# *Fuel Displacement Potential of Advanced Technologies under Different Thermal Conditions*

**2015 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review**

June, 2015


Namwook Kim, Aymeric Rousseau

*Argonne National Laboratory*



Sponsored by David Anderson


**Project ID #VSS154**

# Project Overview

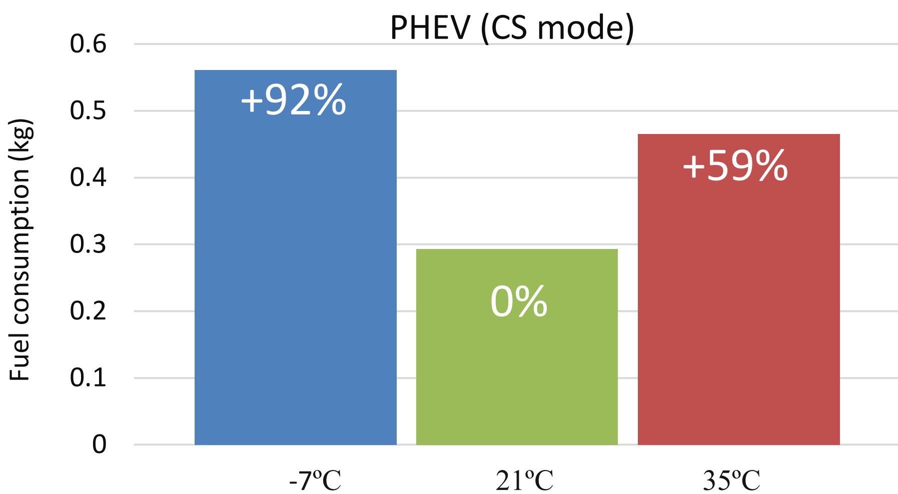
| Timeline | Barriers |
|---|---|
| • Start – September 2014<br>• End – September 2015<br>• 60% Complete | • Implement detailed component thermal models and estimate the model parameters<br>• Assess impact of temperature on fuel displacement |

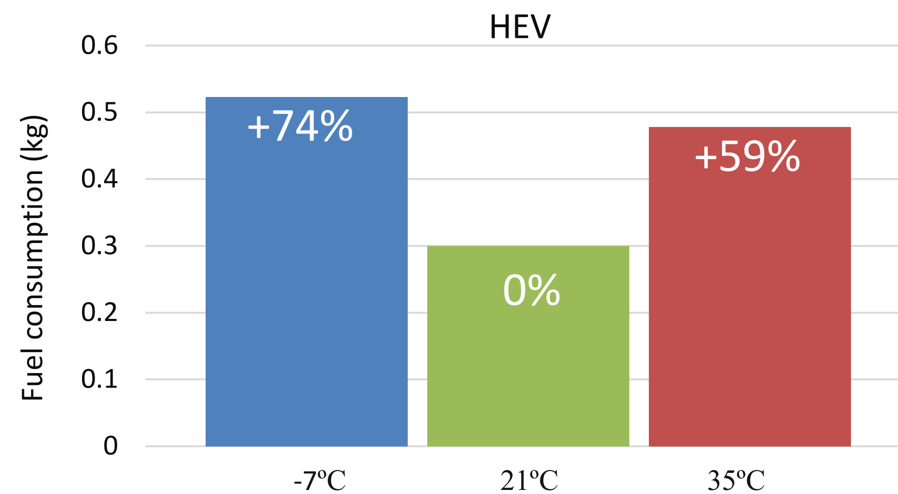
| Budget | Partners |
|---|---|
| • FY15 $275K | • Automotive manufacturer<br>• MathWorks<br>• Argonne: APRF, Mathematics and Computer Science Division<br>• NREL (A/C model) |

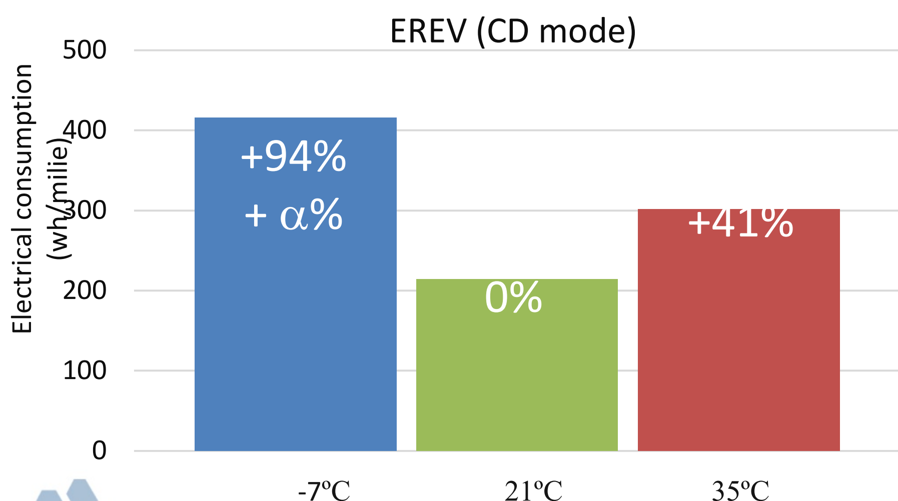
# Relevance

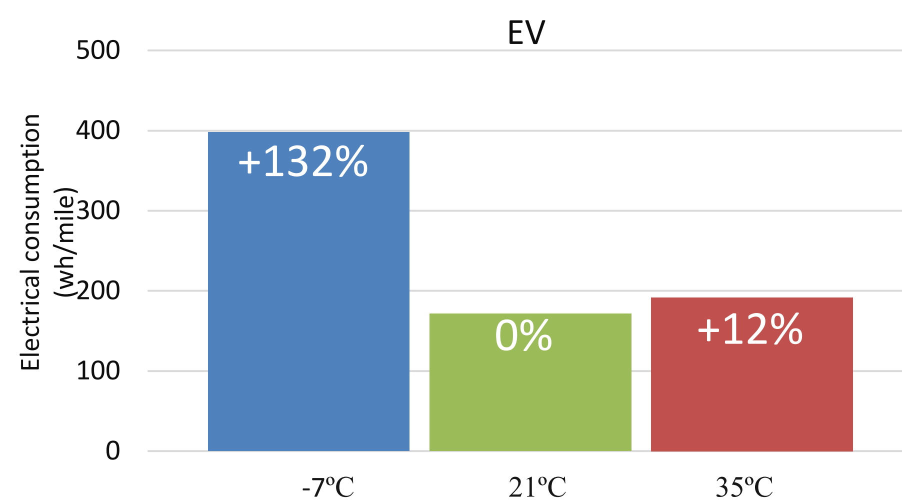
## Temperature Has a Significant Impact on Electric Drive Energy Consumption

