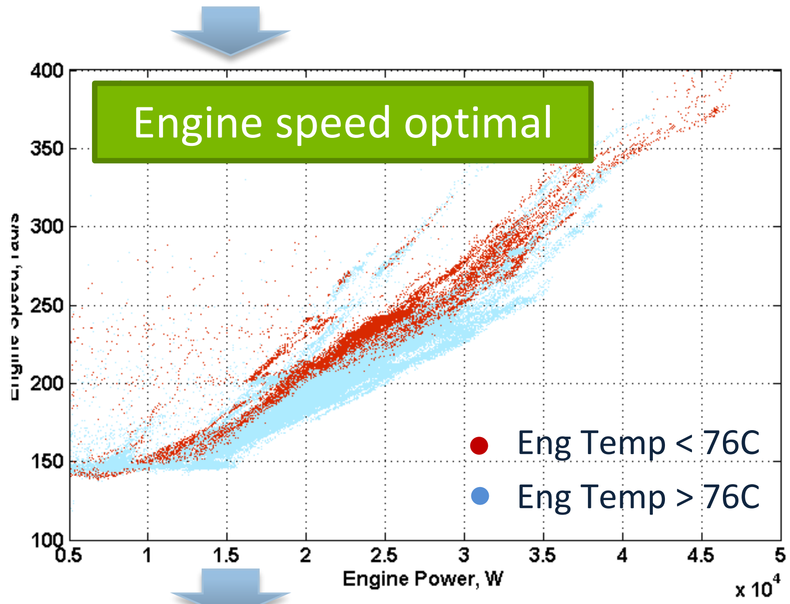
- Engine operating target analysis

- Engine operating target from all tests.

From all tests



Engine power demand

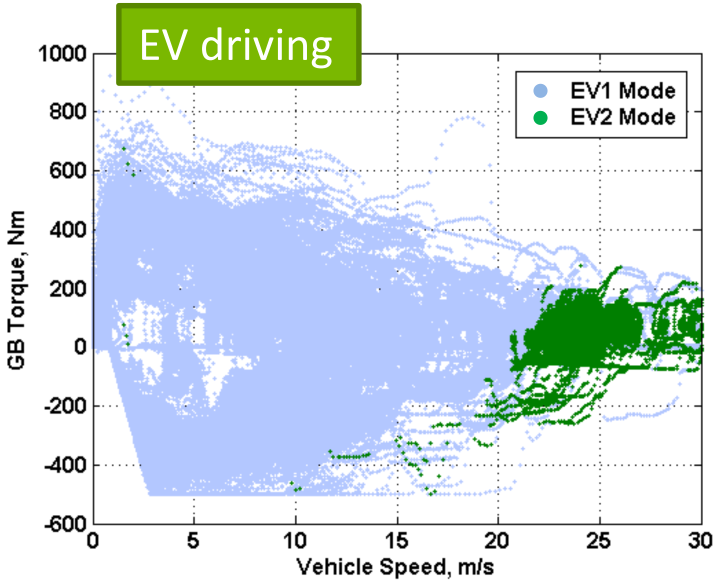


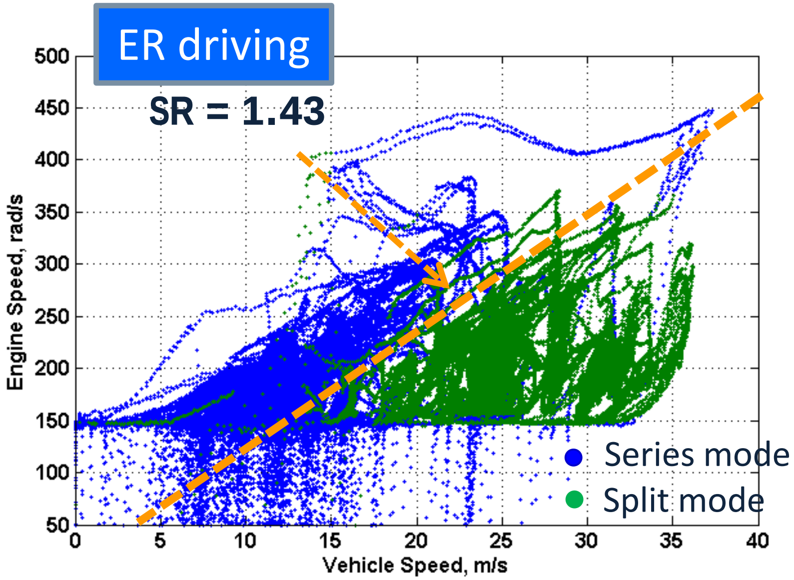
Engine torque desired

Test Data Analysis for Control Model

- Transmission operation modes

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





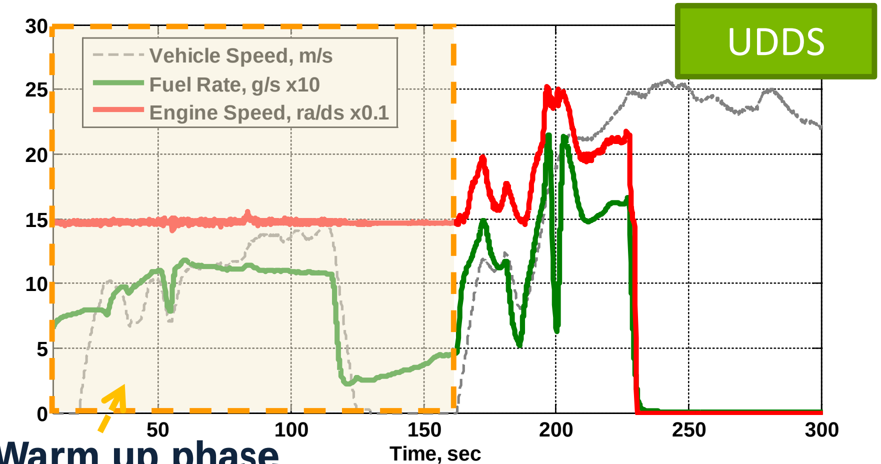
After we convert ER driving results into new map by using vehicle speed and engine speed indexes, the mode selection rule can be defined based on the speed ratio

(Note that GB is the gearbox)

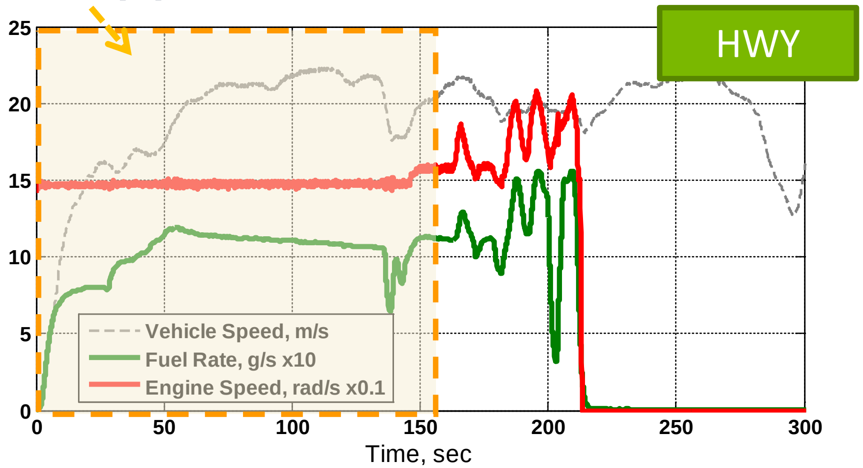
Test Data Analysis for Control Model

- Engine warm up strategy (-6.7 ℃)

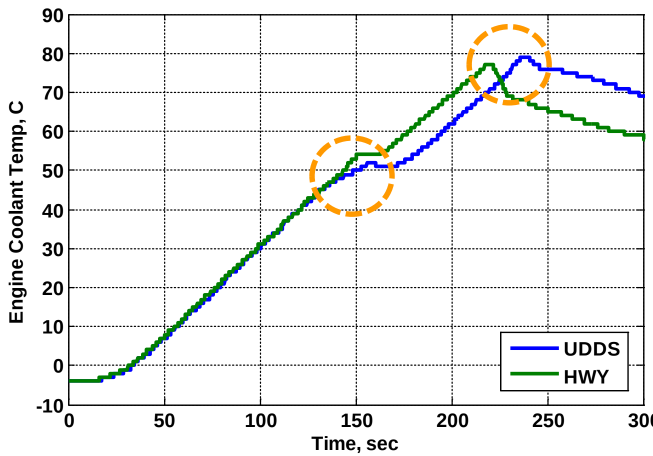
- Constant speed and constant power for 150 seconds used to warm-up battery and heat on under cold conditions (@ high SOC)



Warm up phase

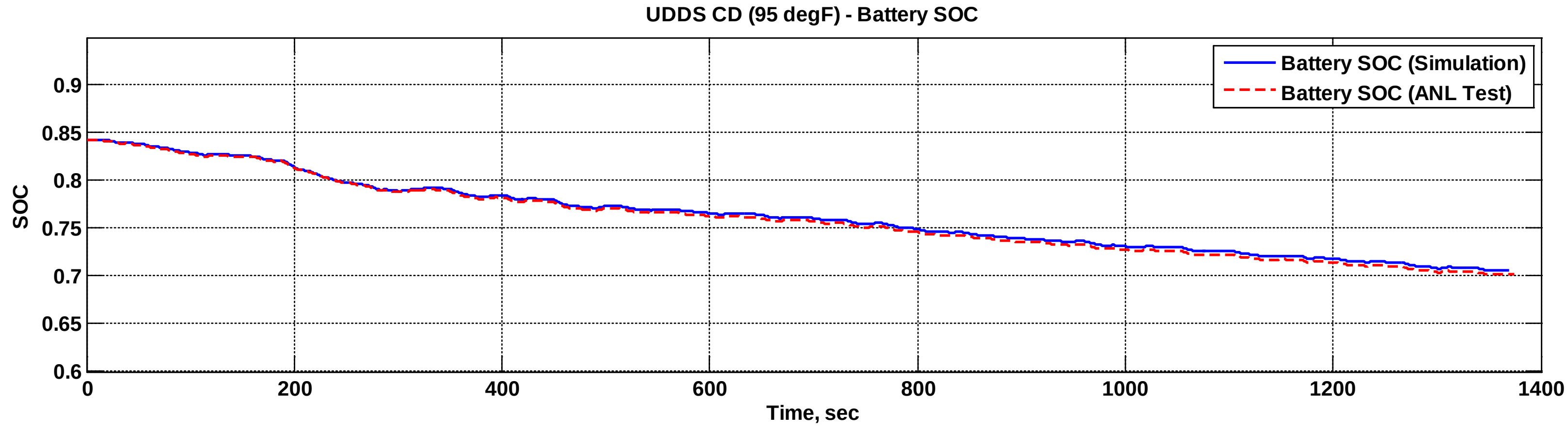


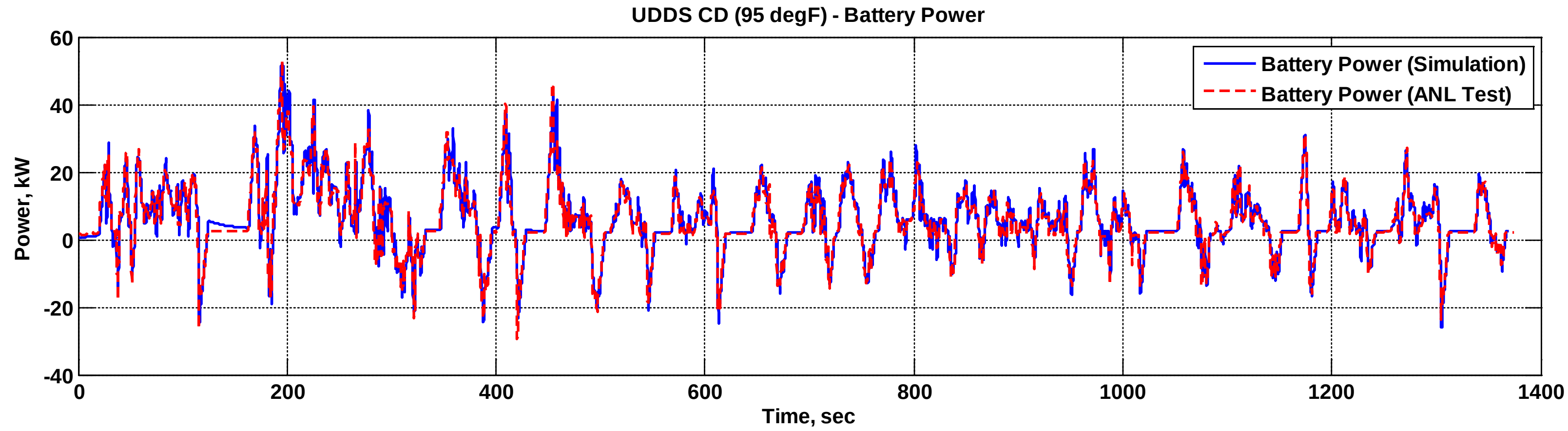
Warm up strategy
- 1450 rpm
- 1.1 g/s fuel
- 150 seconds to reach 50C of engine temp



Model Validation in Autonomie
- urban driving schedule (EV) : 35 ℃

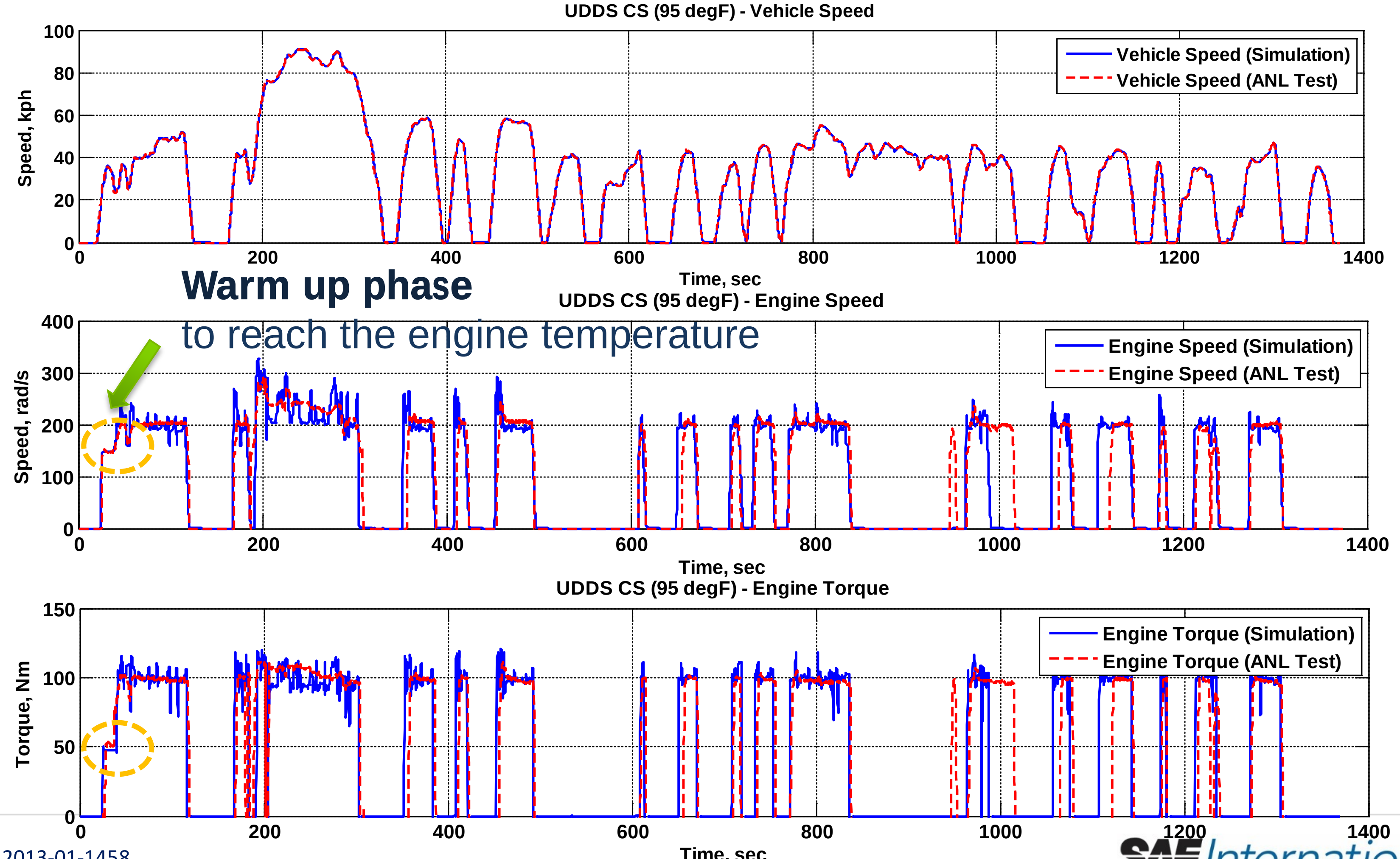
- Battery SOC & power





Model Validation in Autonomie
- urban driving schedule (ER) : 35 ℃

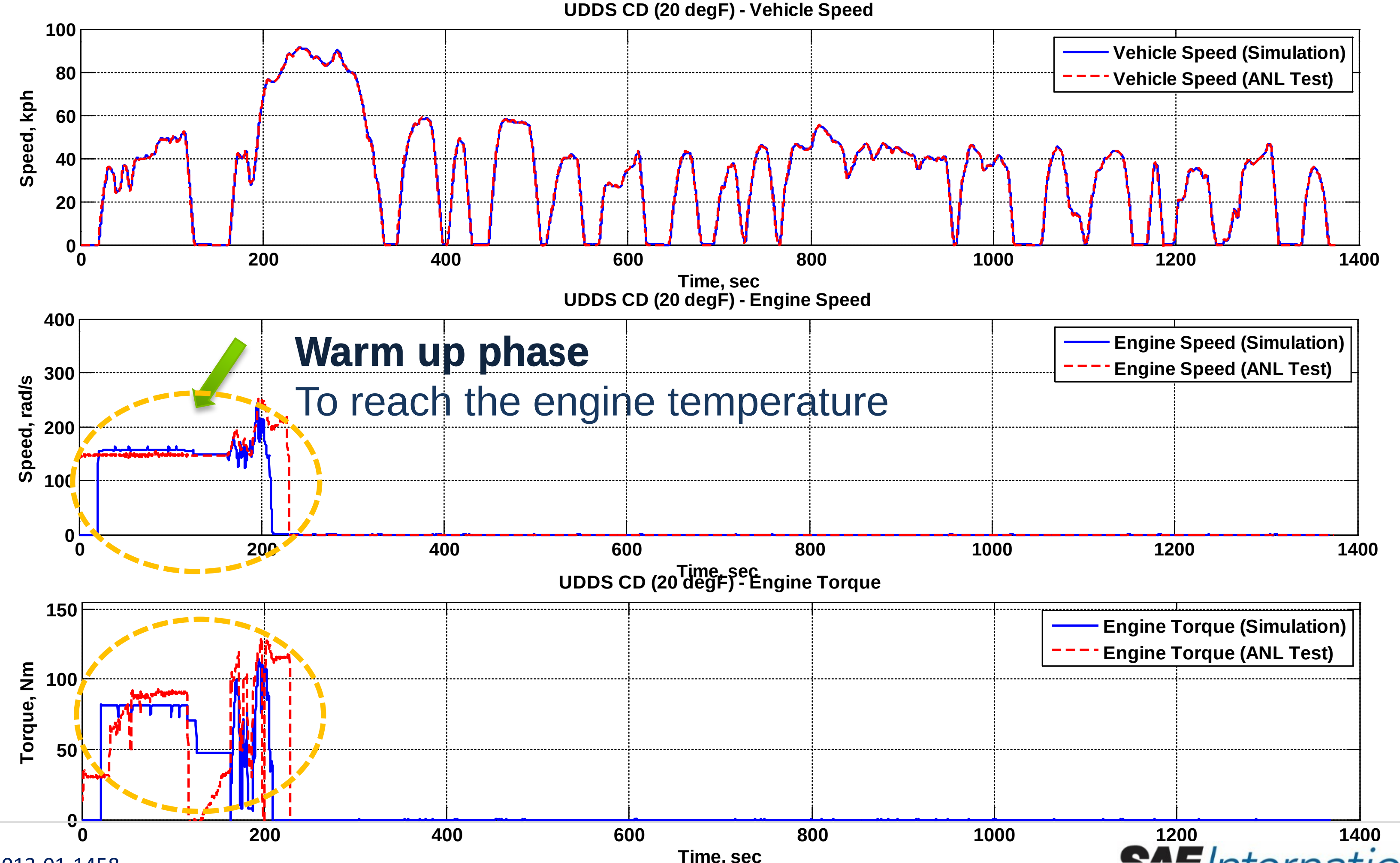
- Engine speed & torque



Model Validation in Autonomie

- urban driving schedule (EV) : -6.7 ℃

- Engine speed & torque



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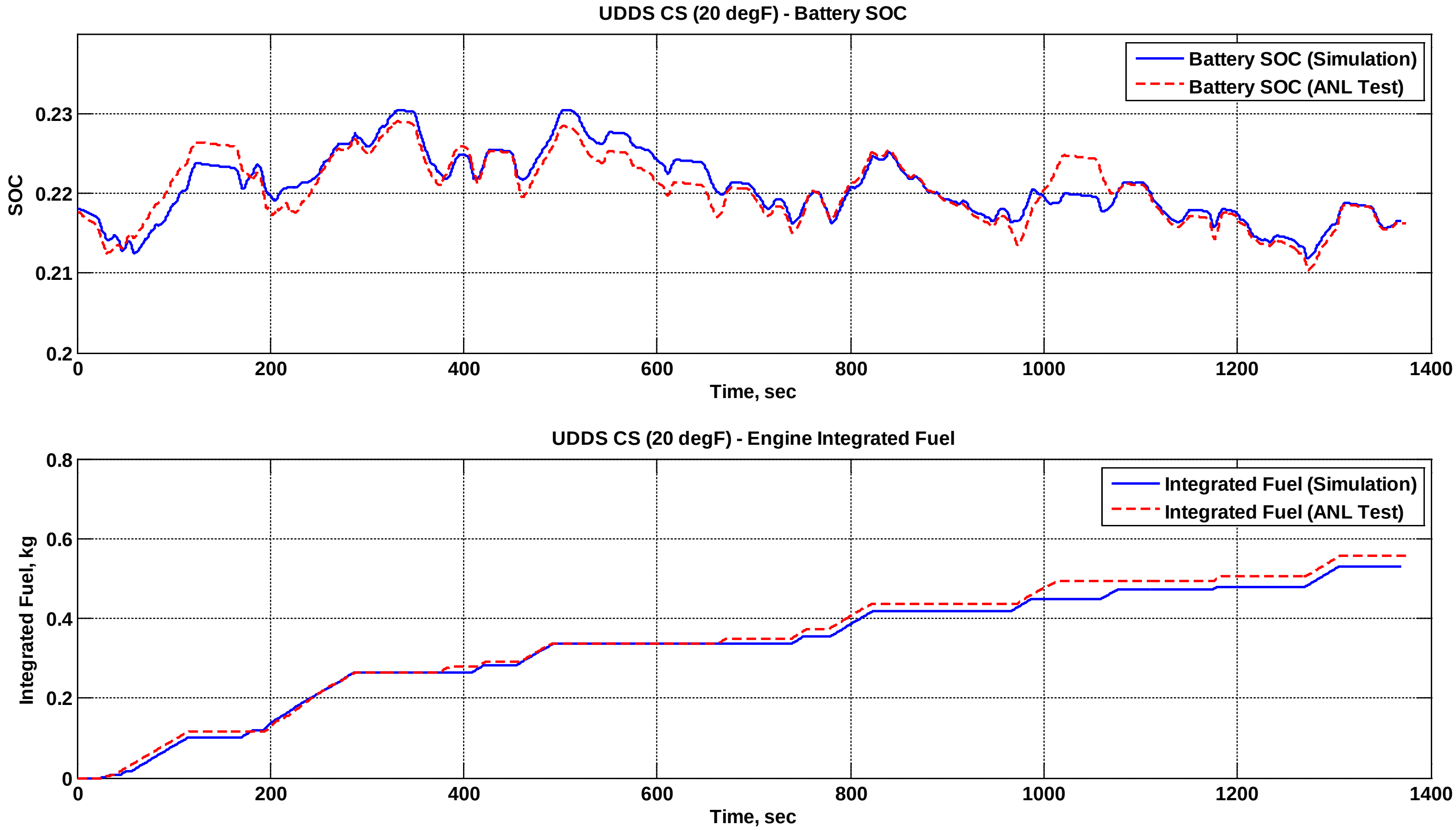
SAE International

Model Validation in Autonomie
- urban driving schedule (ER) : -6.7 ℃

- Battery SOC, engine fuel



Model Validation in Autonomie
- summary (Urban driving schedule)

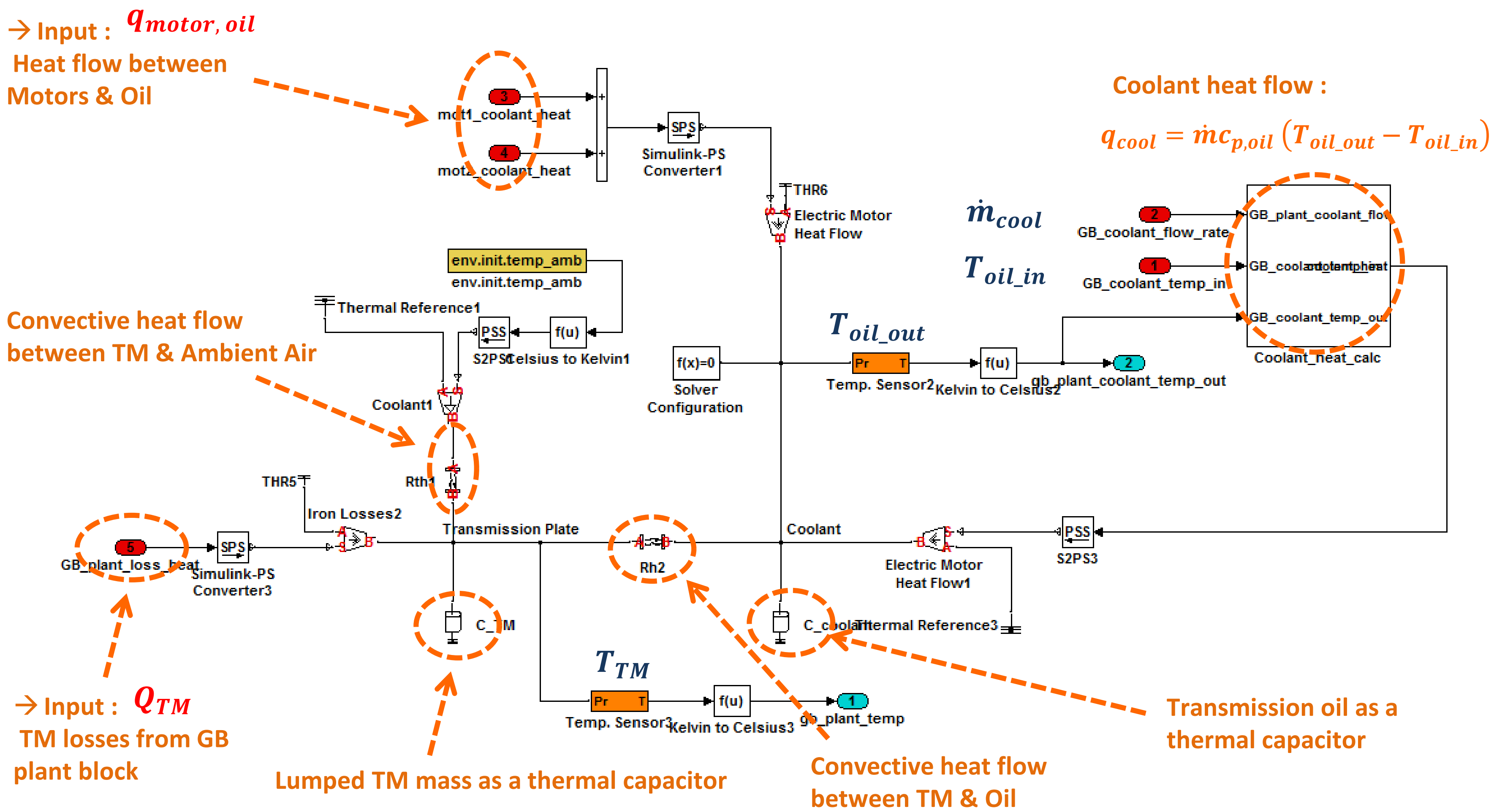
Conditions	Battery Electric consumption (Wh/mi)	
	Test	Simulation
EV(CD) : 22.2 ℃	214.3	201.9 (- 5.7 %)
EV(CD) : 35 ℃ (A/C on)	302.3	312.3 (+ 3.3 %)
EV(CD) : 35 ℃ (A/C off)	203.3	195.4 (- 3.9 %)
EV(CD) : -6.7 ℃ (Heater on)	416.2	414.1 (- 0.5 %)

Conditions	Fuel Consumption (kg)	
	Test	Simulation
ER(CS) : 22.2 ℃	0.454	0.435 (- 4.2 %)
ER(CS) : 35 ℃ (A/C on)	0.758	0.772 (+ 1.8 %)
ER(CS) : -6.7 ℃ (Heater on)	0.555	0.529 (- 4.8 %)

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

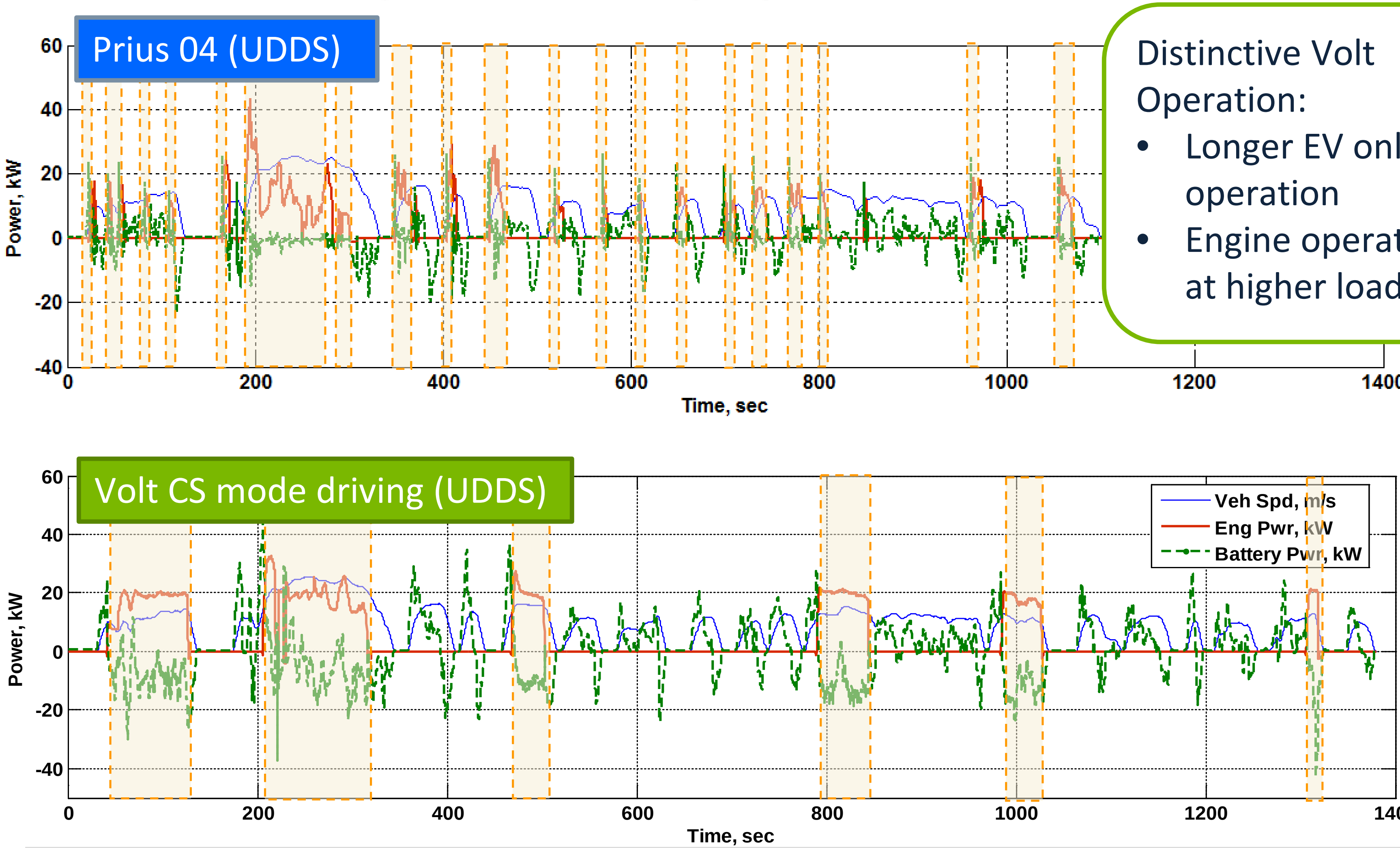
Transmission Thermal Management System

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



Test Data Analysis for Control Model

- Charge sustaining operation on Hot UDDS

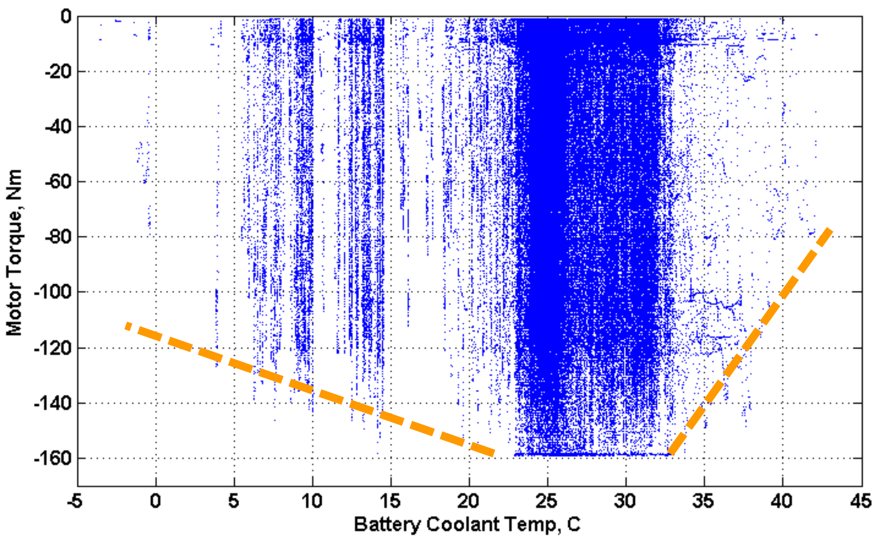


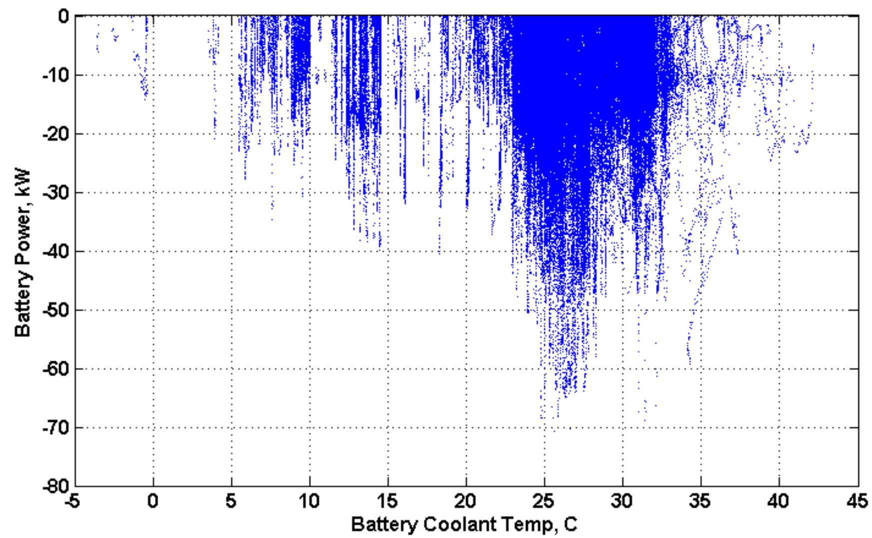
Distinctive Volt Operation:

- Longer EV only operation
- Engine operates at higher loads

Test Data Analysis for Control Model
- motor operating on regeneration mode

- Motor operating as a function of coolant temp.