APRF Test Data on UDDS

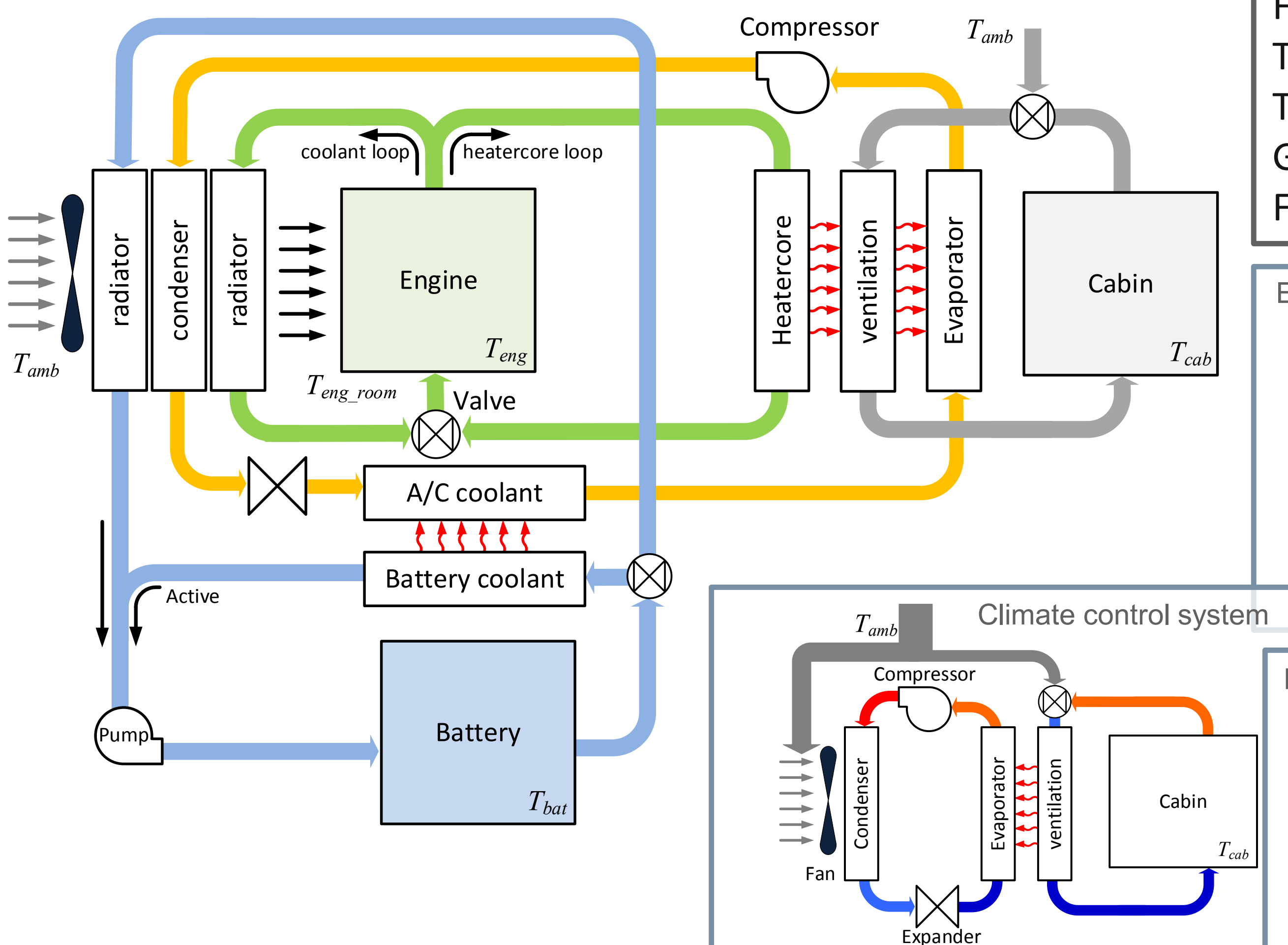


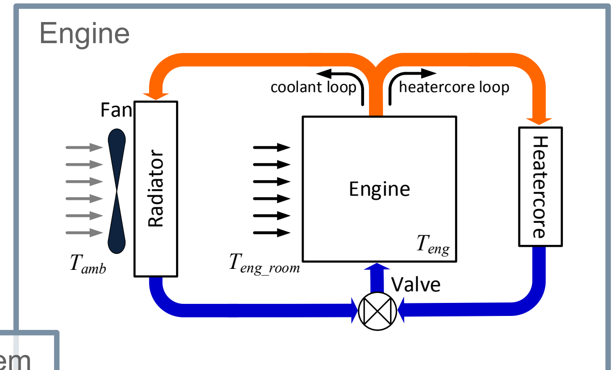



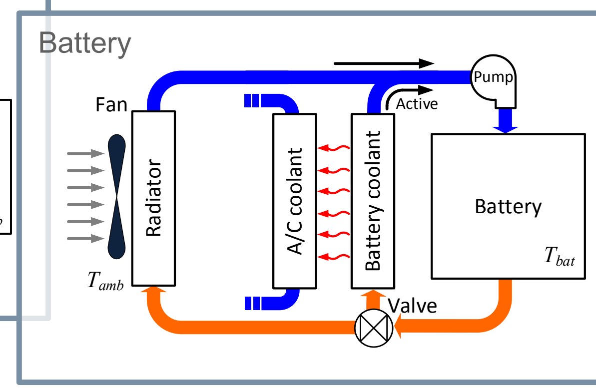



# DOE VTO Effort to Develop and Validate Complete Thermal Models Has Been Ongoing for Several Years

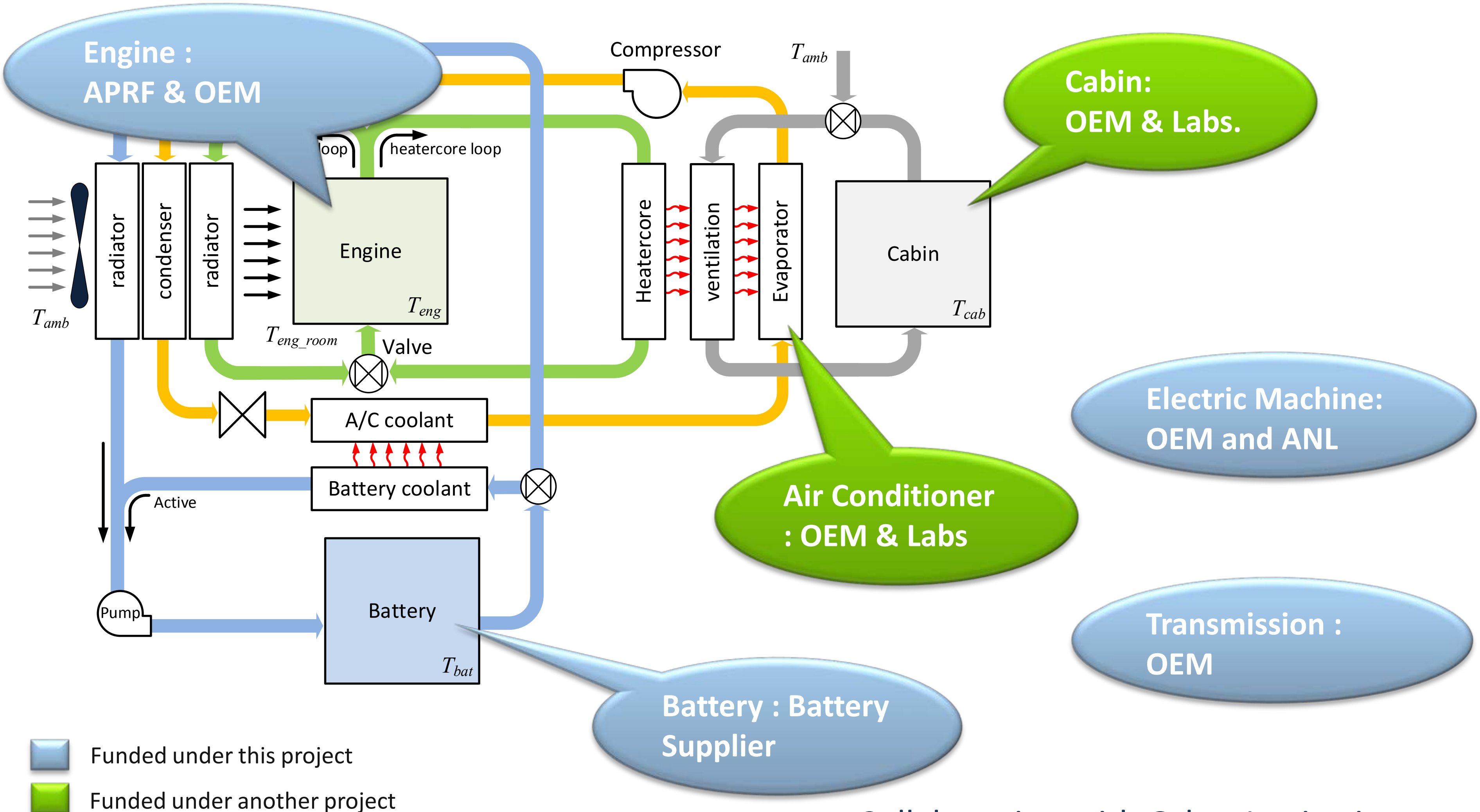



Ford Fusion Conv.
Toyota Prius HEV
Toyota Prius PHEV
GM Volt
Ford Focus BEV



# In Order to Complete The Mission, ANL Has Been Collaborating with Numerous Partners




Collaboration with Other Institutions

# Relevance

***The objective is to assess the impact of the thermal conditions on energy consumption with entire vehicle thermal management systems***

- Energy consumption affected by cold and hot temperatures results in lower fuel economy, shorter range and higher emissions.
- Vehicle thermal management system (VTMS) models are integrated to evaluate the thermal impact under various vehicle thermal and driving conditions.
- Further conditions including temperature, real-world driving cycles, and powertrain technologies will be used to improve the evaluation process with VTMS.

# Approach

## 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

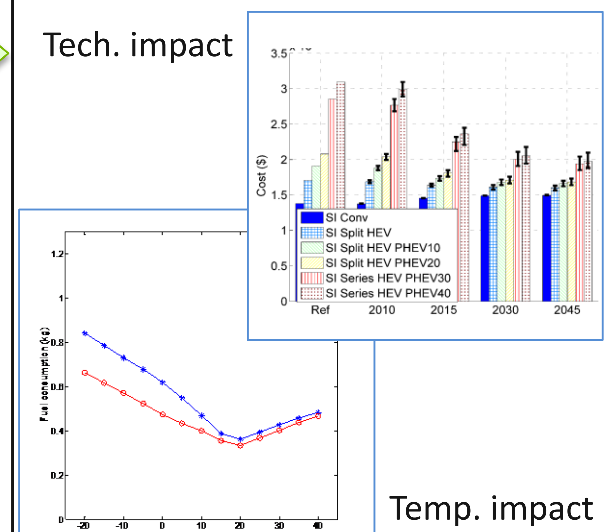
- Large scale simulation process
- Database analysis