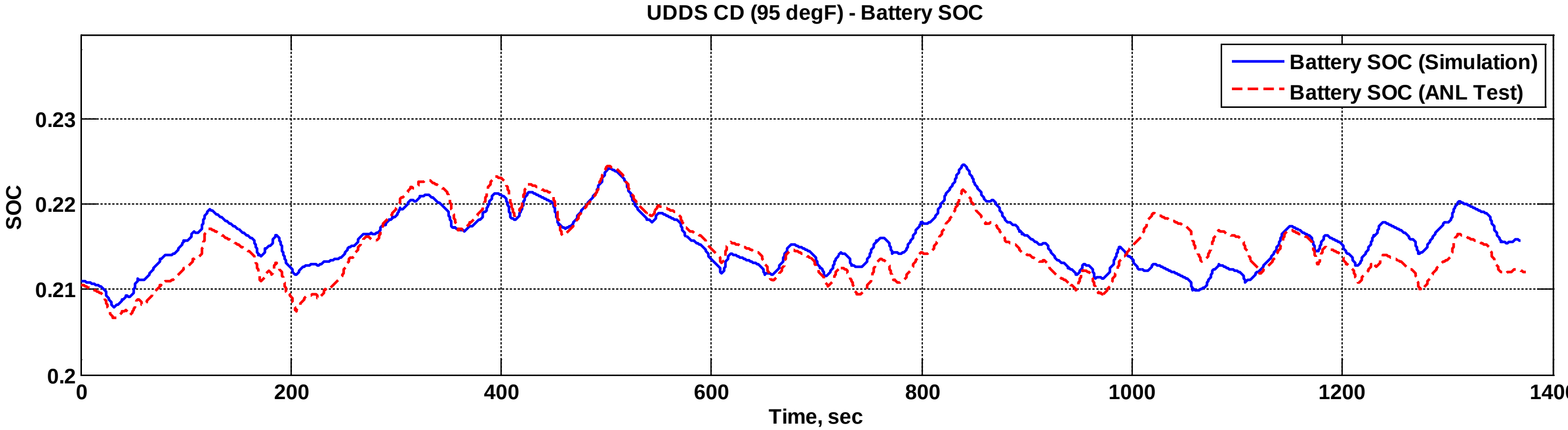
Current limit
on low/high temperature

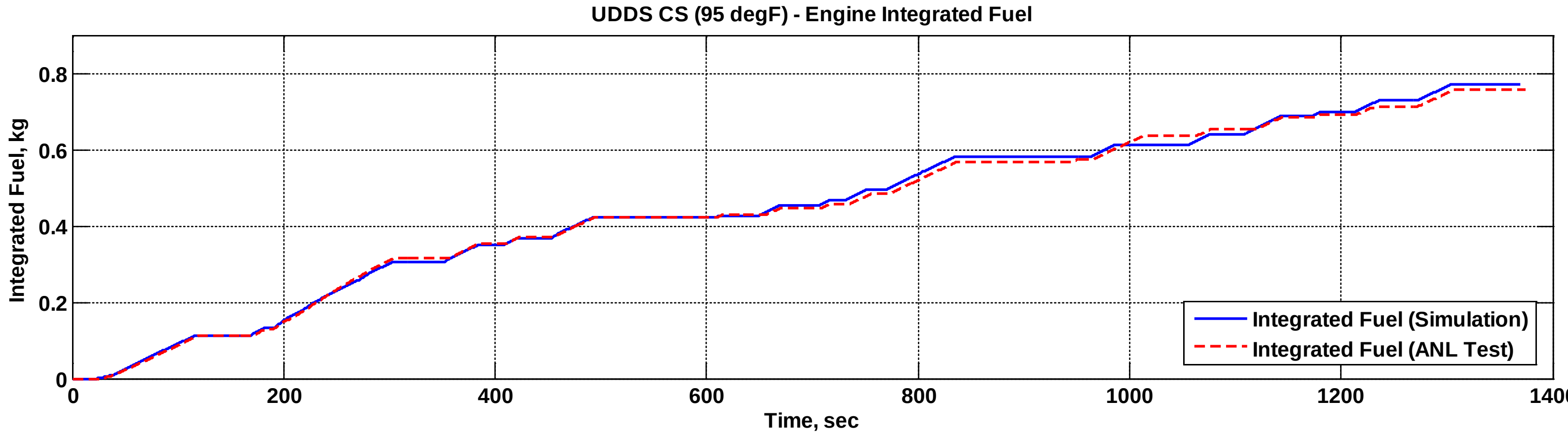
Battery maximum
regenerative power ~ 70kW

Model Validation in Autonomie

- urban driving schedule (ER) : 35 ℃

- Battery SOC, engine fuel

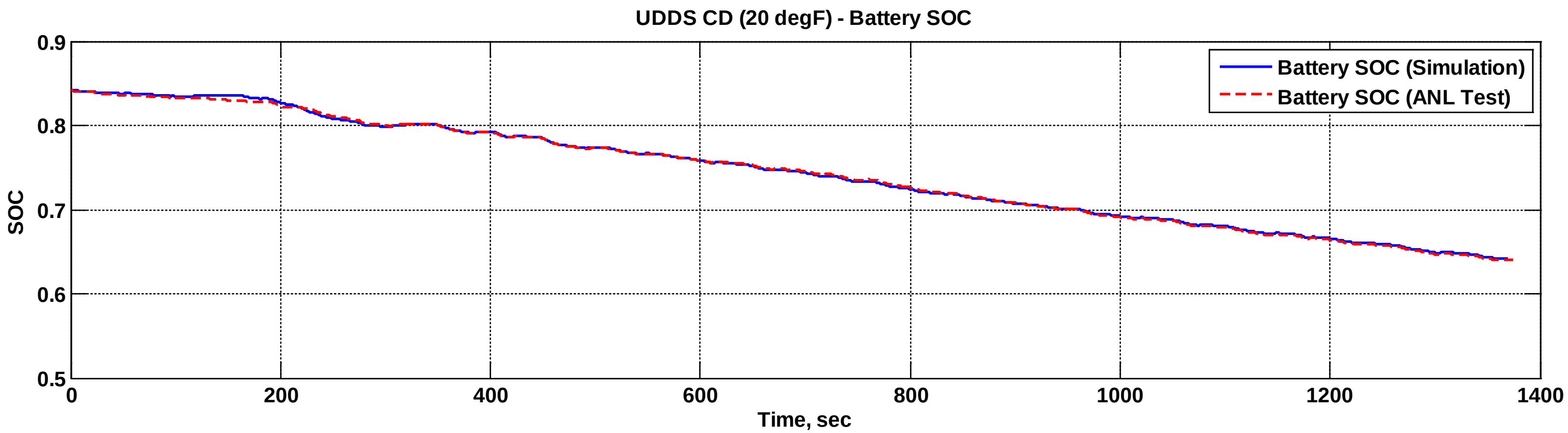


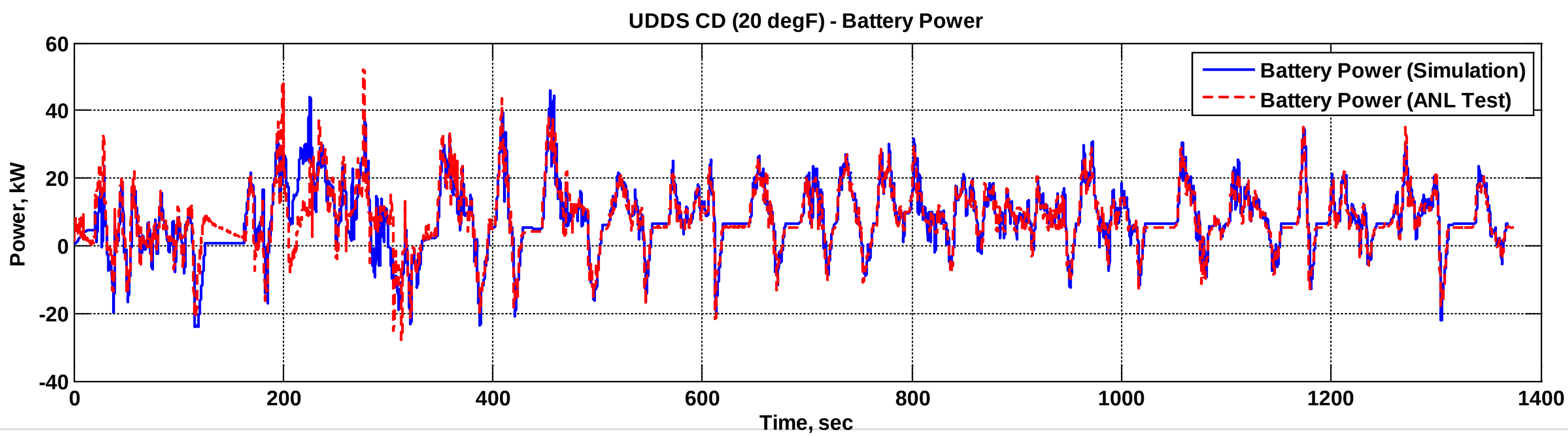


Model Validation in Autonomie

- urban driving schedule (EV) : -6.7 ℃

- 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

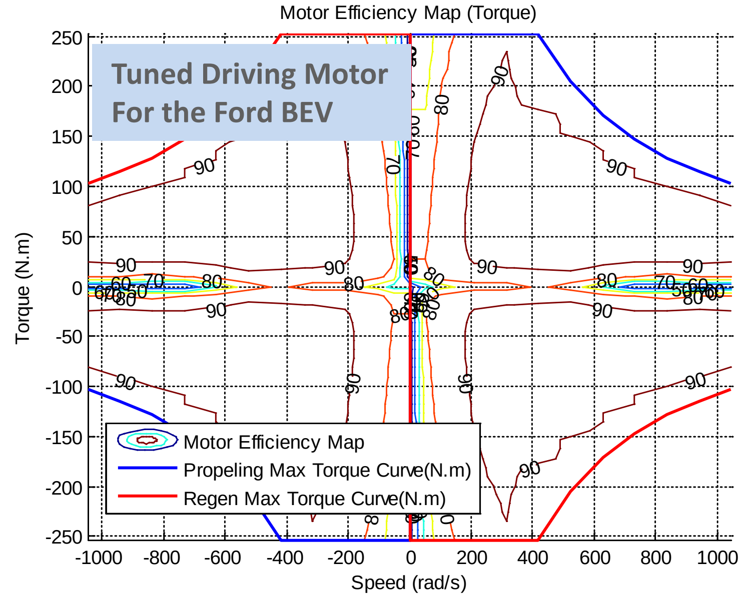
Ford Focus BEV

Import Test Data into Autonomie

Assumption to Calculate Additional Signals

Vehicle Specifications

Parameters	Value
Tire radius	0.321 m
Final drive ratio	7.82
Final drive efficiency	97.5%
Torque coupler ratio	1:1
Torque coupler efficiency	98%
Vehicle mass	1700 kg
Frontal Area	2.42 m^2
Drag coefficient	0.26
Driving motor power/torque	107 kW/250 N-m
Battery pack capacity	23 kWh



	Nissan Leaf (Public) Li-ion	Ford BEV (Assumption) Li-ion
Total cell #	192	430
cell # per module	4	86
cell V (max)	3.8 (4.2)	3.8 (4.2)
cell Ah	33.1	13
module #	48	5
module series #	24	1
module parallel #	2	5
module V (max)	15.2	326 (361)
module Ah	33.1	13
pack V	364.8	326 (361)
pack Ah	66.2	65
pack kWh	24.1	23.4
Max Current [A]	264.8	305.5
Max Power [W]	96599.04	110346.6

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

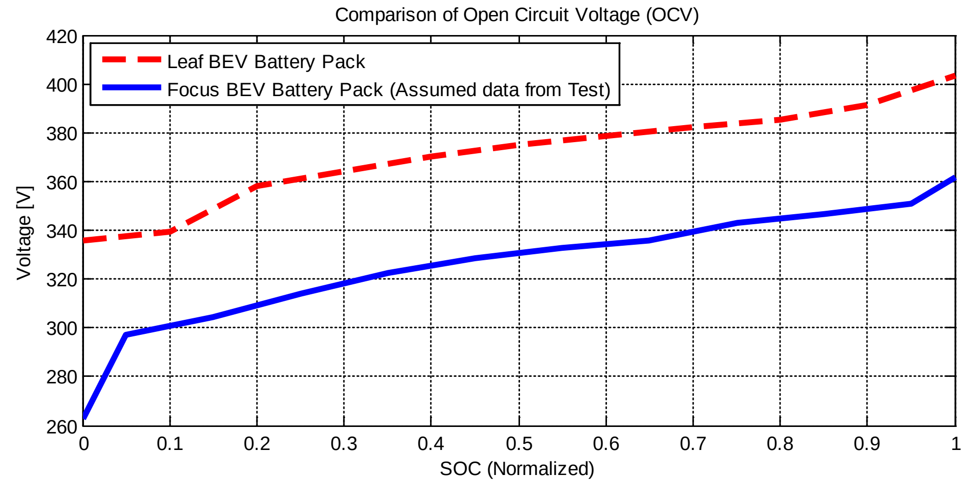
- ✓ 1 speed gear ratio (FD ratio)

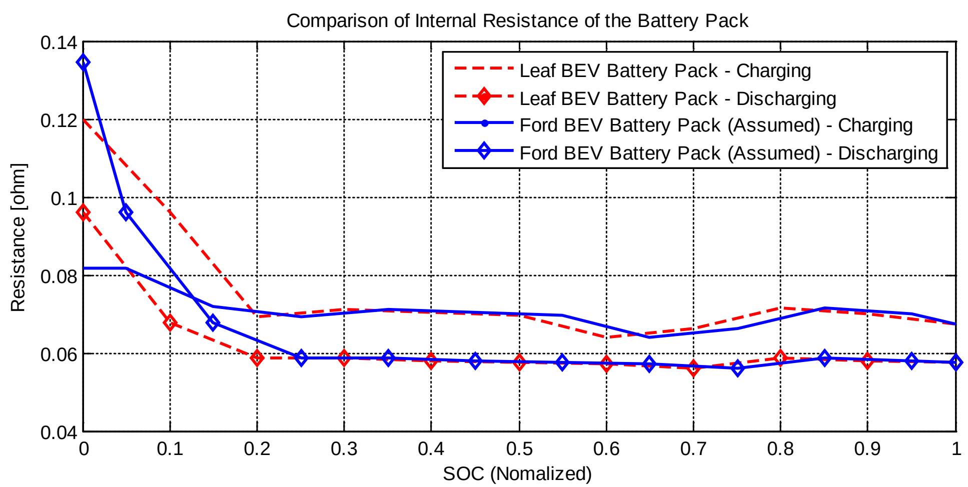
Import Test Data into Autonomie

Battery Performance Estimation

Battery Model :
Internal Resistance Model

$$V_{out} = V_{ocv} - I_{out} \times R_{int}$$



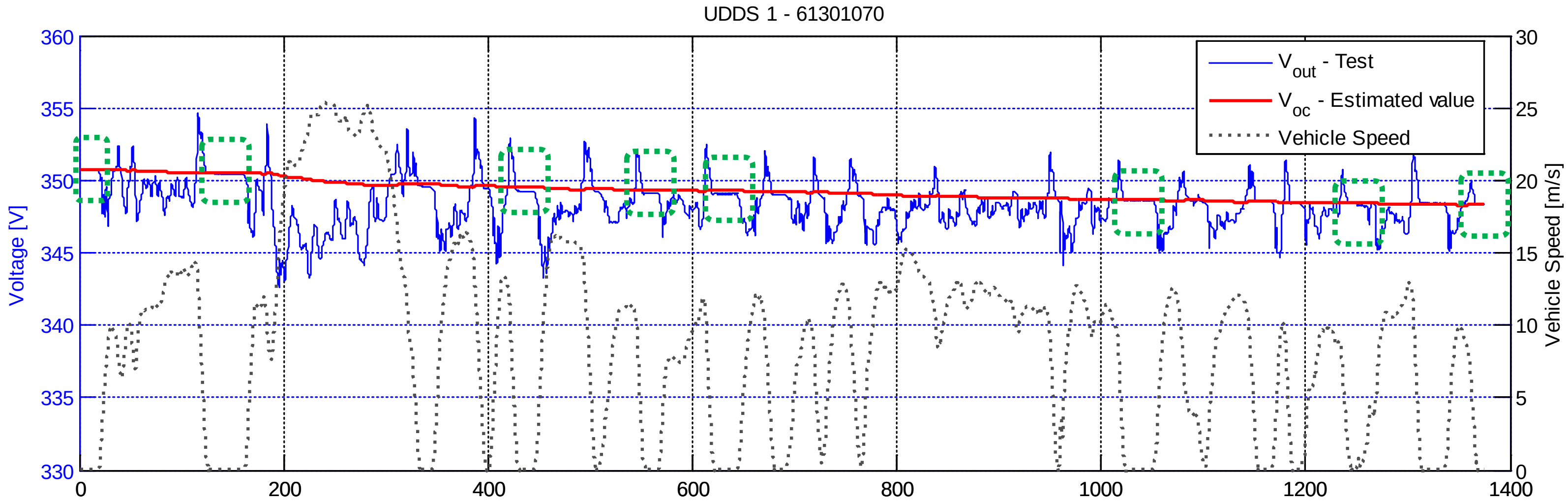


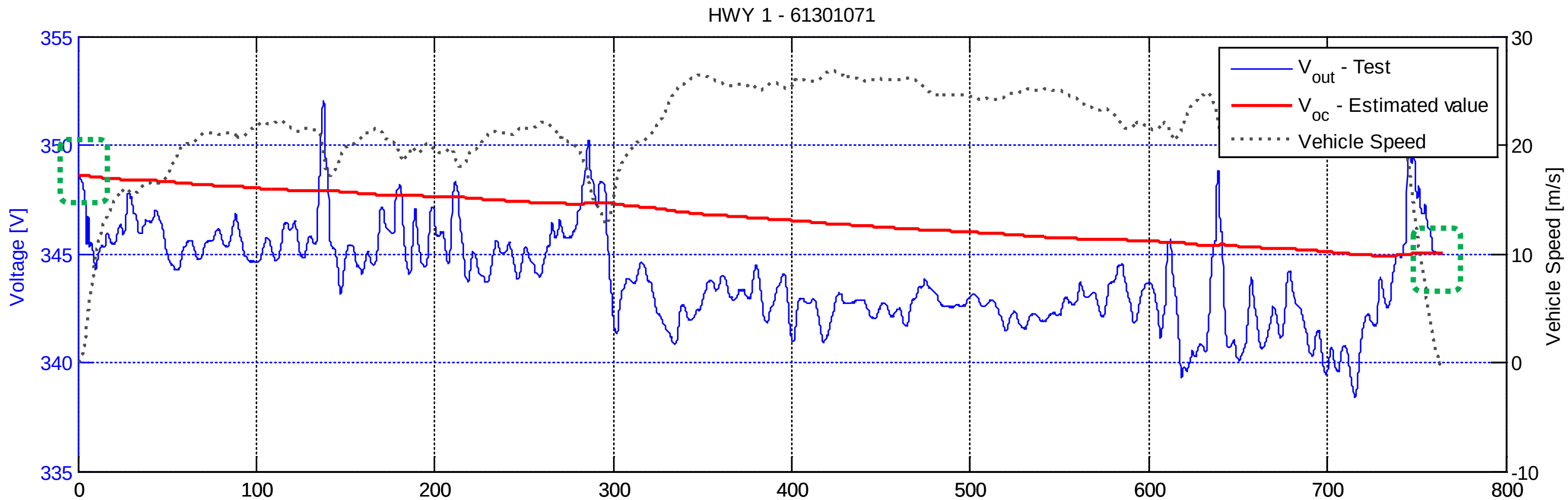
To calculate V_{out} , the battery model needs V_{ocv} and R_{int} as the initialization data. Therefore, we have newly developed the characteristic data based on the test results of the Ford BEV, and by modifying the original Leaf battery data.