↓

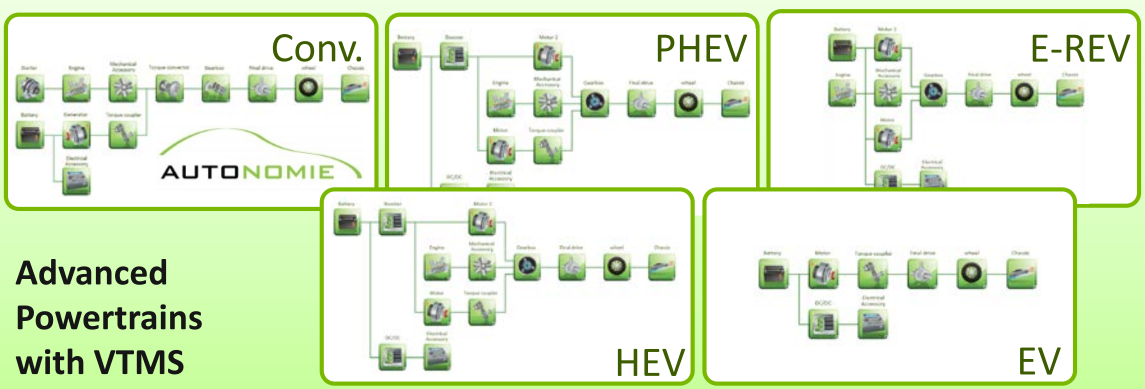
## Thermal Impact on Energy

- Energy consumptions
- Impact of driving conditions

Tech. impact

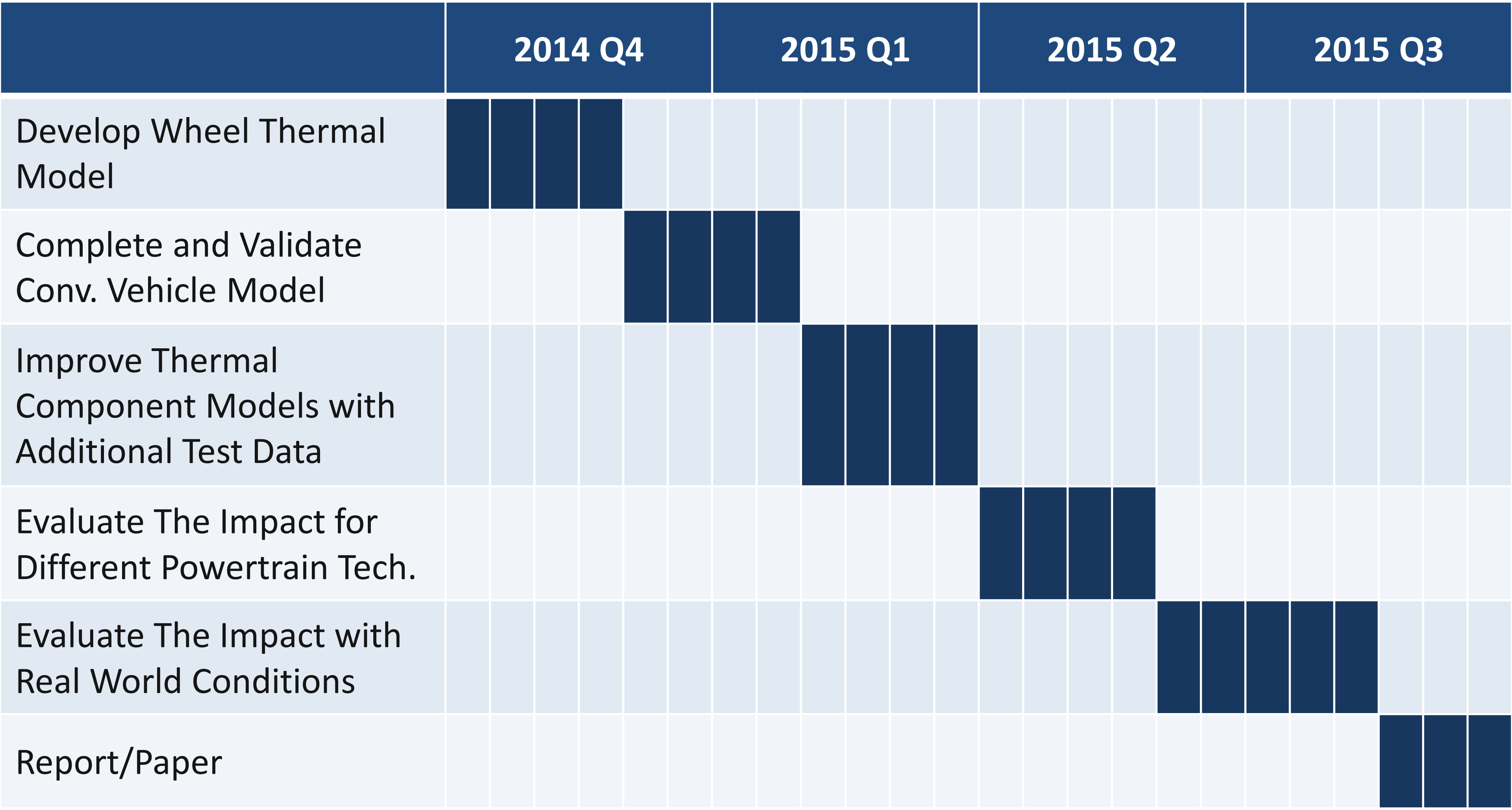



Temp. impact



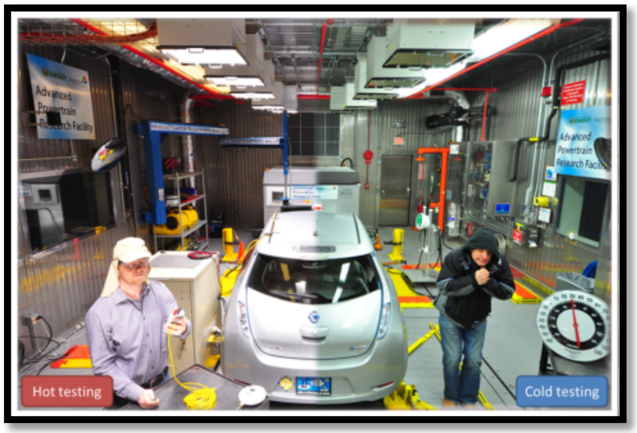

**Advanced Powertrains with VTMS**

# Milestones


2014 Q4
2015 Q1
2015 Q2
2015 Q3
Develop Wheel Thermal Model
Complete and Validate Conv. Vehicle Model
Improve Thermal Component Models with Additional Test Data
Evaluate The Impact for Different Powertrain Tech.
Evaluate The Impact with Real World Conditions
Report/Paper

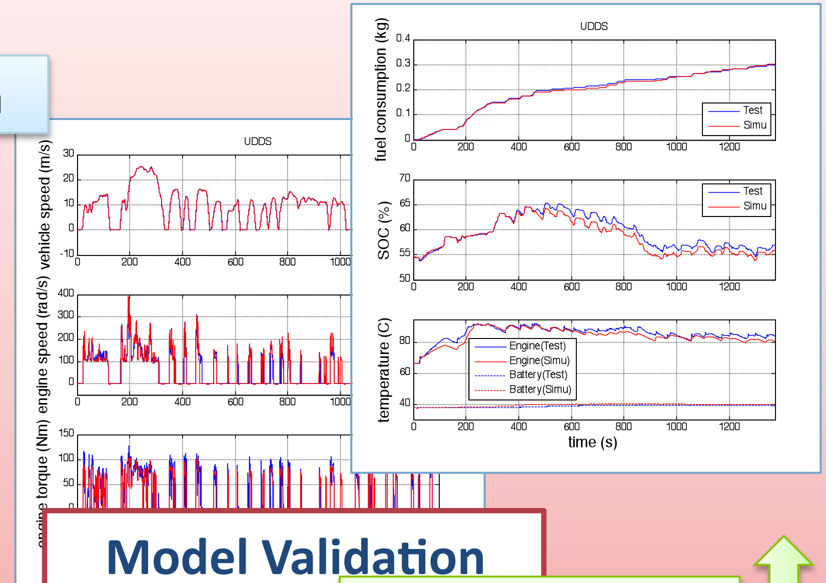
# Technical Accomplishments
## Standard Model Development Process

### Test data from APRF (ANL)




| °C |
|---|
| -7 |
| 21 |
| 35 |

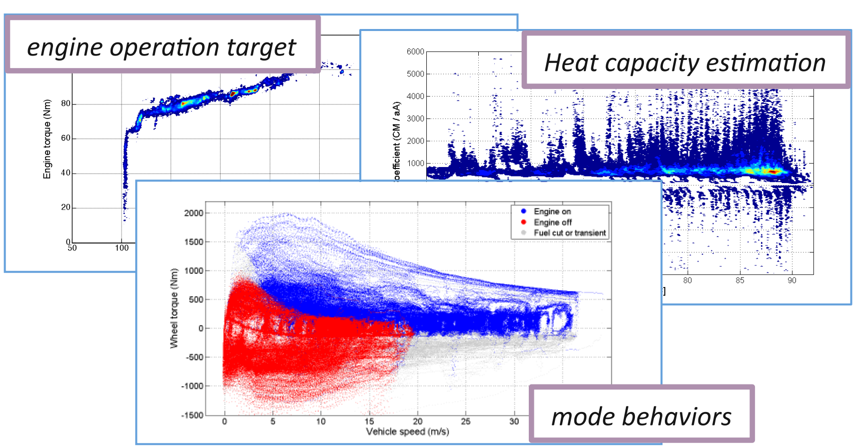
Test data



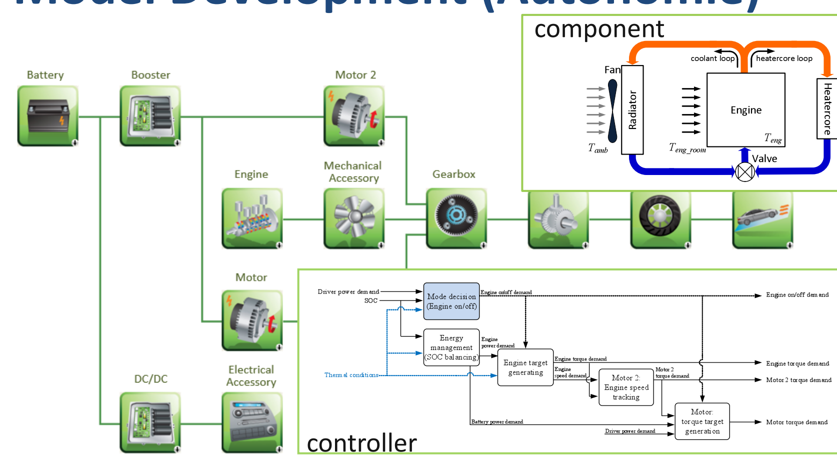

Model Validation

Simulation data

### Control and Performance Analysis




### Model Development (Autonomie)

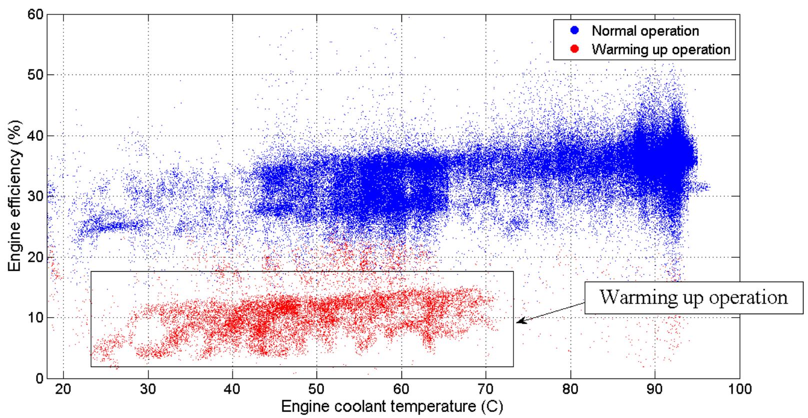


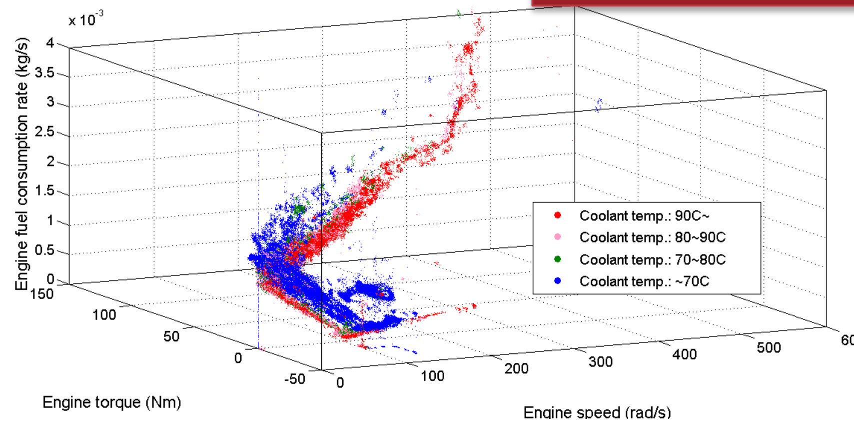
# Technical Accomplishments

## Component Performances Developed Using Generic Processes

### Engine performance analysis

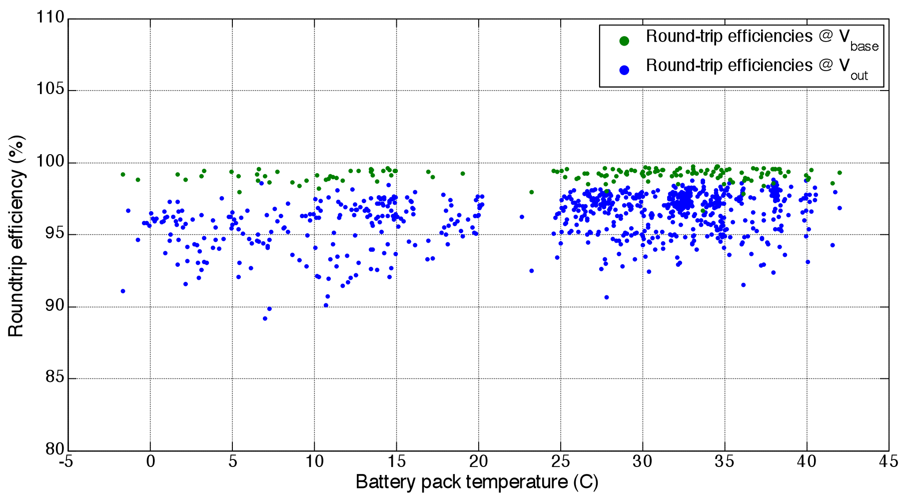
e.g. Prius PHEV

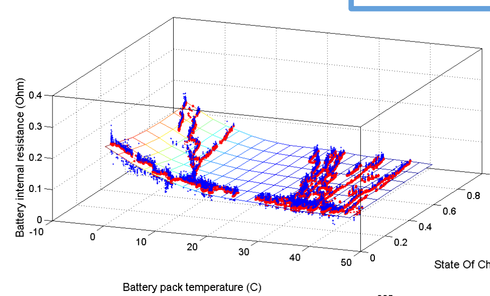


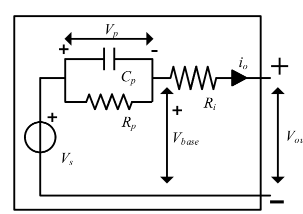



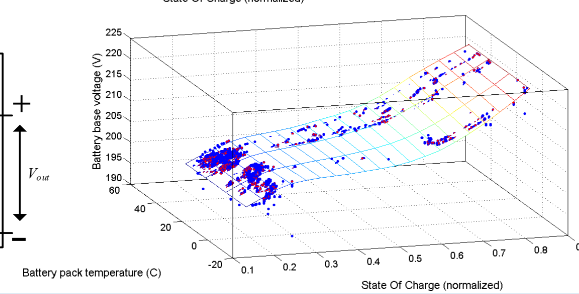

Engine efficiency decreases as the coolant temperature decreases.

### Battery performance analysis



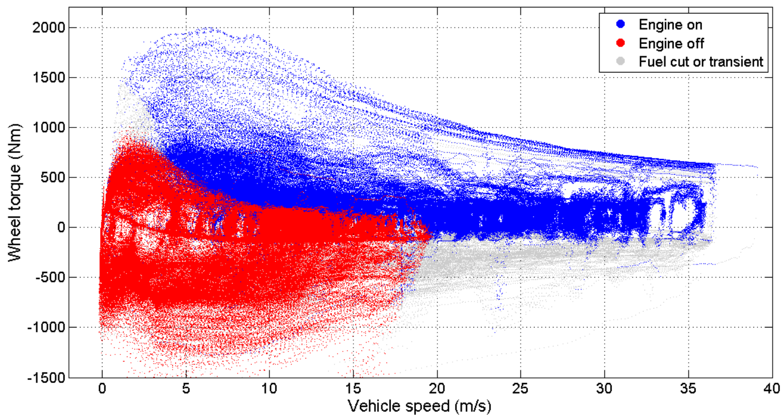




Round-trip efficiency decreases as battery temperature decreases

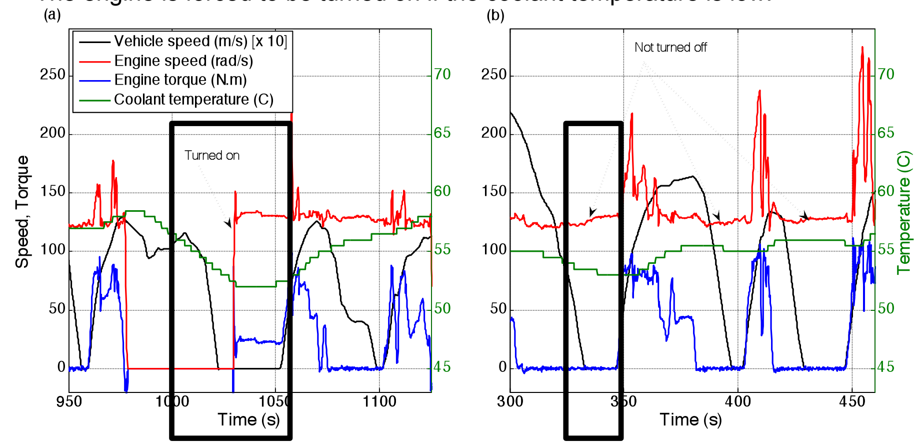
# Technical Accomplishments

## Vehicle Level Controls Analyzed

Mode Control (Engine On/Off)



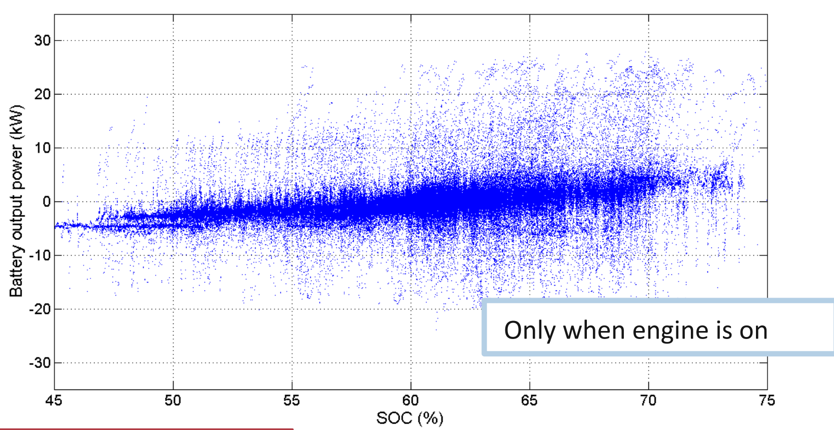

The engine is forced to be turned on if the coolant temperature is low.

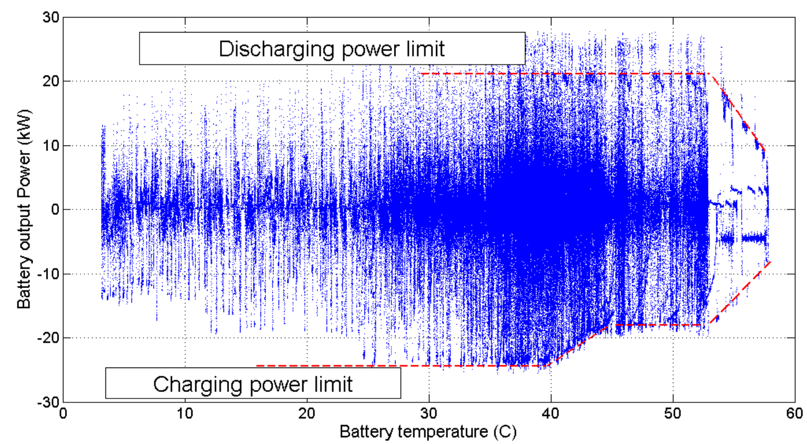



The engine is not turned off if the coolant temperature is low.

Desired battery power is proportional to SOC.

SOC Balancing




Battery power is constrained by the battery temperature.