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

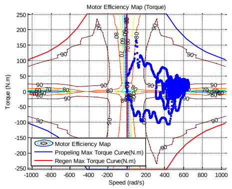
Results of Estimated OCV from MCT Data





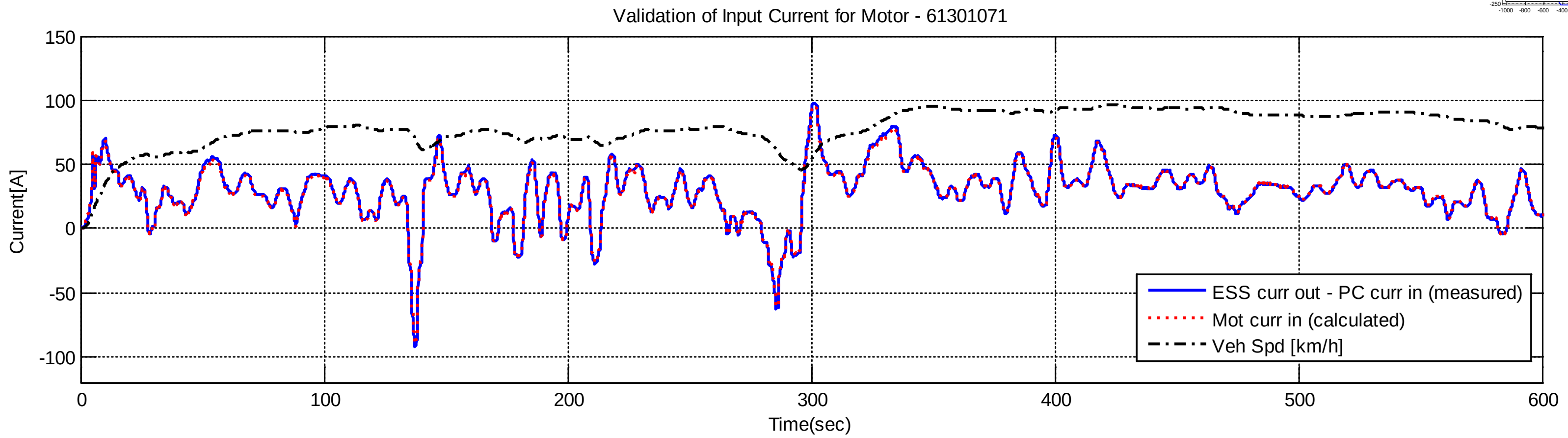
Verification of Estimated Signals

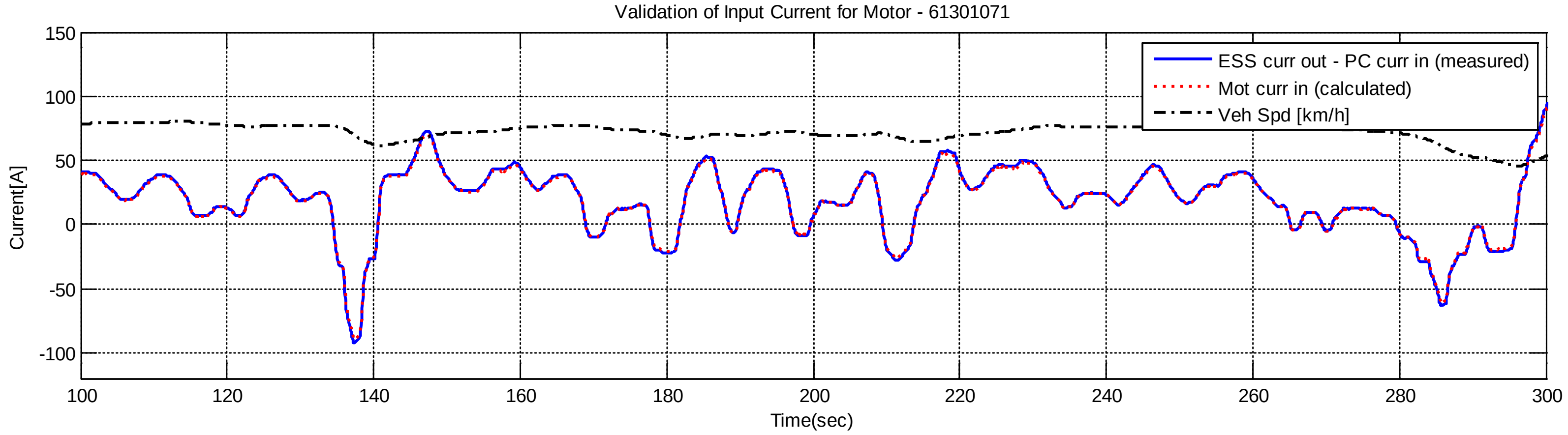
Comparison between Test Data and Calculated Signals



Verification of Electric Current Input to the Driving Motor

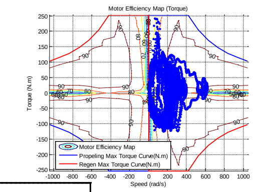
- ✓ 61301071_HWY





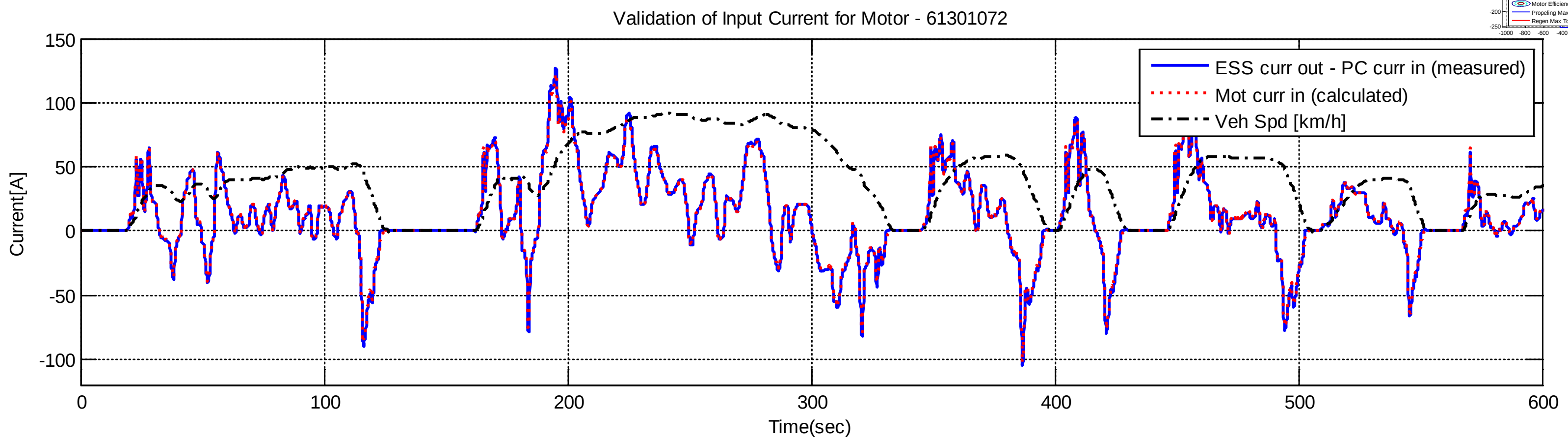
Verification of Estimated Signals

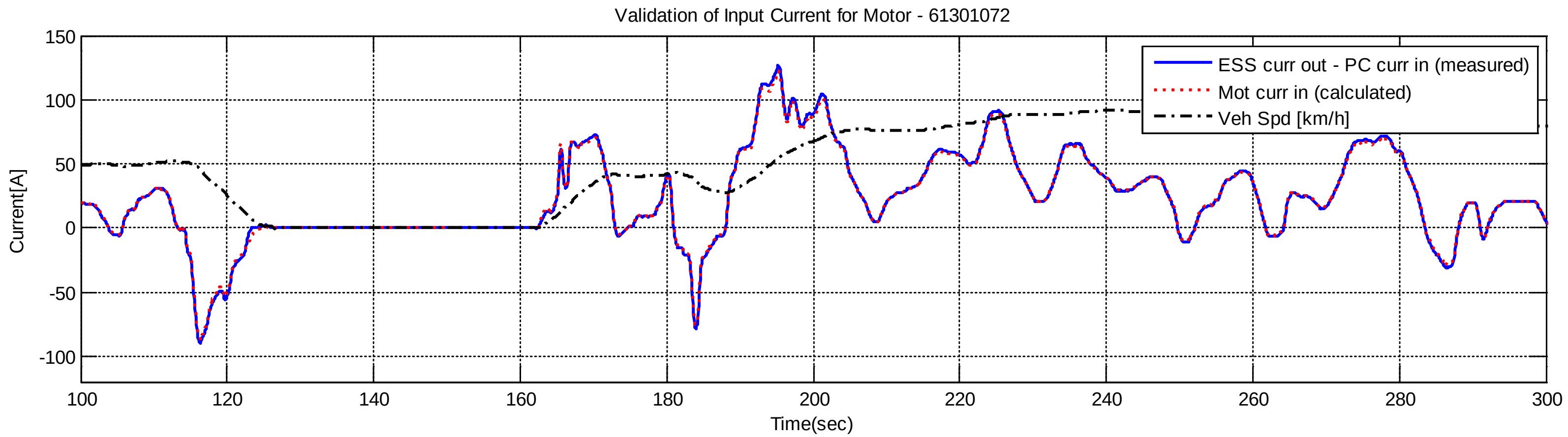
Comparison between Test Data and Calculated Signals



Verification of Electric Current Input to the Driving Motor

✓ 61301072_UDDS





Verification Conclusion:

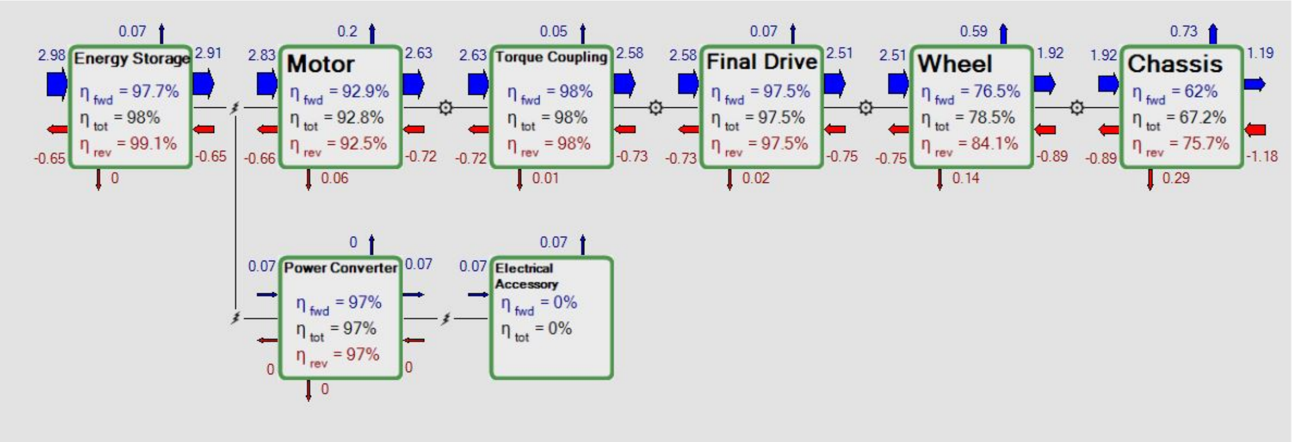
Compared signals between measured data and calculated value show good coincident result.
Therefore, we can think that the Ford motor map data developed is reasonable and can be applied to a vehicle model.

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



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

‘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.

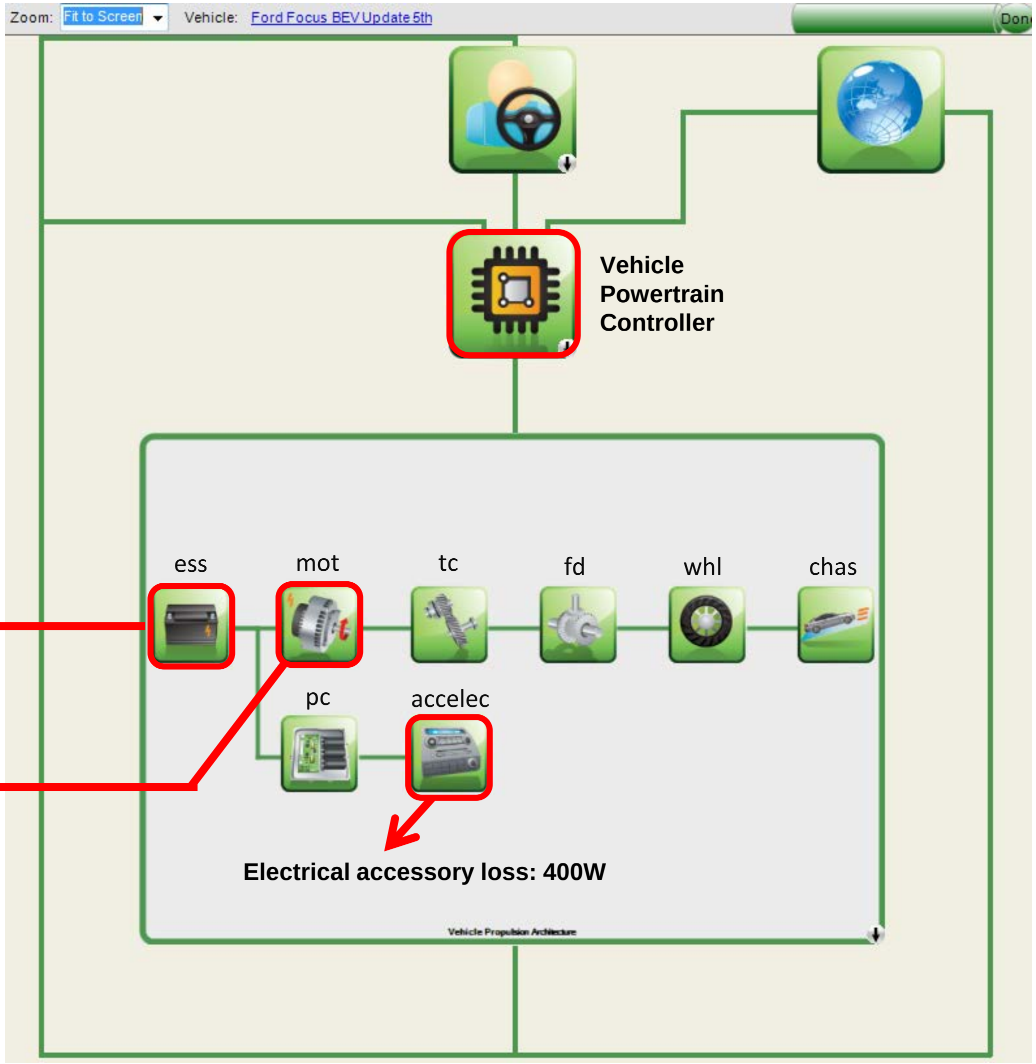
Vehicle Model Development and Validation

Introduction of Vehicle Model in Autonomie

Parameters	Value
Tire radius	0.321 m
Final drive ratio	7.82
Final drive efficiency	97.5%
Torque coupler ratio	1:1
Torque coupler efficiency	98%
Electric accessory loss	400W
Vehicle mass	1700kg
Battery pack capacity	23kWh

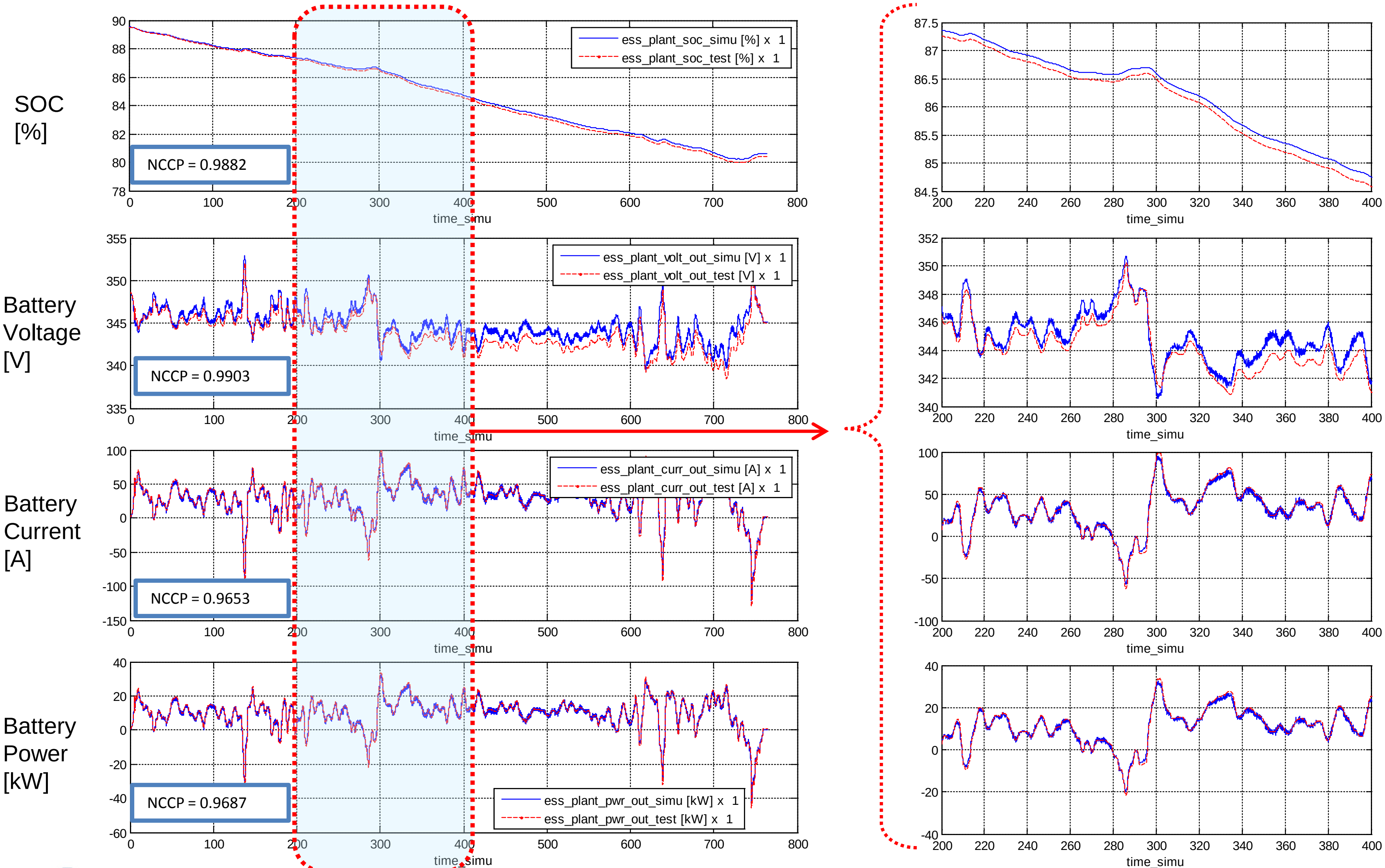
Init file: ess_plant_li_66_430_Ford_Focus_EV.m modified from the Leaf battery data