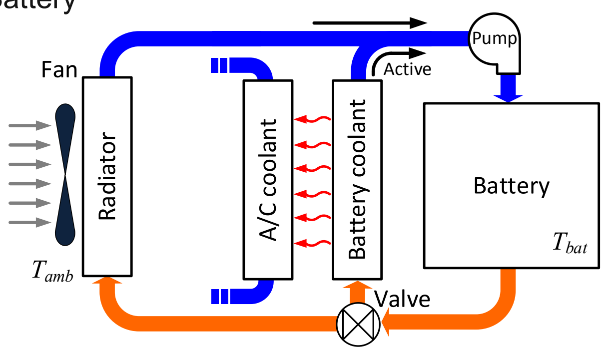
e.g. Prius HEV

# Technical Accomplishments

## Simulation Model Development

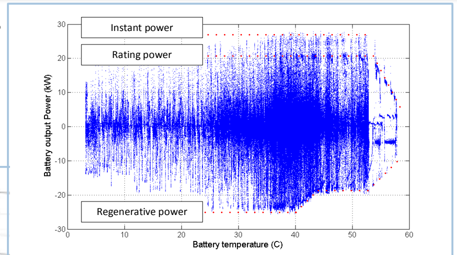
### Component model development

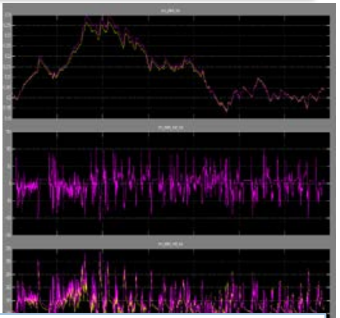
e.g. Battery



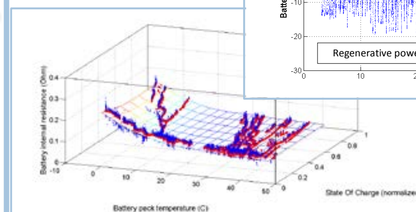

### Component level validation

Control analysis



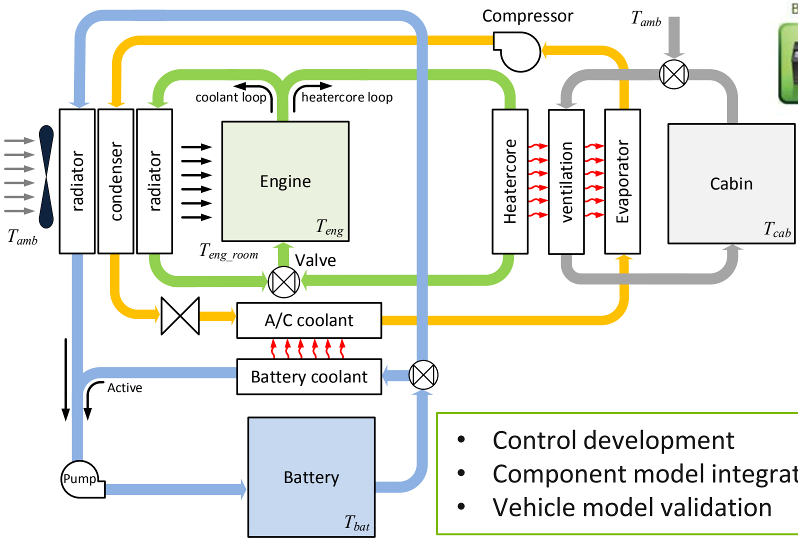
Internal resistance



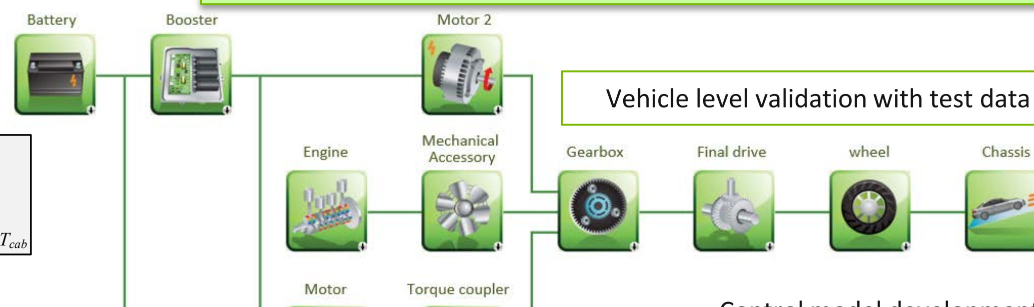

Validations with test data in component level

### System Integration and vehicle level validation

Example Thermal System

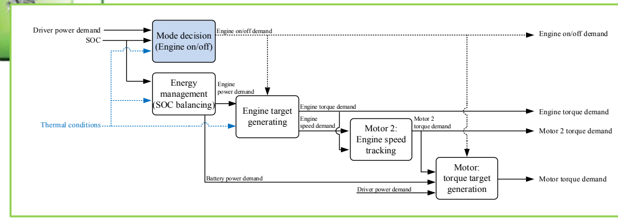



- Control development
- Component model integration
- Vehicle model validation




Vehicle level validation with test data

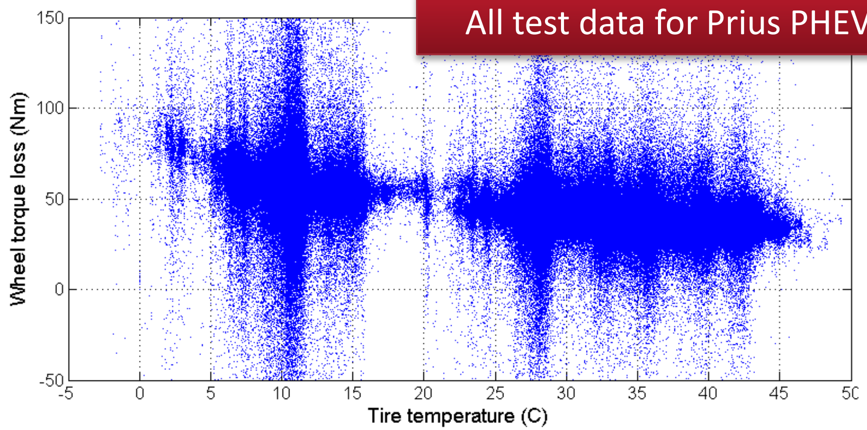
Control model development

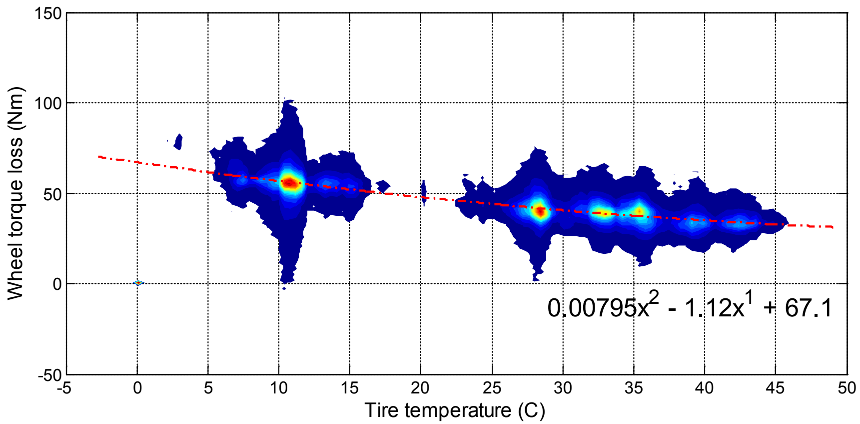


# Technical Accomplishments
## Wheel Thermal Model Developed

Wheel torque loss vs. Temperature

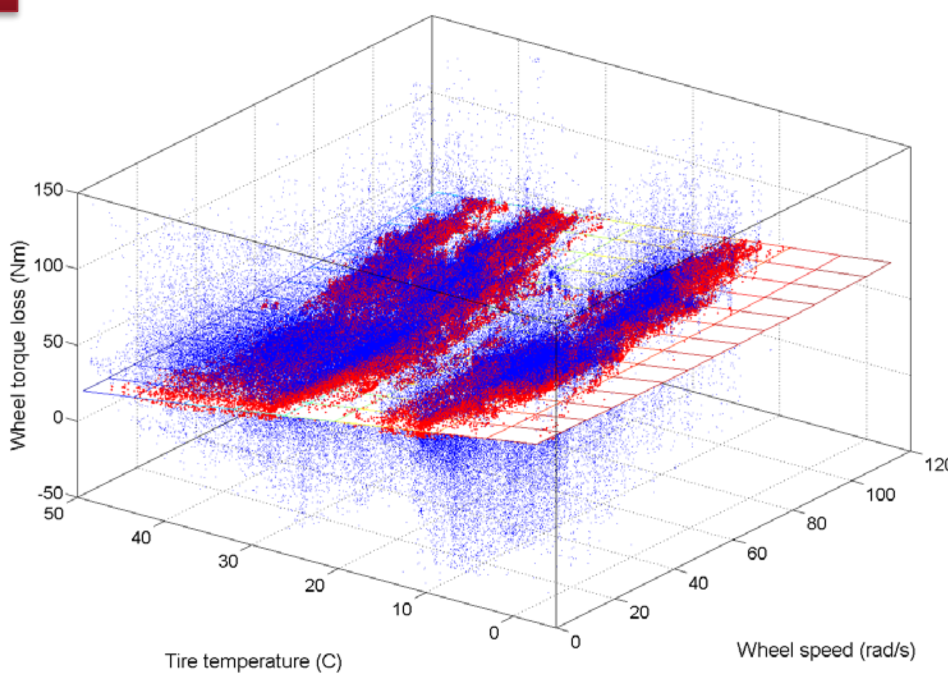
All test data for Prius PHEV



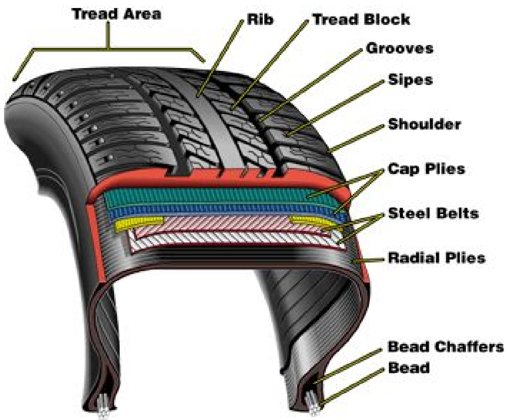

Wheel loss is significantly changed in relation to the tire temperature.

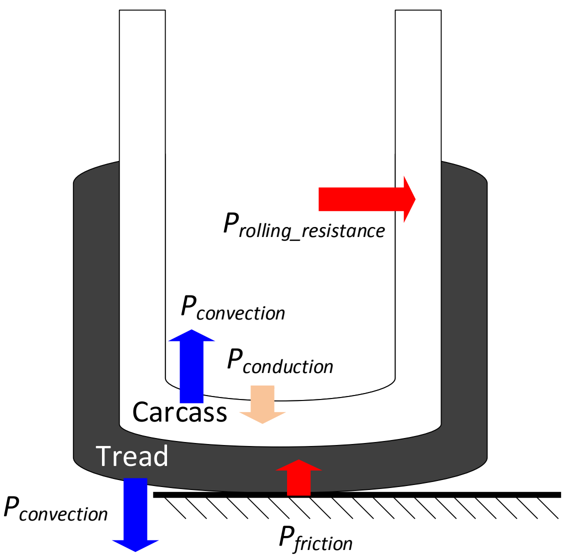
Wheel temperature model



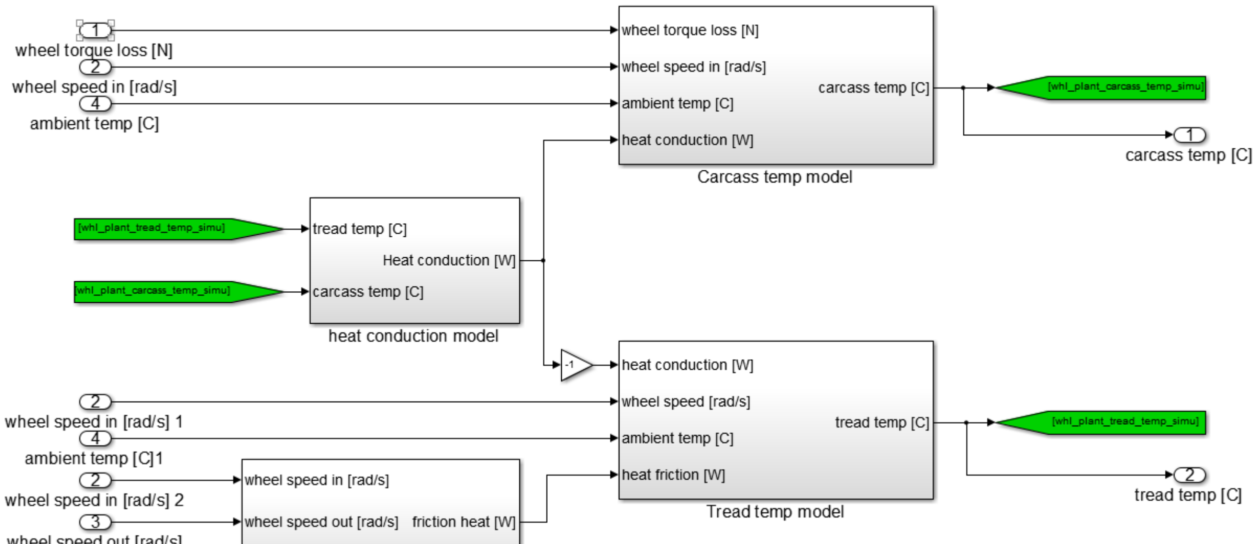

Numerical loss model in relation to the wheel speed and the tire temperature

# Technical Accomplishments
## Wheel Thermal Model Validated

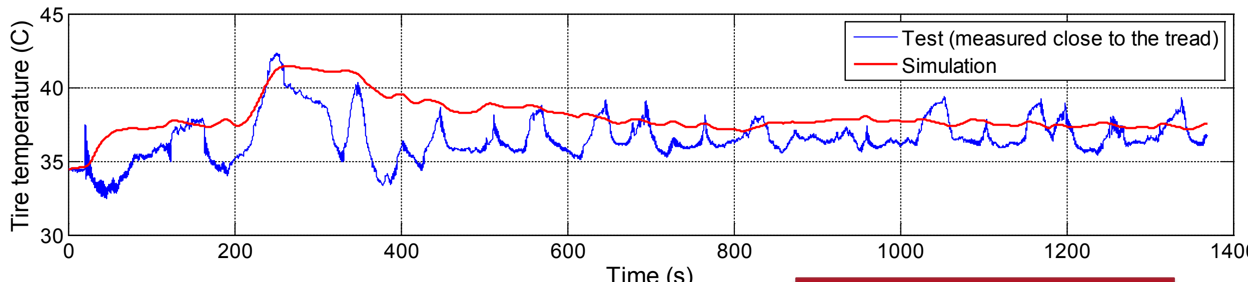



Simulation model

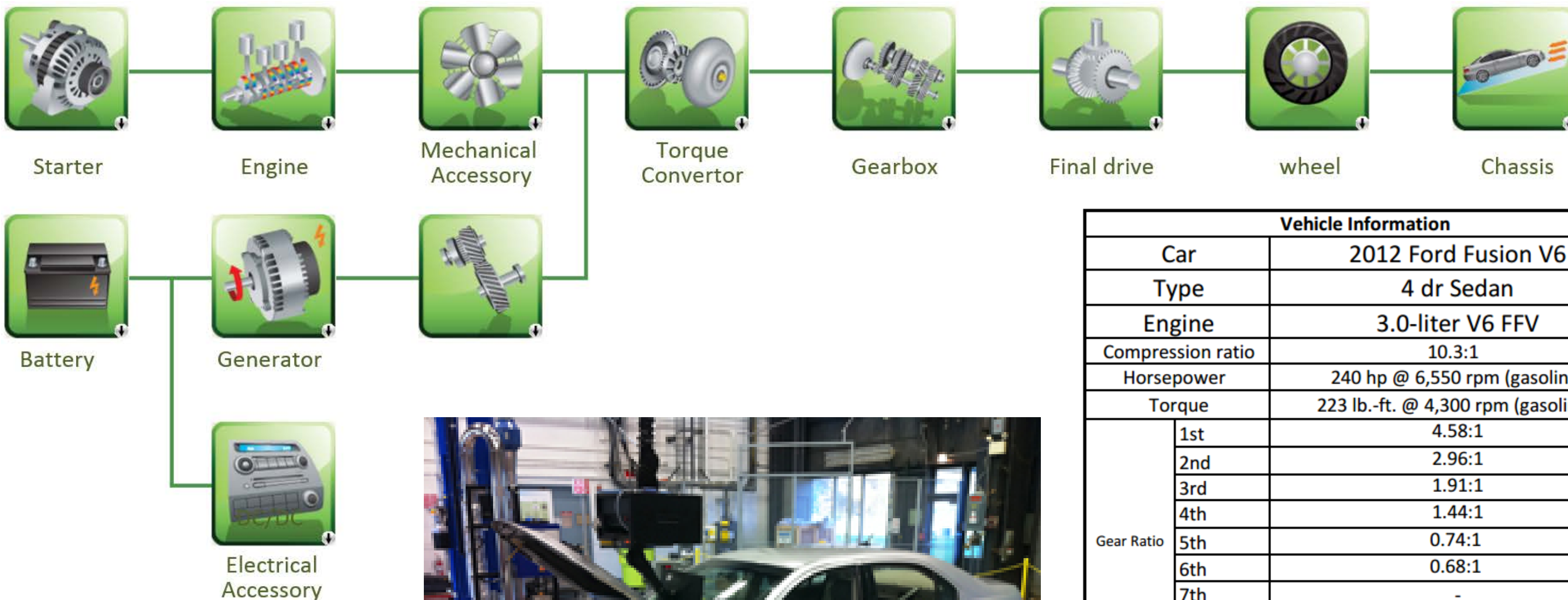



Aldo Sorniotti, "Tire Thermal Model for Enhanced Vehicle Dynamics Simulation Aldo Sorniotti," SAE paper 2009-01-0441




Prius PHEV (UDDS)

# Technical Accomplishments
## Conventional Vehicle Thermal Model Developed




Ford Fusion Conv.

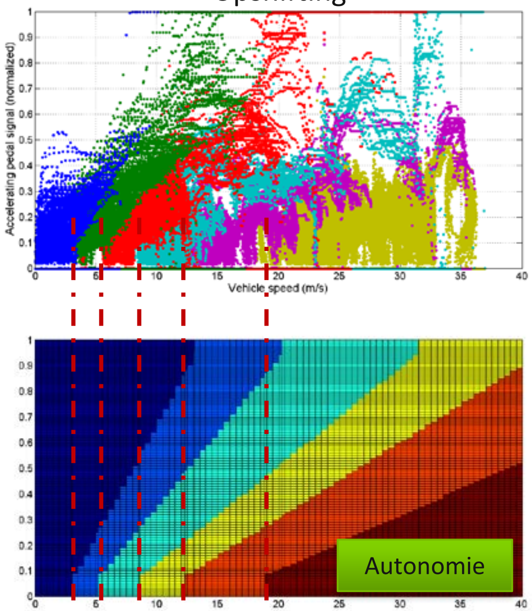
| Vehicle Information | | |
|---|---|---|
| Car | | 2012 Ford Fusion V6 |
| Type | | 4 dr Sedan |
| Engine | | 3.0-liter V6 FFV |
| Compression ratio | | 10.3:1 |
| Horsepower | | 240 hp @ 6,550 rpm (gasoline) |
| Torque | | 223 lb.-ft. @ 4,300 rpm (gasoline) |
| Gear Ratio | 1st | 4.58:1 |
| | 2nd | 2.96:1 |
| | 3rd | 1.91:1 |
| | 4th | 1.44:1 |
| | 5th | 0.74:1 |
| | 6th | 0.68:1 |
| | 7th | - |
| | 8th | - |
| | Final Drive | 3.20:1 |
| Wet or Dry Clutch | | |
| Label EPA Fuel Economy | HWY | 20 |
| | Urban | 28 |
| | Combined | 23 |
| 0 to 60 time [s] | | 7 |
| 2 Whl Dyno GUI table | Test weight | 3744 |
| | a | 33.84 |
| | b | -0.2066 |
| | c | 0.02372 |

| Fuel Info | | | | | |
|---|---|---|---|---|---|
| Fuel Name: | Tier II EEE HF437 | Density: | 0.74 | [g/ml] |
| CWF: | 0.8618 | Net HV: | 18344 | [BTU/lbm] |

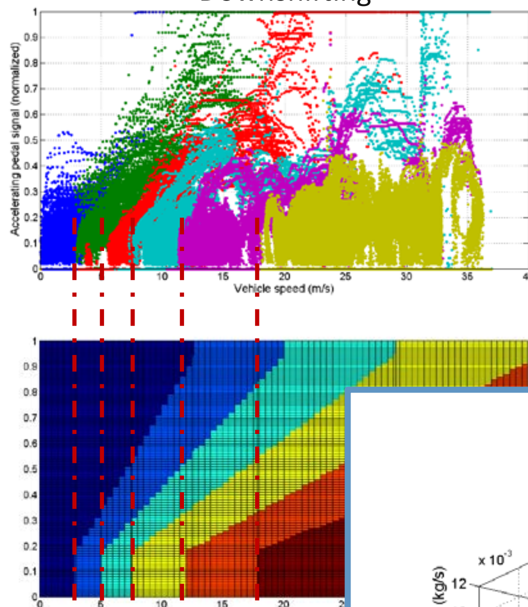
# Technical Accomplishments
## Conventional Vehicle Model Developed