Init file: mot_plant_pm_53_107_Ford_Focus_EV.m modified from the Leaf motor data



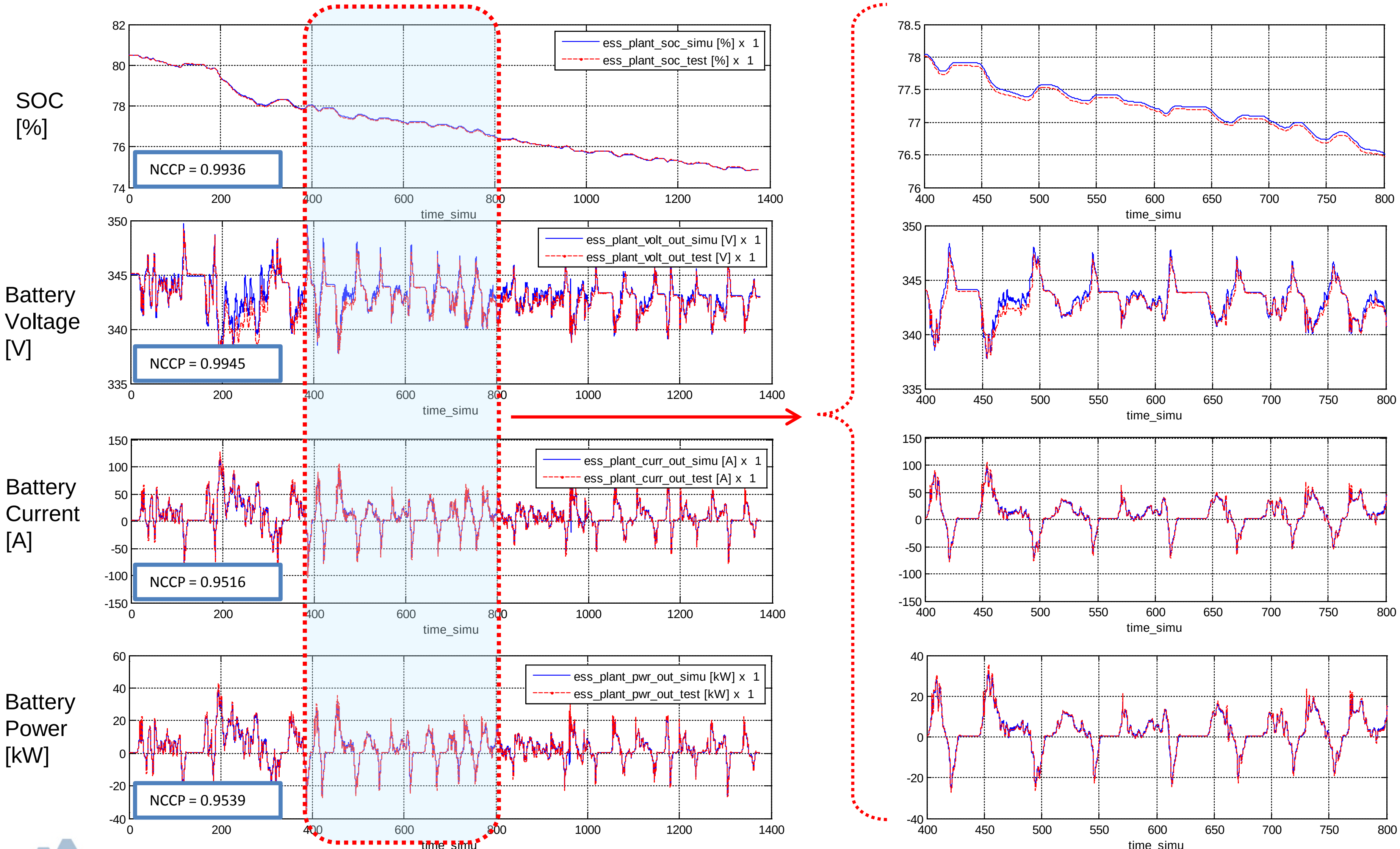
Vehicle Model Development and Validation

Validation Results : HWFET #1 - 61301071



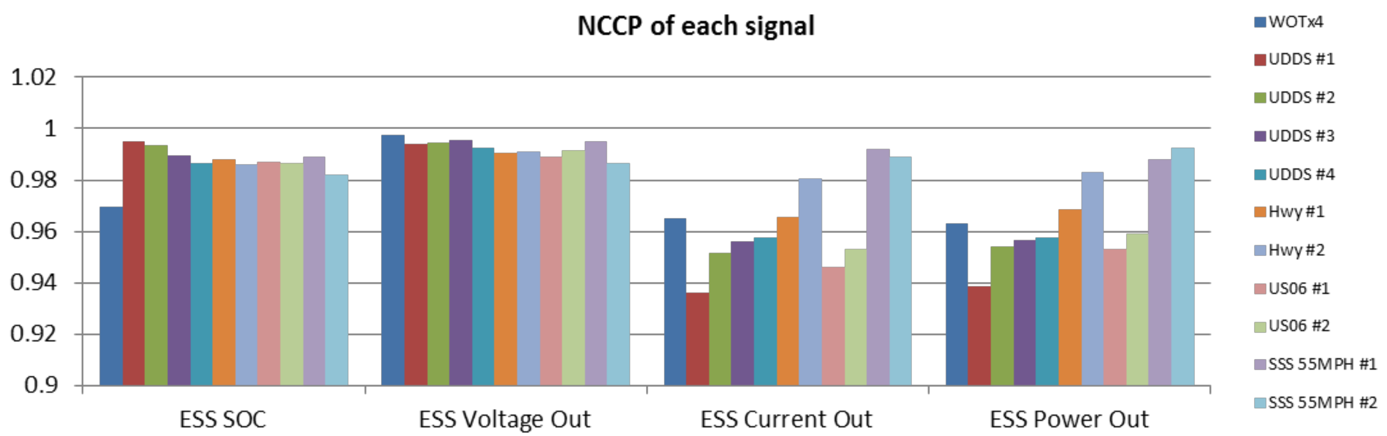
Vehicle Model Development and Validation

Validation Results : UDDS #2 - 61301072



Vehicle Model Development and Validation
Verification Results - NCCP

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



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

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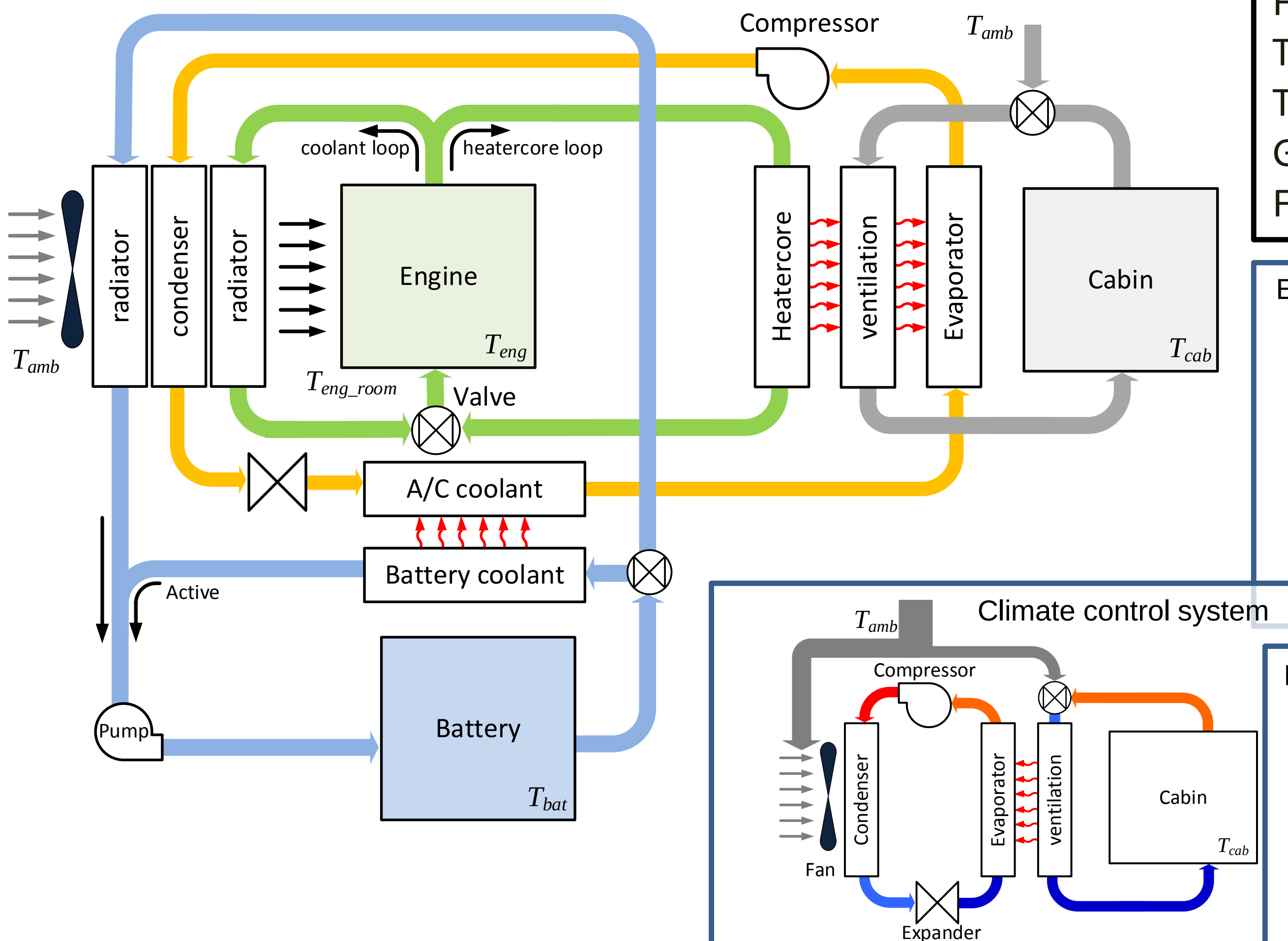
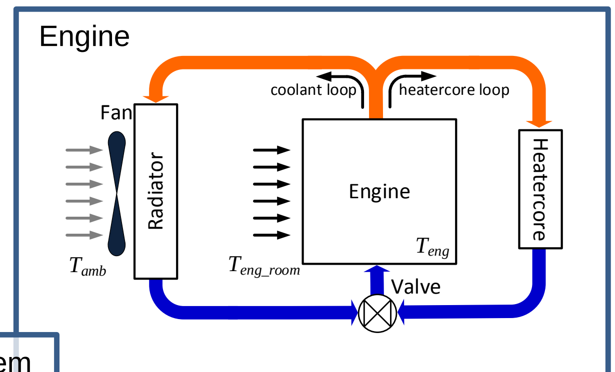
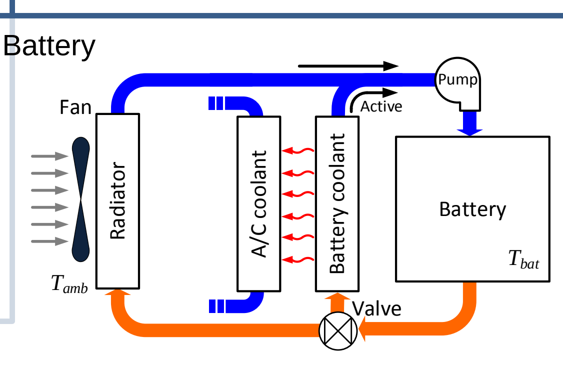
Thermal Models and Controls Developed Over Multiple Years

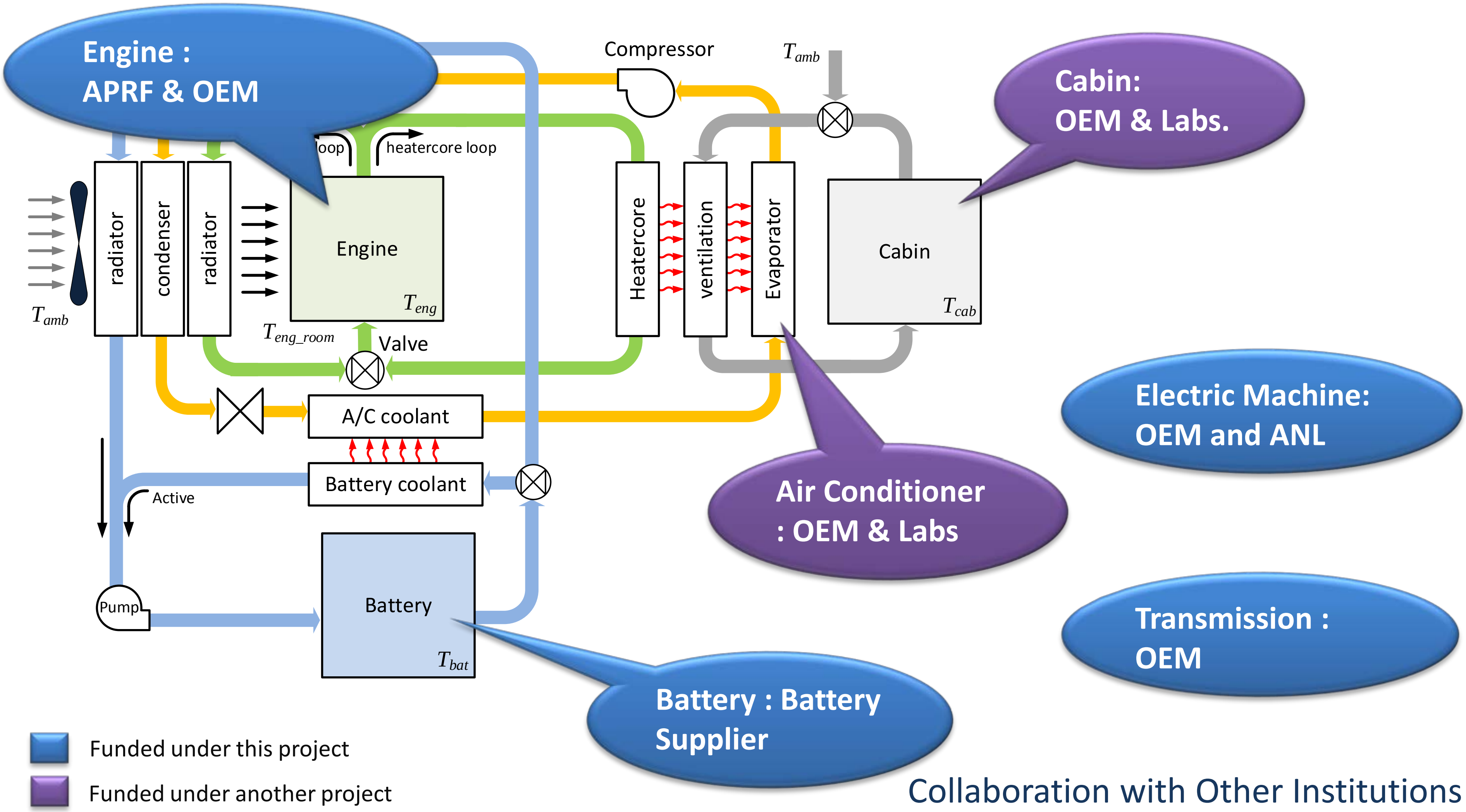


Ford Fusion Conv.
Toyota Prius HEV
Toyota Prius PHEV
GM Volt
Ford Focus BEV





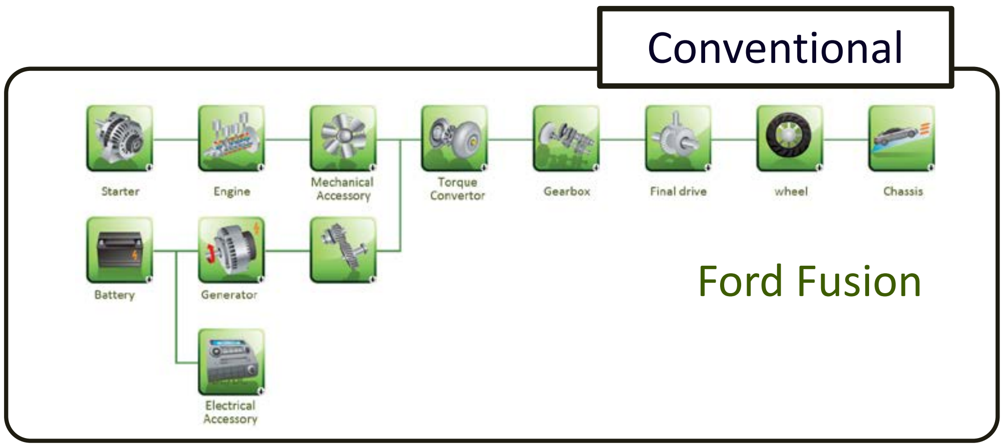
Multi-Entity Collaboration Leveraged

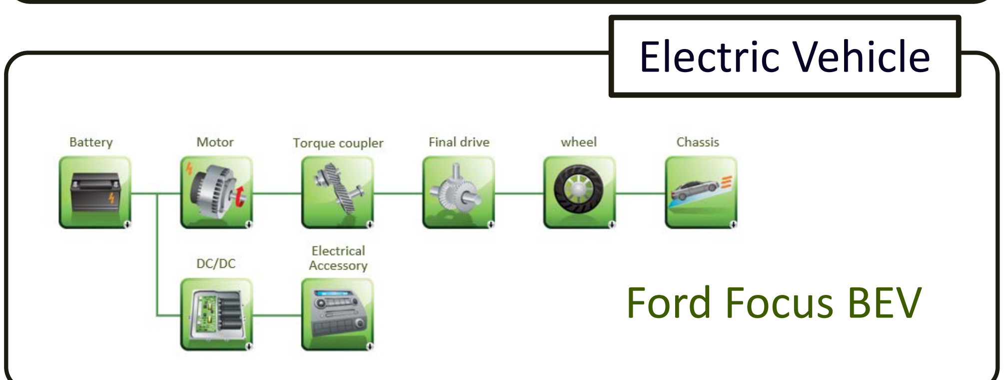


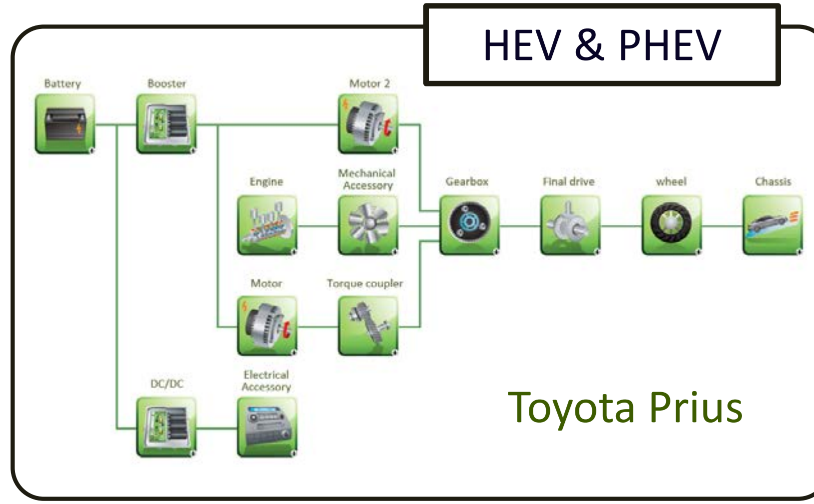
Collaboration with Other Institutions

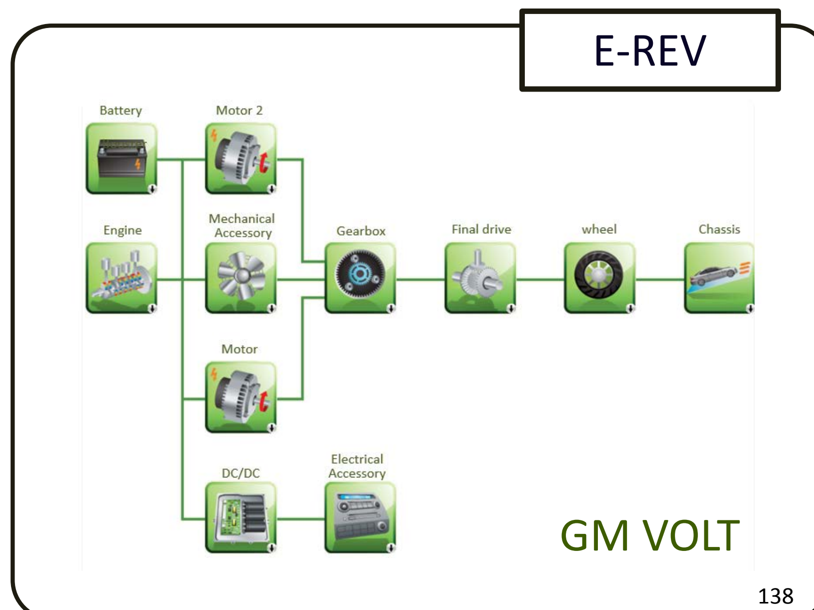
Multiple Powertrain Configurations Considered