Control Analysis

Upshifting

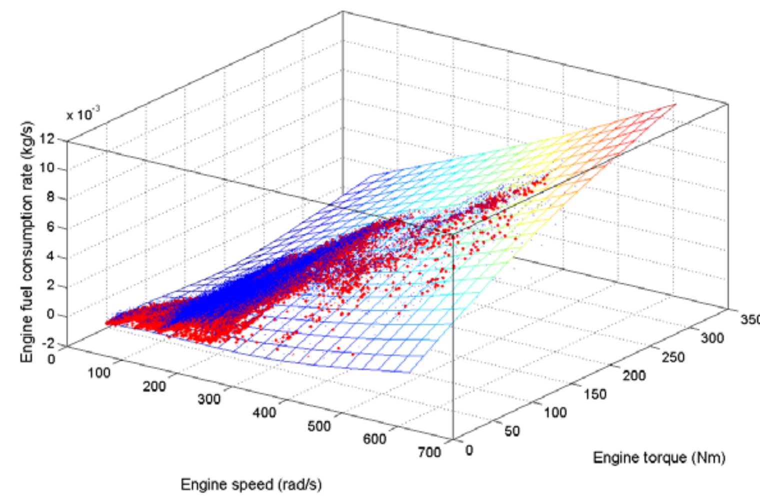



Downshifting

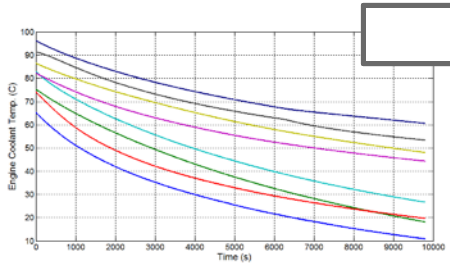


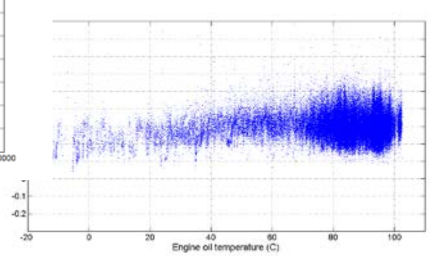

Test data for Ford Fusion was imported and analyzed for control and performances

Performance analysis

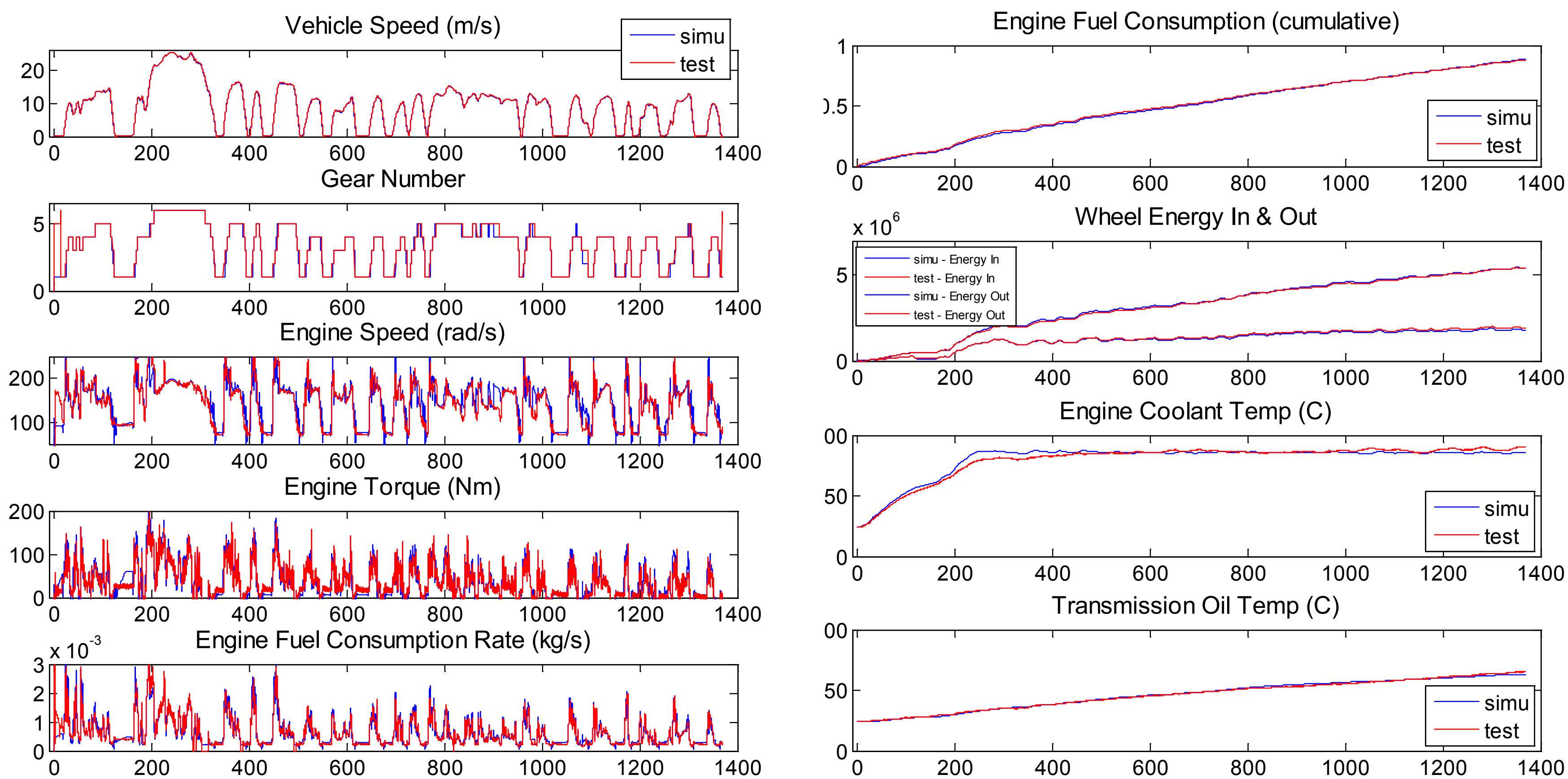



Thermal Impact Analysis



# Technical Accomplishments
## Conventional Vehicle Model Validated

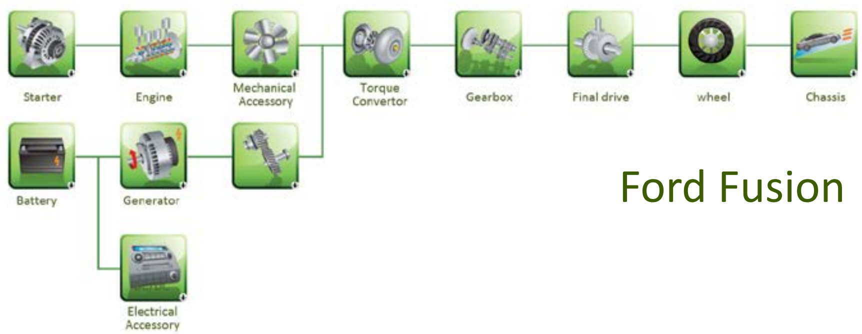


# Technical Accomplishments

## Validated Thermal Models For Multiple Powertrains

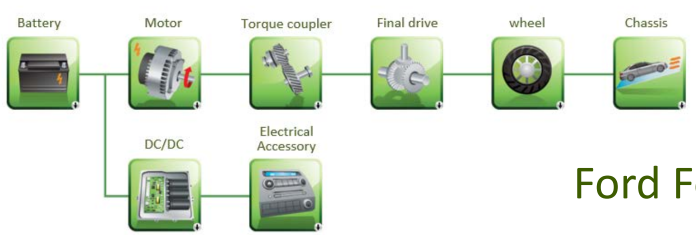
- Conventional Vehicle **– Ford Fusion**
- Extended Range Electric Vehicles (E-REV) – **GM Volt**
- Hybrid Electric Vehicles (HEV) – **Toyota Prius Hybrid**
- Battery Electric Vehicles (BEV) – **Ford Focus BEV**
- Plug-In HEVs (PHEV) – **Toyota Prius Plug-in Hybrid**