- 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**



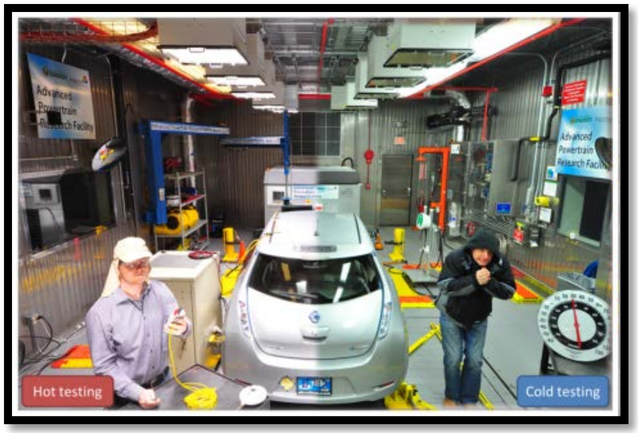






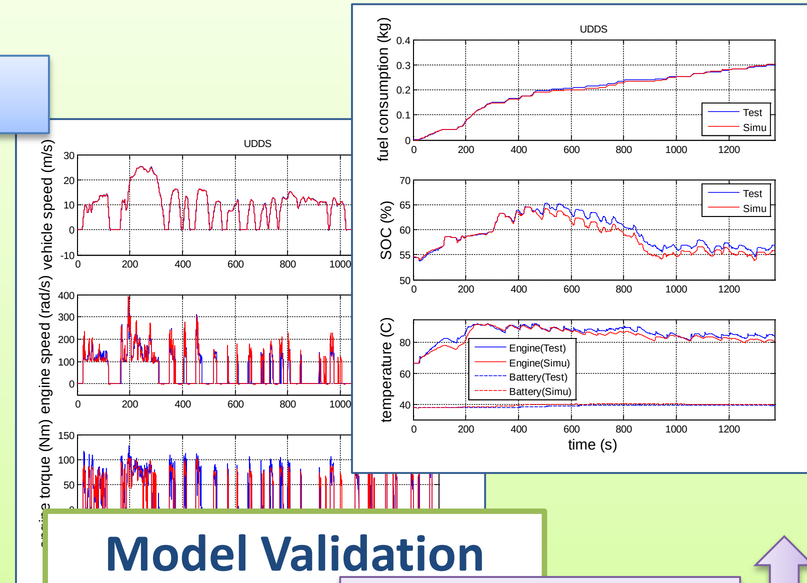
Standard Model Validation Process Developed

Test data from APRF (ANL)



°C
-7
21
35

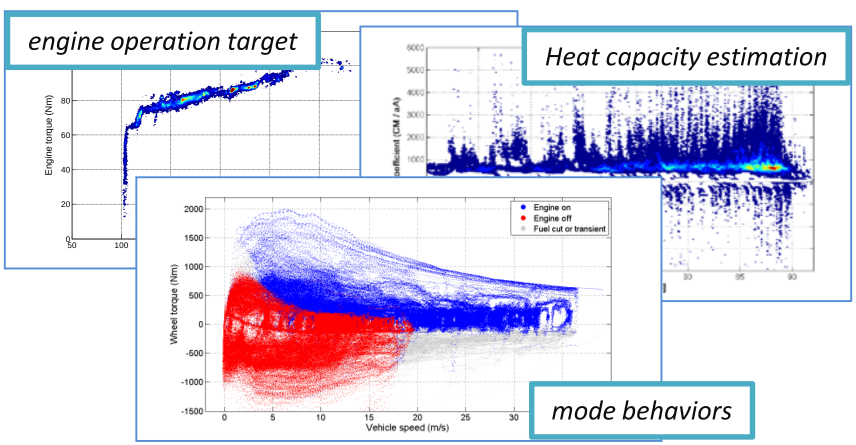
Test data



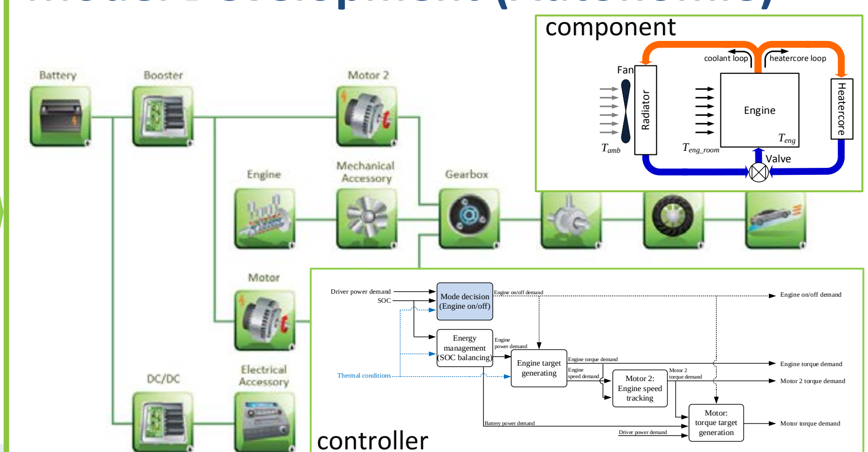
Model Validation

Simulation data

Control and Performance Analysis



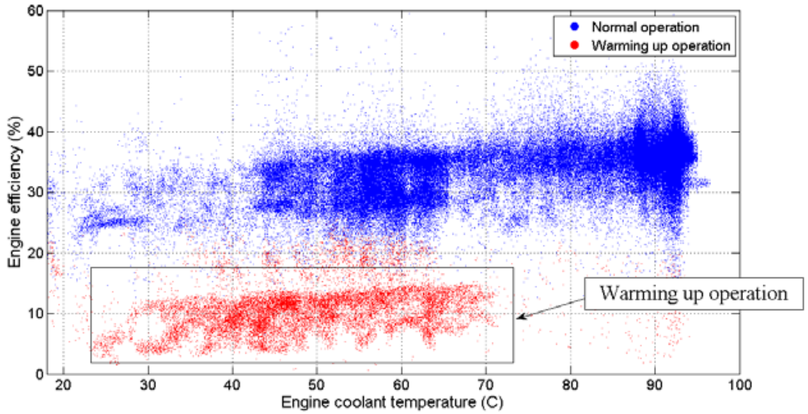
Model Development (Autonomie)

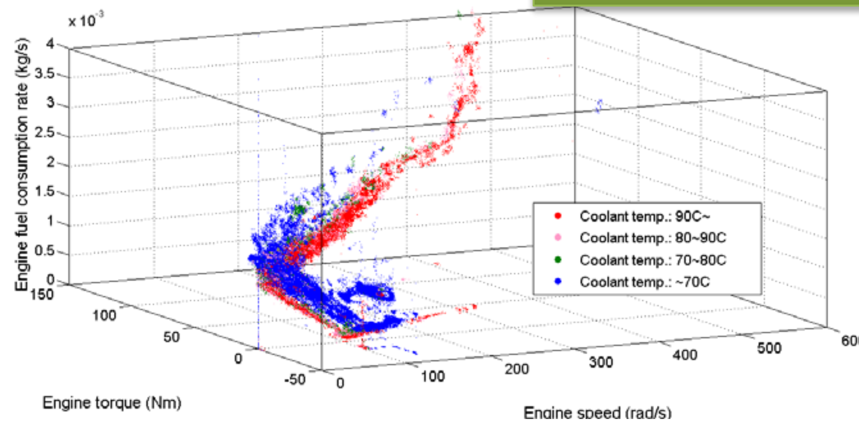


Component Performance Data Developed from Vehicle Testing

Engine performance analysis

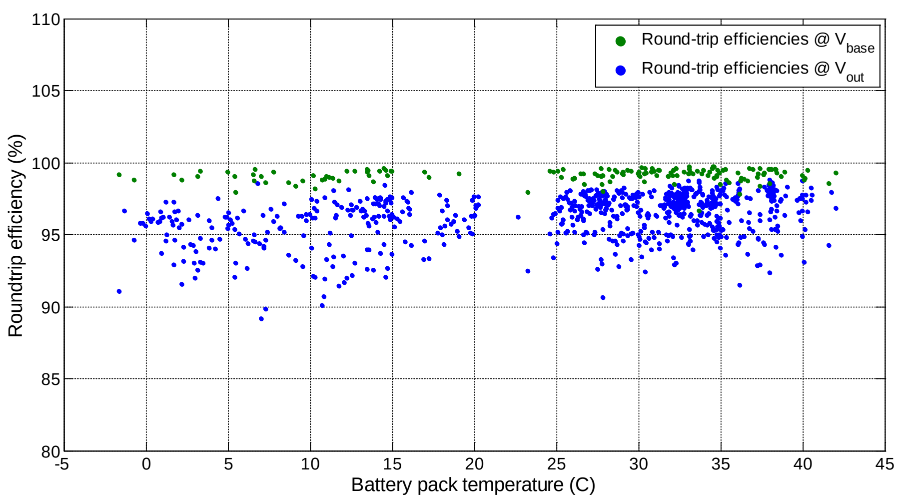
e.g. Prius PHEV

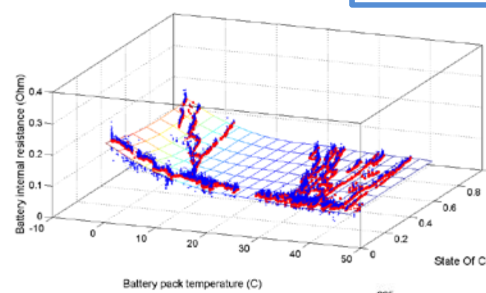


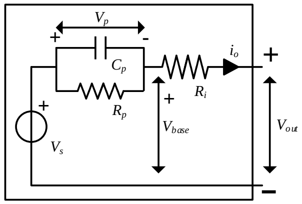


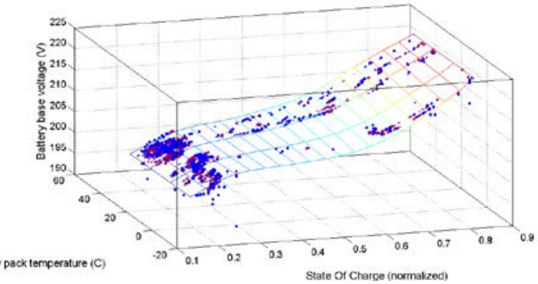
Engine efficiency decreases as the coolant temperature decreases.

Battery performance analysis





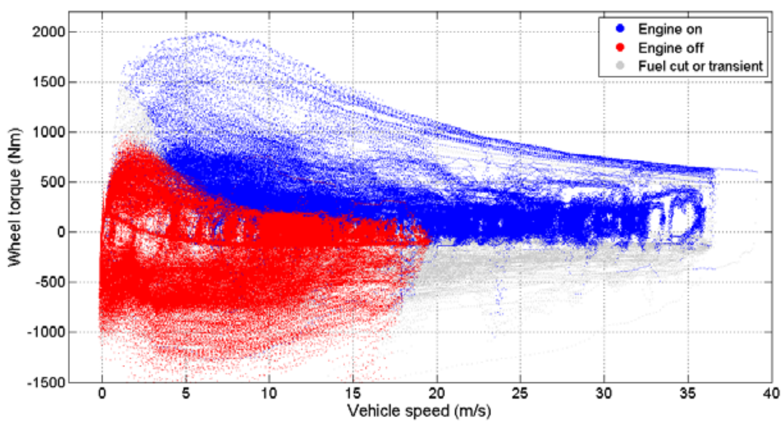




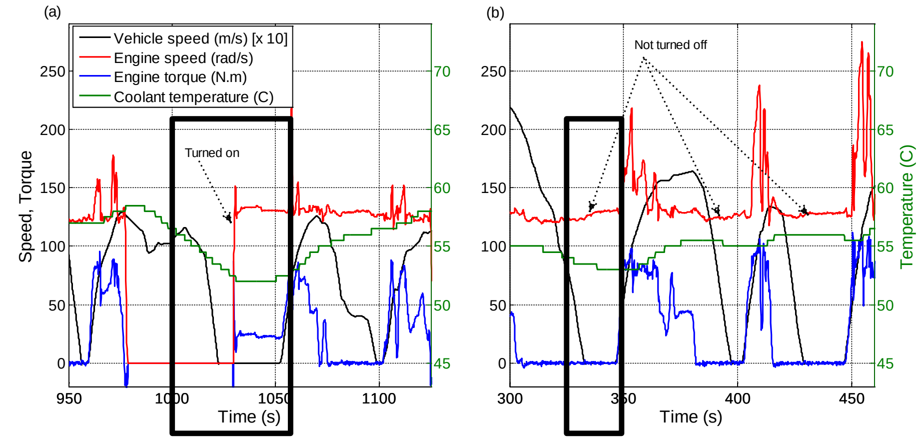
Round-trip efficiency decreases as battery temperature decreases

Vehicle Level Controls Analysis Performed

Mode Control (Engine On/Off)



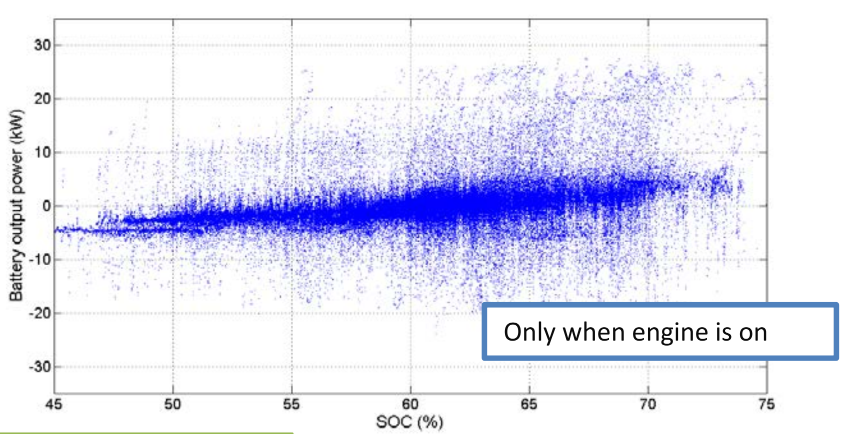
The engine is forced to be turned on if the coolant temperature is low.

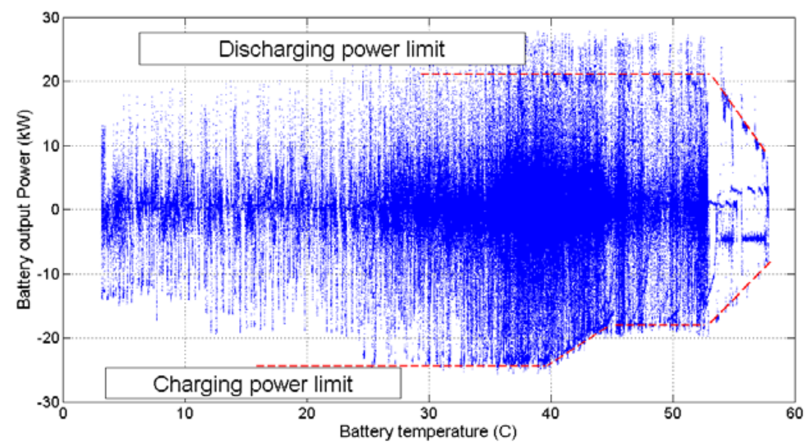


The engine is not turned off if the coolant temperature is low.

Desired battery power is proportional to SOC.

SOC Balancing



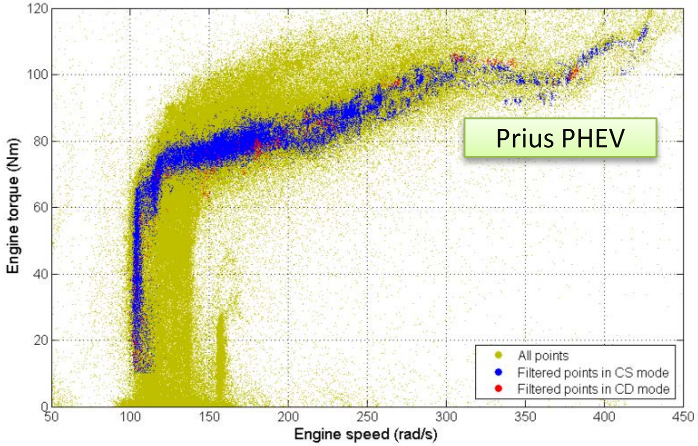


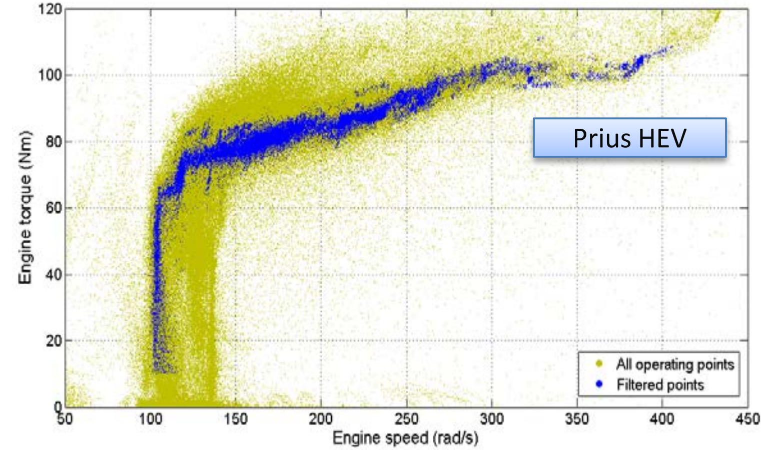
e.g. Prius HEV

Battery power is constrained by the battery temperature.

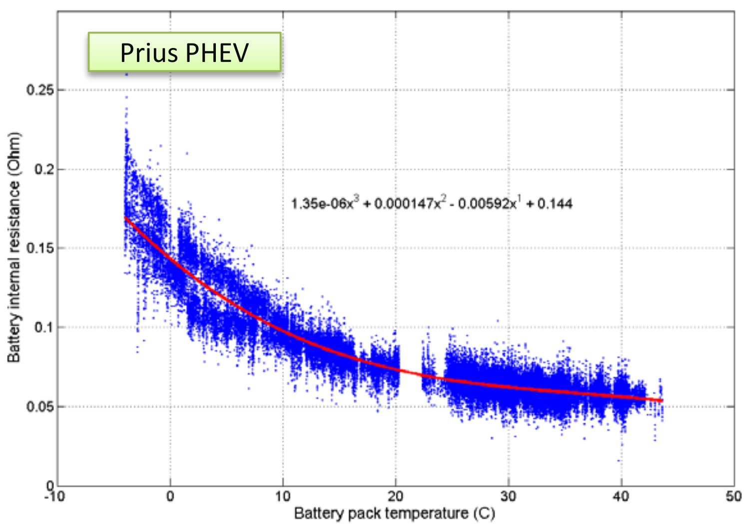
Comparative Analysis for Ctrl. & Perfo.

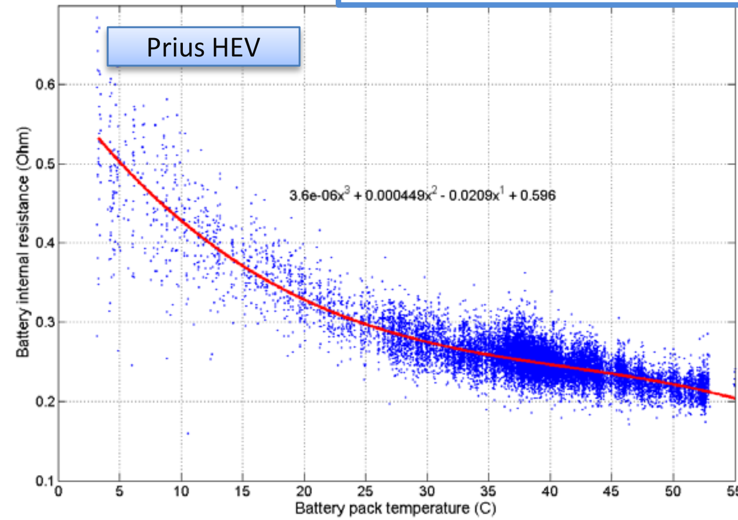
Target Control (Engine Operating)





Performance of battery

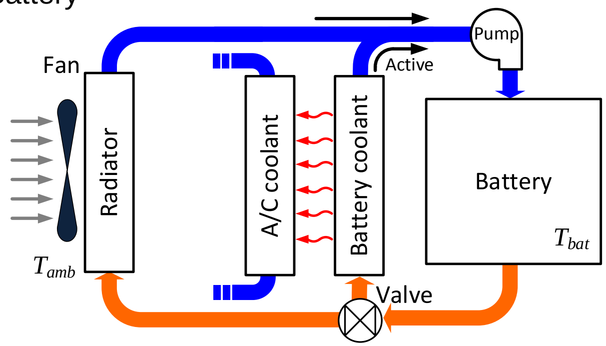




Component & Vehicle Model Developed

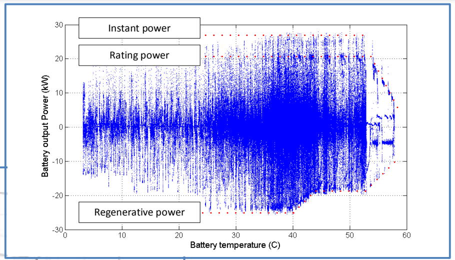
Component model development

e.g. Battery

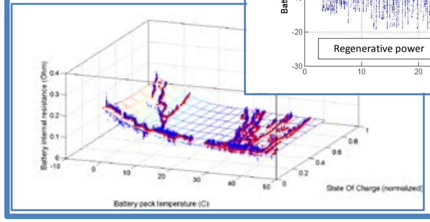


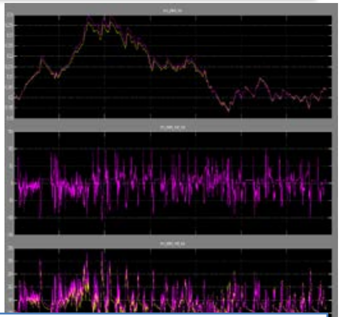
Component level validation

Control analysis



Internal resistance

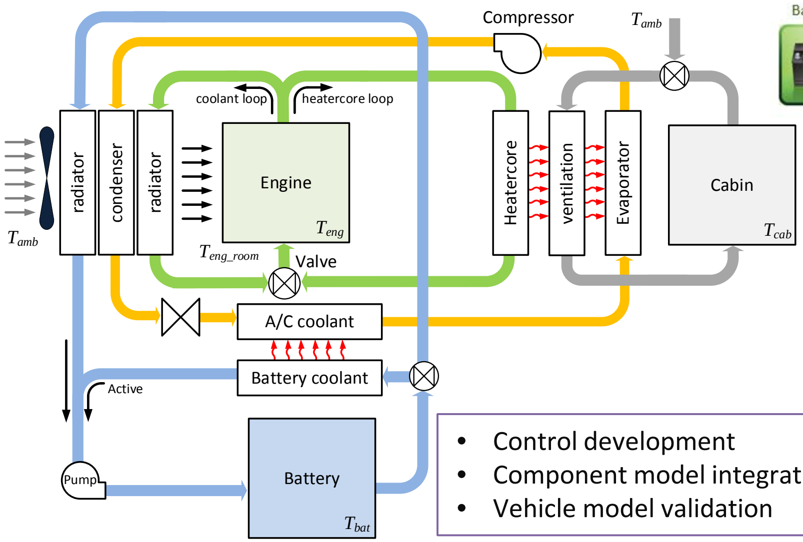




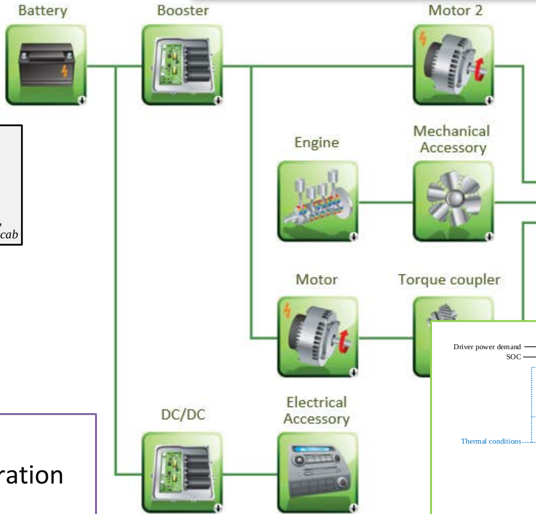
Validations with test data in component level

System Integration and vehicle level validation

Example Thermal System

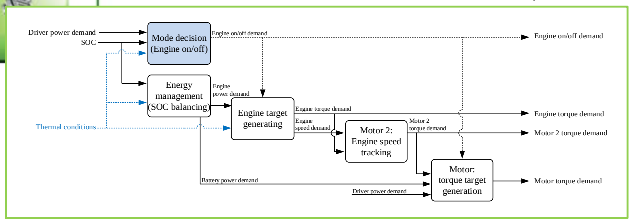


- Control development
- Component model integration
- Vehicle model validation

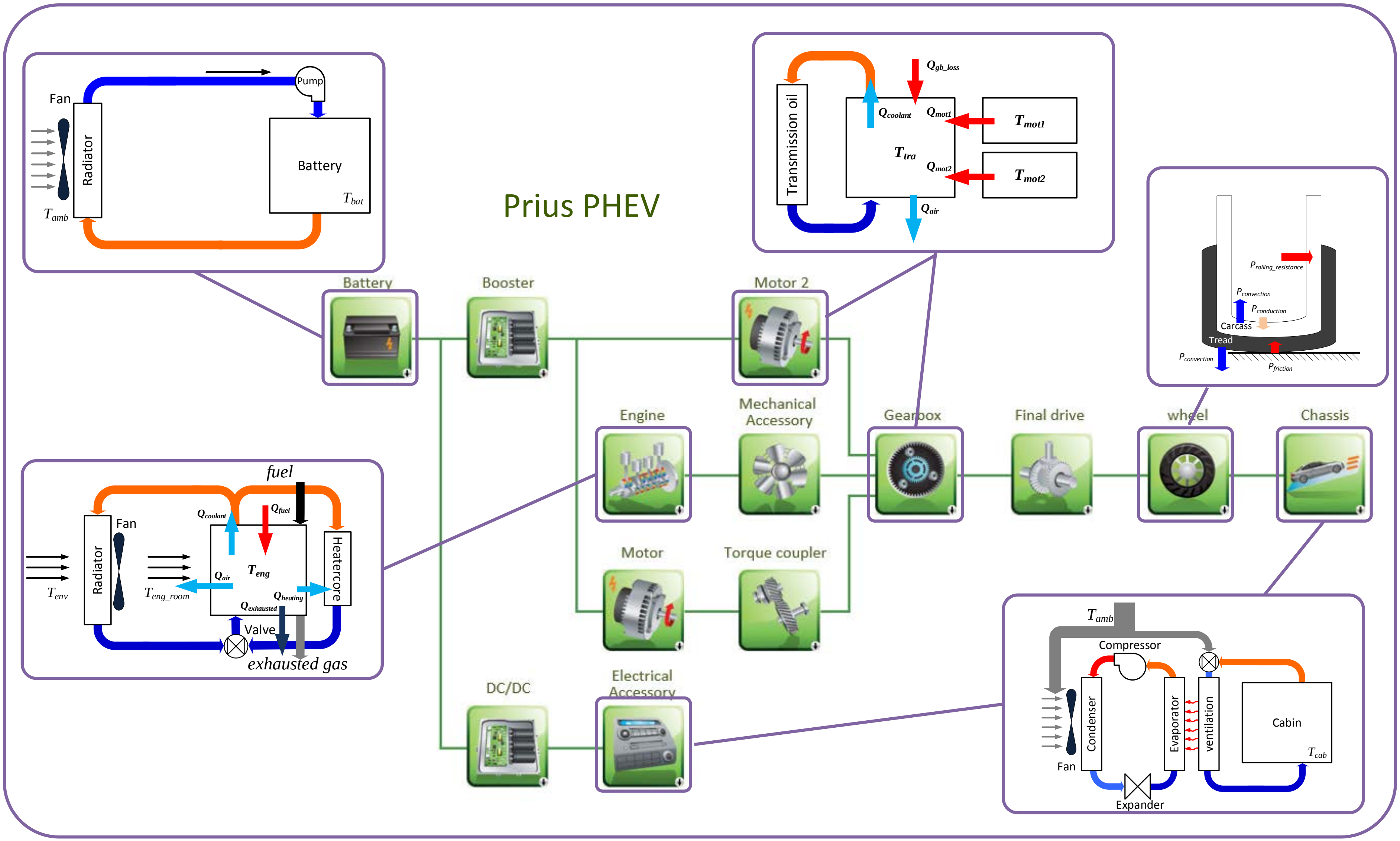


Vehicle level validation with test data

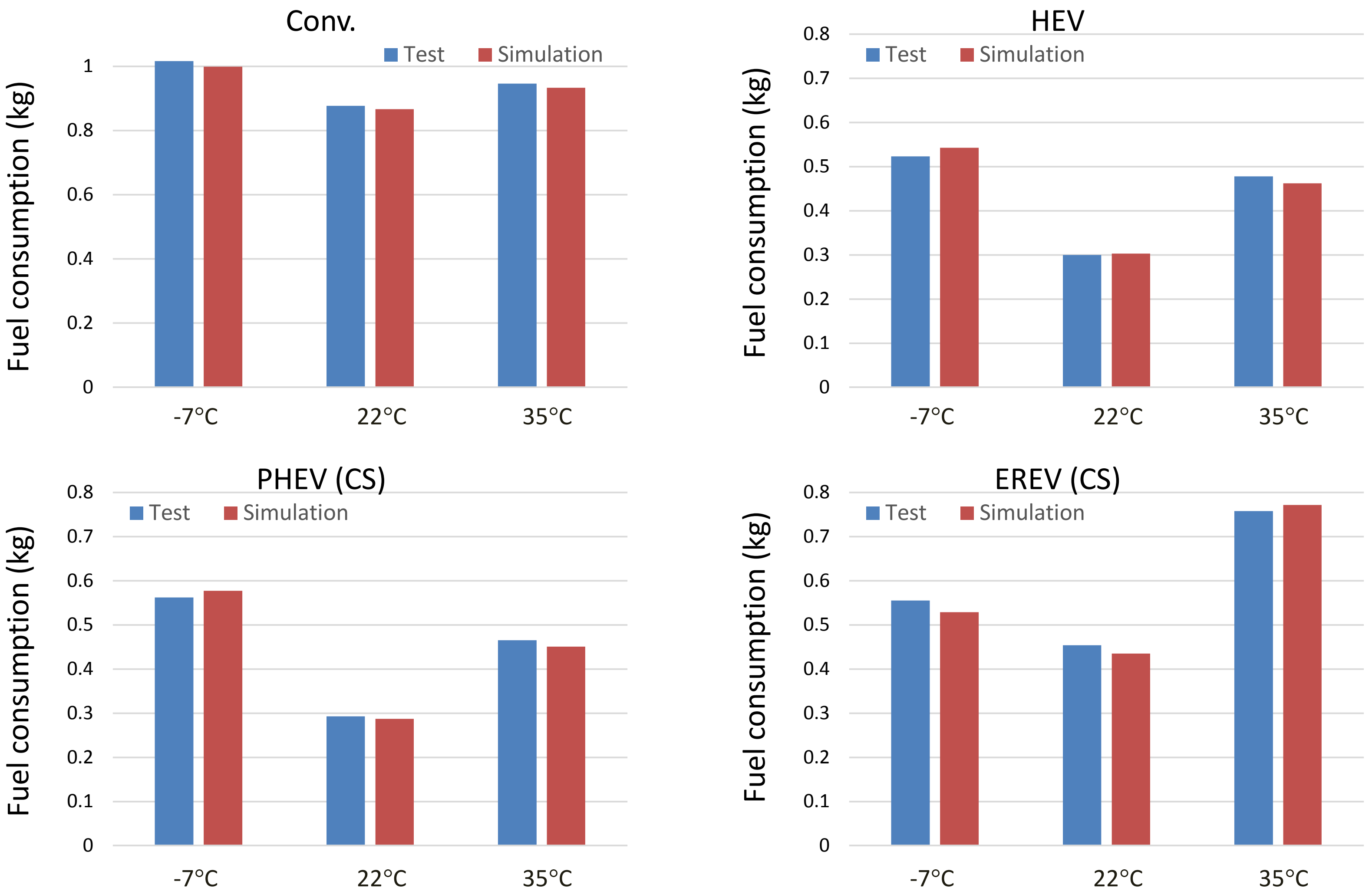
Control model development



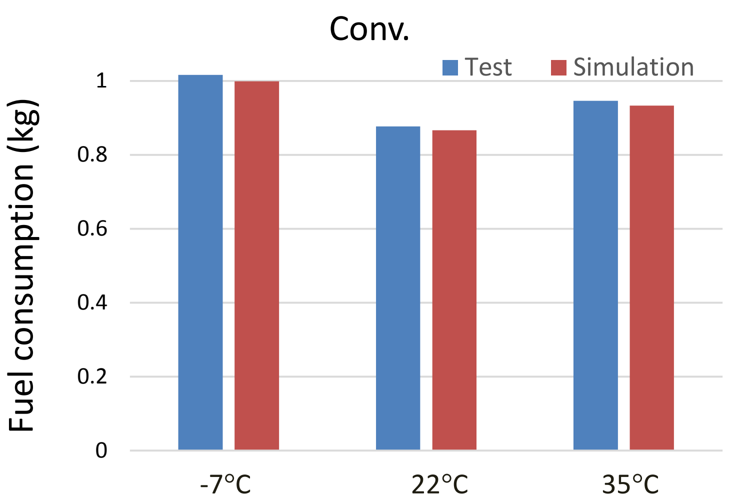
Components Integrated into Vehicle

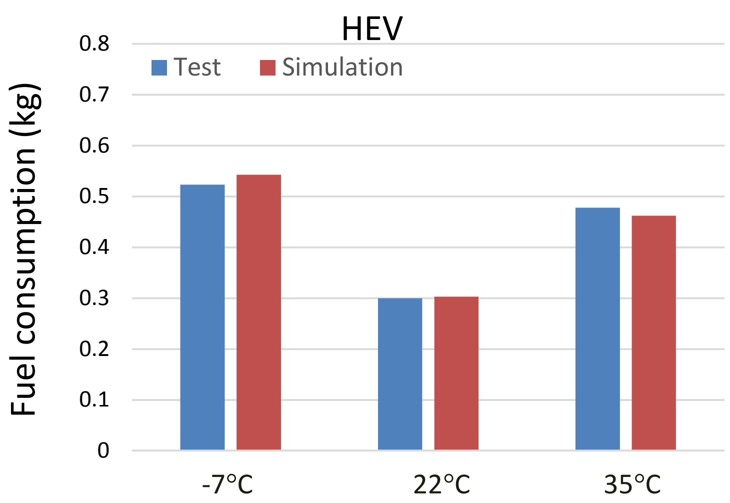


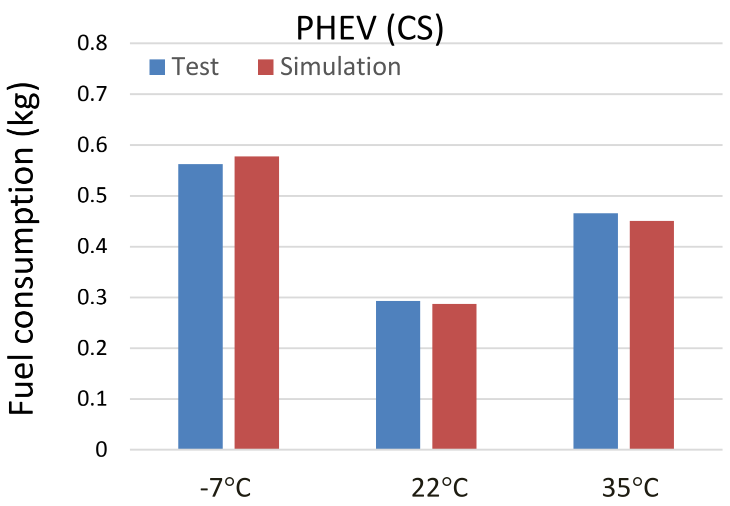
Models Validated within Test to Test Uncertainty

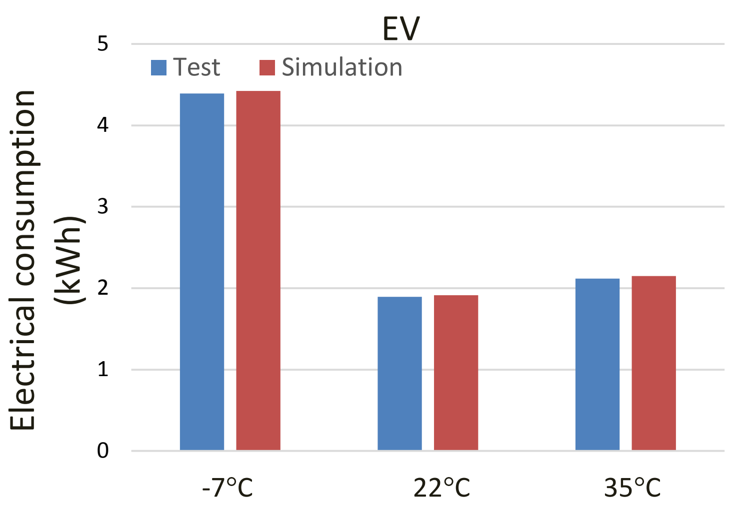


Models Validated within Test to Test Uncertainty









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

From various studies

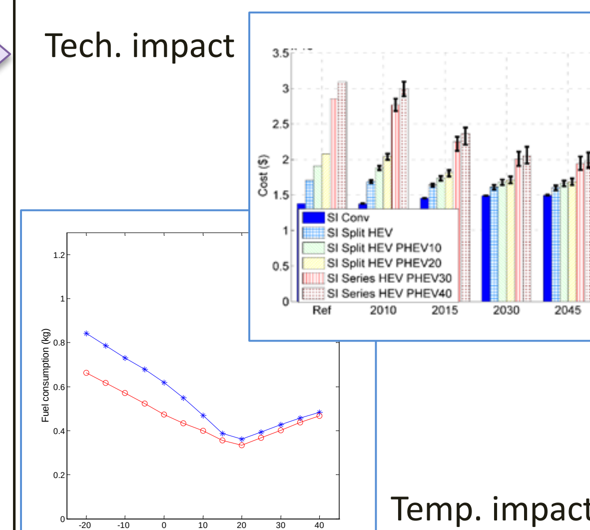
Simulation techniques

- Large scale simulation process
- Database analysis

Thermal Impact on Energy

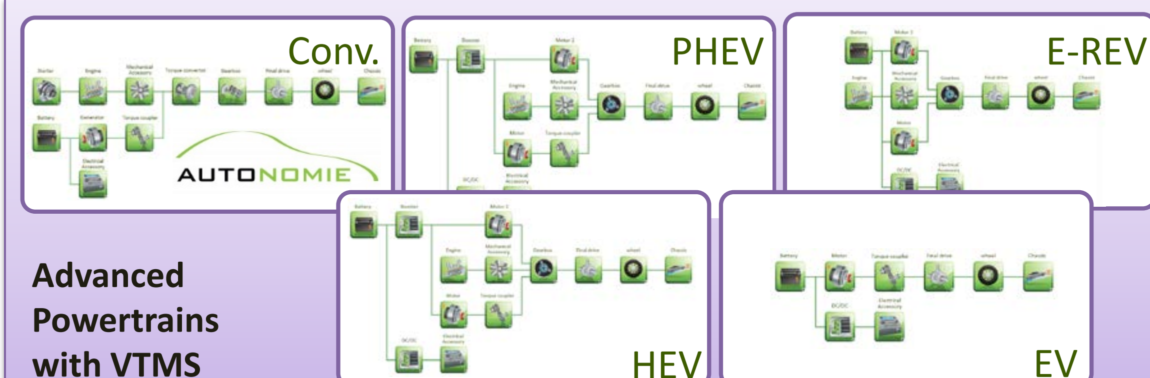
- Energy consumptions
- Impact of driving conditions

Tech. impact

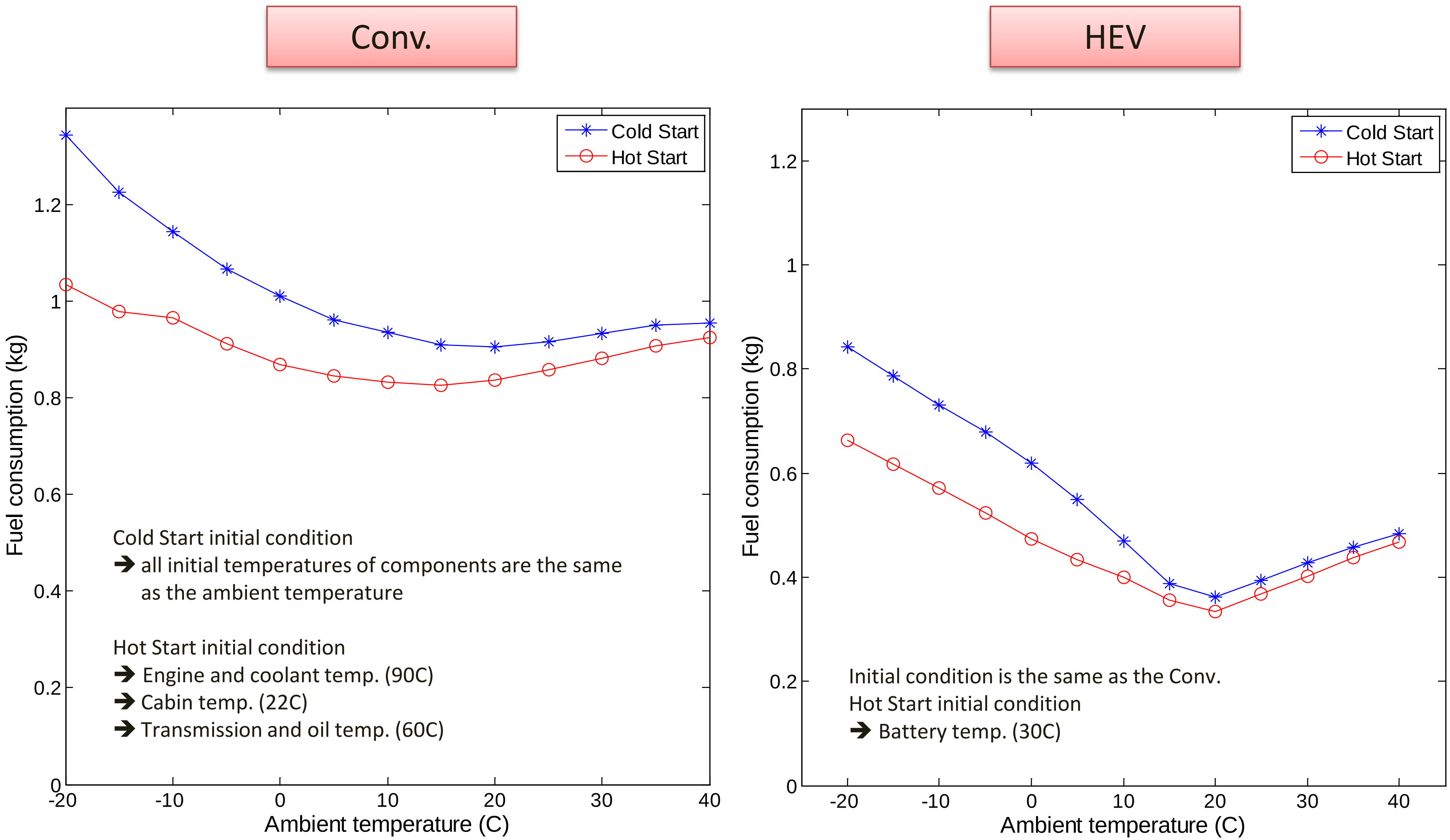


Temp. impact

Advanced Powertrains with VTMS



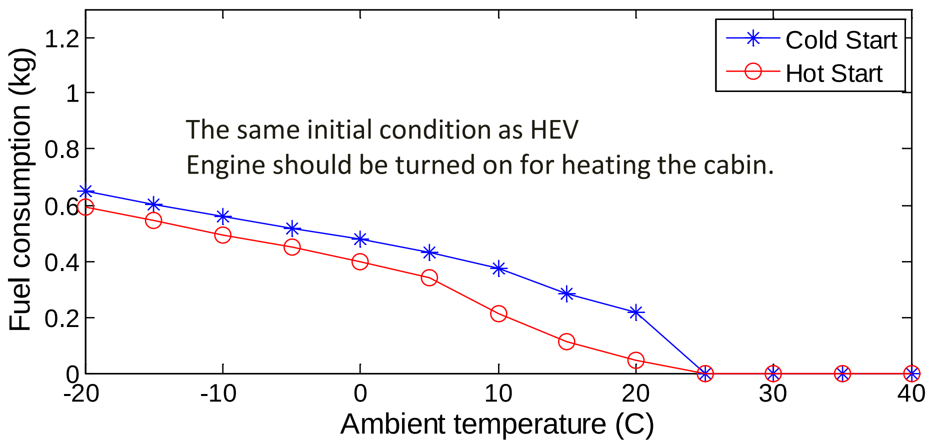
Thermal Impact On Energy Consumption

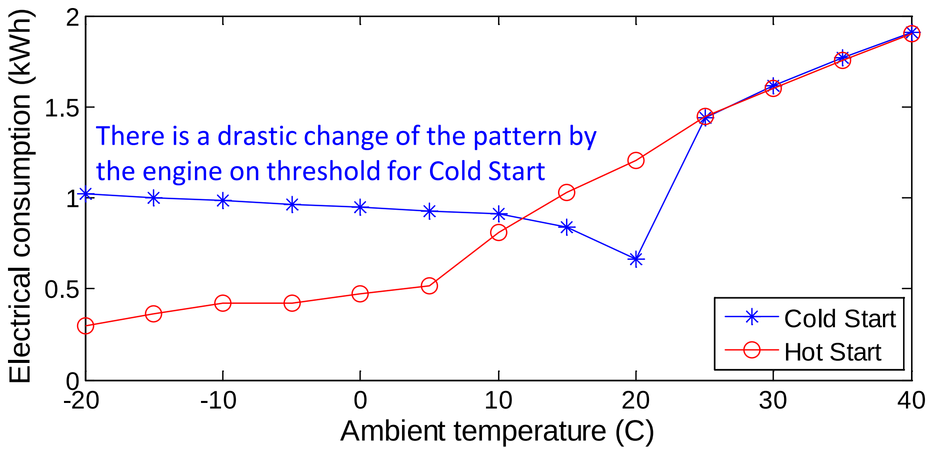


Cabin is sized, so that all vehicles have the similar hvac power consumption

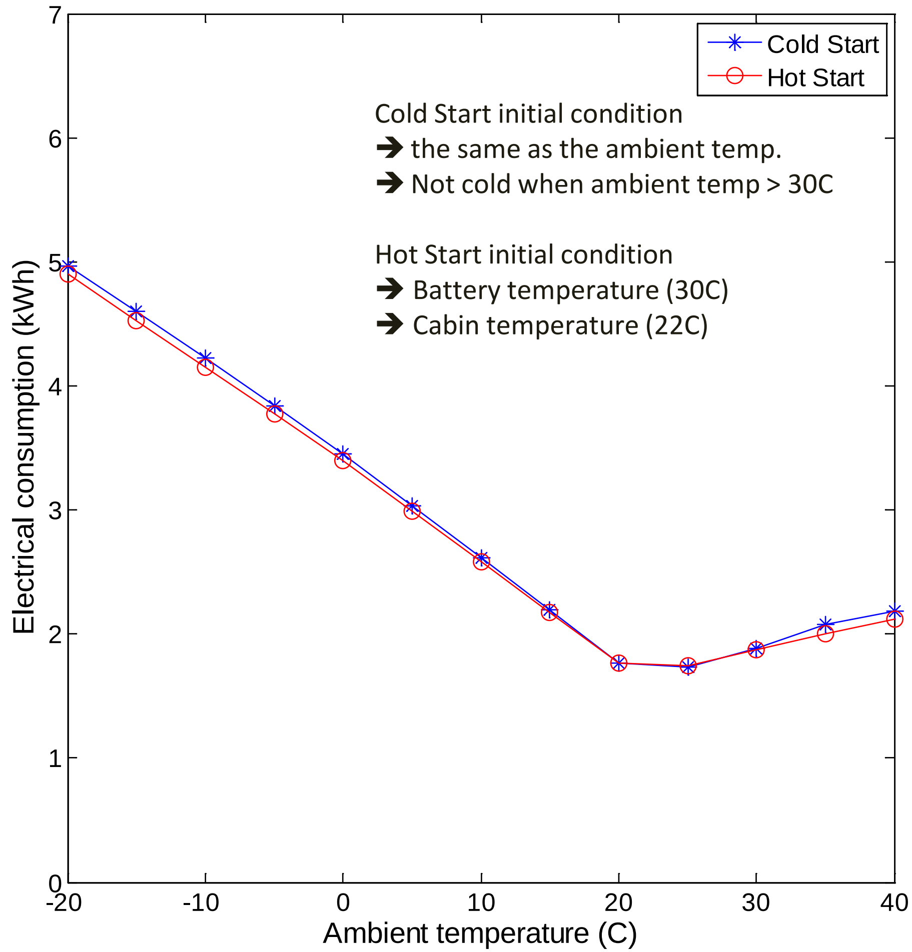
Thermal Impact On Energy Consumption

PHEV

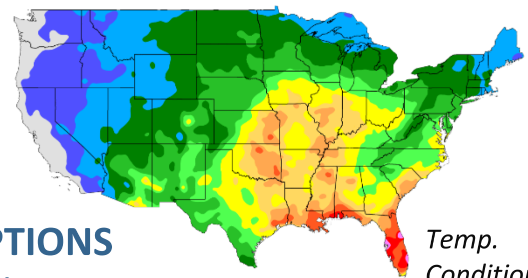




EV



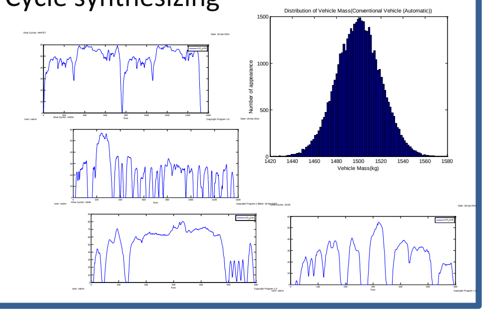
Real-World Scenario with VTMS



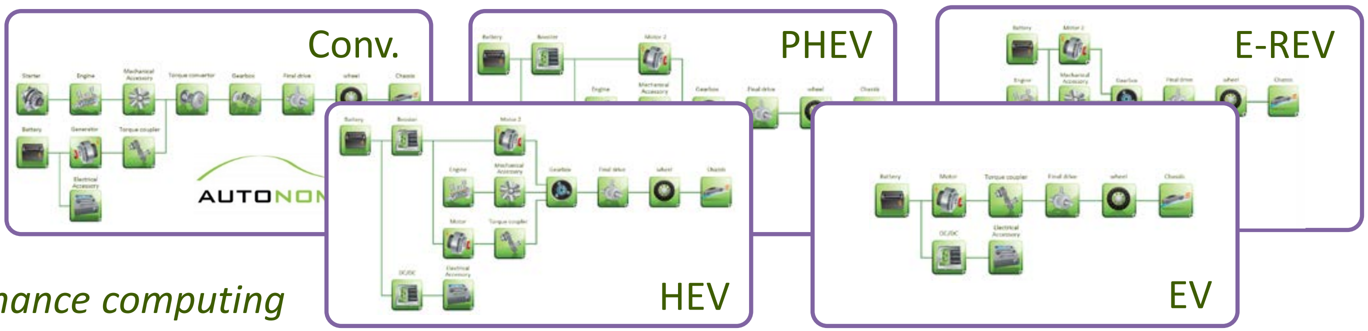
Temp.
Conditions

Real World
Driving Cycles

Cycle synthesizing

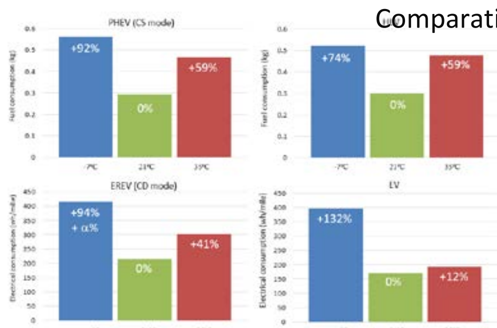


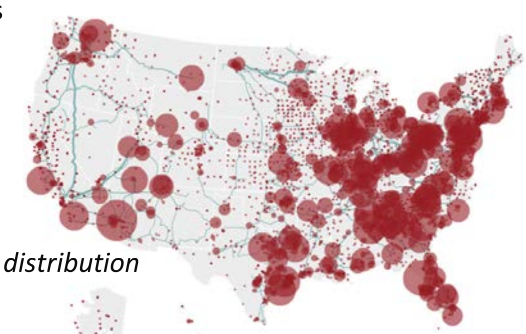
ASSUMPTIONS
from multi-resources



AUTONOMIE
on high performance computing

Comparative studies





Energy distribution

ANALYSIS
by database tool

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 rage 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/OF, # shifting events, pedal tip-in, reserve torque…)
  - …

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
- N. Kim, A. Rousseau, and H. Lohse-Busch, “Advanced Automatic Transmission Model Validation Using Dynamometer Test Data”, SAE 2014-01-1778, SAE World Congress, Detroit, Apr14
- N. Kim, E. Rask and A. Rousseau, “**Control Analysis under Different Driving Conditions for Peugeot 3008 Hybrid 4**”, SAE 2014-01-1818, SAE World Congress, Detroit, Apr14
- D. Lee, A. Rousseau, E. Rask, “**Development and Validation of the Ford Focus BEV Vehicle Model**”, 2014-01-1809, SAE World Congress, Detroit, Apr14
- N. Kim, A. Rousseau, D. Lee, and H. Lohse-Busch, “**Thermal Model Development & Validation for the 2010 Toyota Prius**”, 2014-01-1784, SAE World Congress, Detroit, Apr14
- N. Kim, N. Kim, A. Rousseau, M. Duoba, “**Validating Volt PHEV Model with Dynamometer Test Data using Autonomie**”, SAE 2013-01-1458, SAE World Congress, Detroit, Apr13
- N. Kim, A. Rousseau, E. Rask, “**Autonomie Model Validation with Test Data for 2010 Toyota Prius**”, SAE 2012-01-1040, SAE World Congress, Detroit, Apr12
- N. Kim, R. Carlson, F. Jehlik, A. Rousseau, “**Tahoe HEV Model Development in PSAT**”, SAE paper 2009-01-1307, SAE World Congress, Detroit (April 2009).
- Cao, Q., Pagerit, S., Carlson, R., Rousseau, A., "**PHEV hymotion Prius model validation and control improvements**," 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, (Dec. 2007).
- Rousseau, A., Sharer, P., Pagerit, S., Duoba, M., "**Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT**," SAE paper 2006-01-0667, SAE World Congress, Detroit (April 2006).
- Pasquier, M., Rousseau, A., Duoba, M, "**Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedures**," 18th International Electric Vehicle Symposium (EVS18), Berlin, Germany, 12 pgs. (October 2001).
- Rousseau, A., Deville, B., Zini, G., Kern, J., Anderson, J., and Duoba, M., "**Honda Insight Validation Using PSAT**," Future Transportation Technology Conference, Costa-Mesa, 01–FTT49 (August 2001).
- Rousseau, A., and Pasquier, M., "**Validation of a Hybrid Modeling Software (PSAT) Using Its Extension for Prototyping (PSAT-PRO)**," Global Powertrain Congress, Detroit (June 2001).