### Conventional



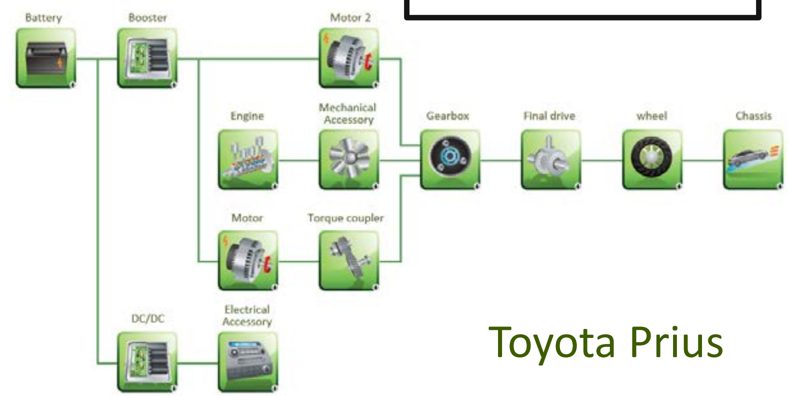

Ford Fusion

### Electric Vehicle




Ford Focus BEV

### HEV & PHEV



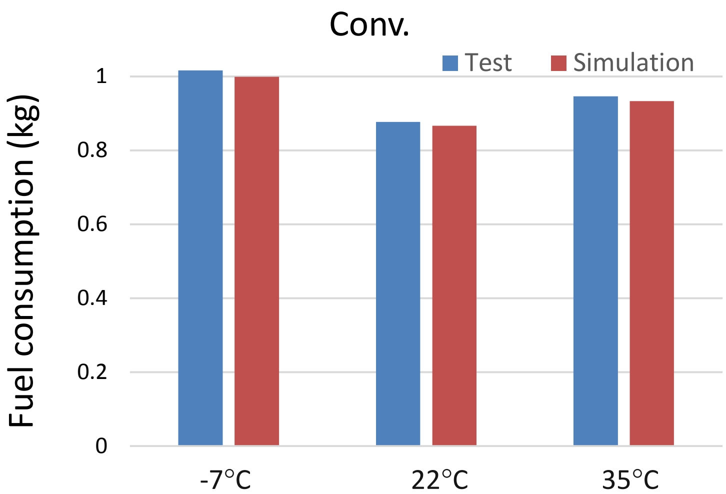

Toyota Prius

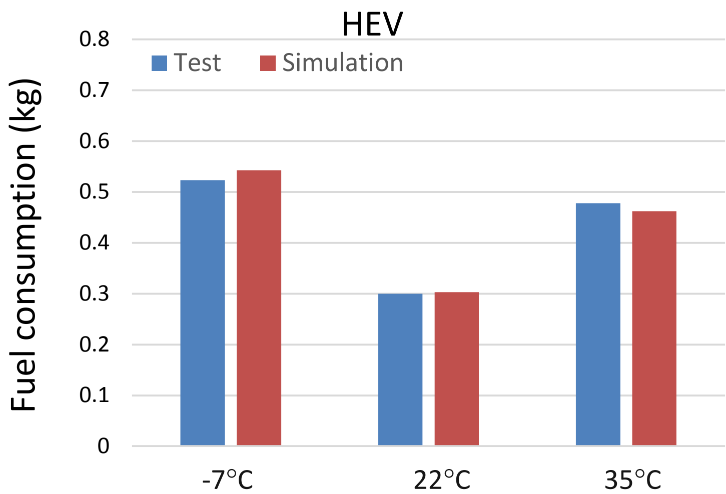
### E-REV

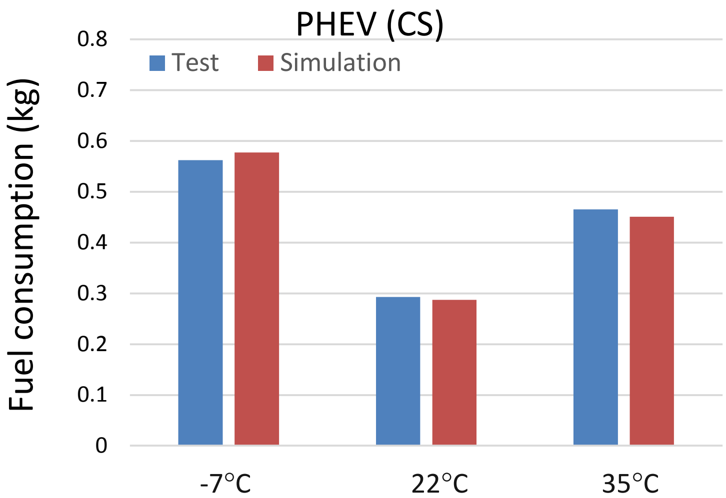

GM VOLT

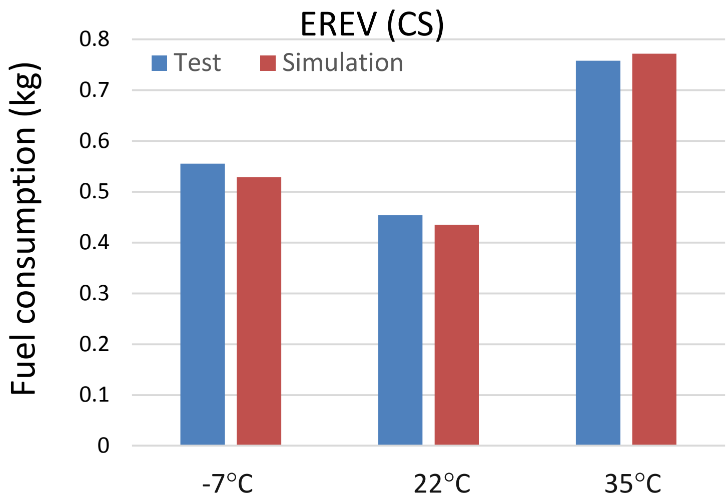
# Technical Accomplishments

## Models Validated within Test to Test Uncertainty

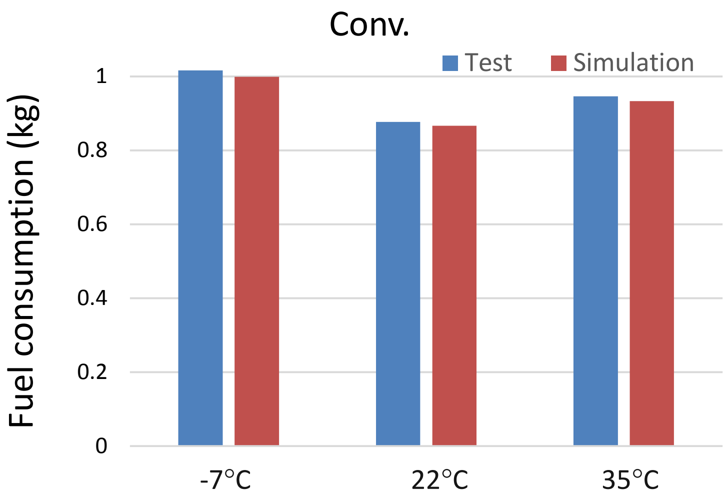


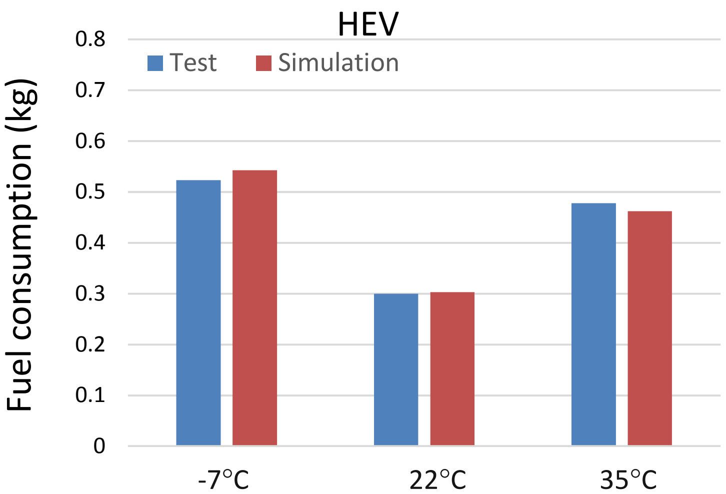



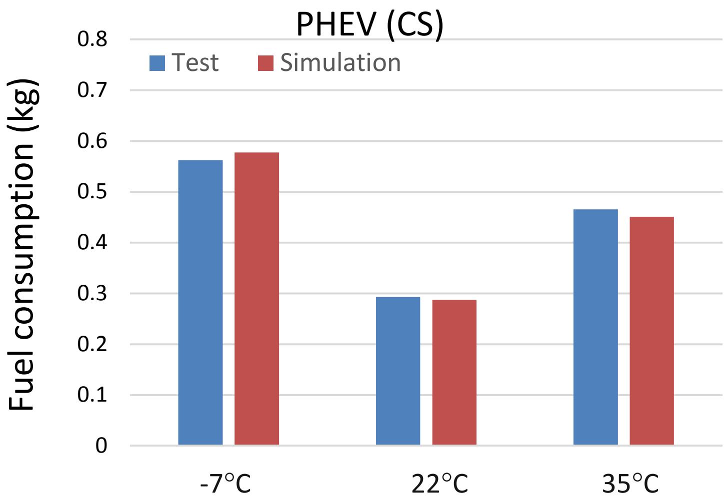



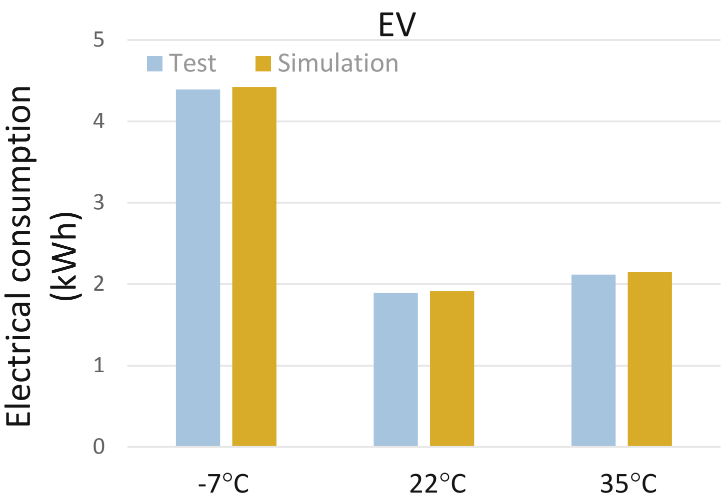



# Technical Accomplishments
## Models Validated within Test to Test Uncertainty



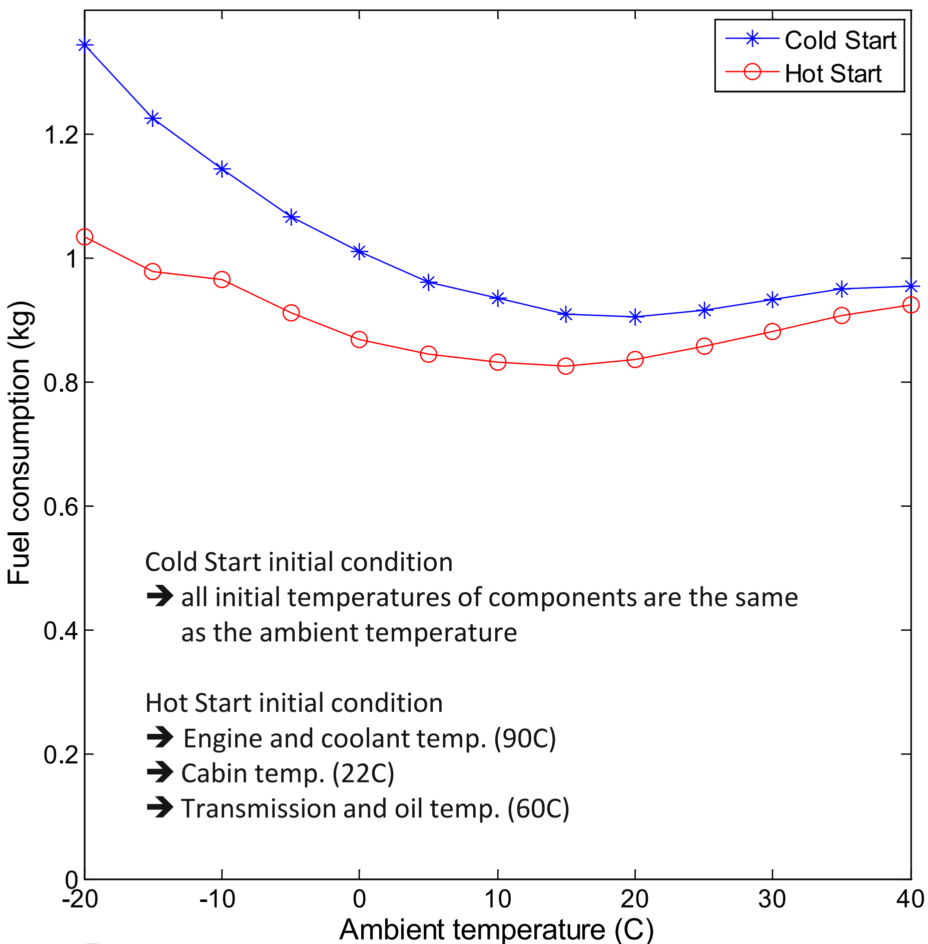



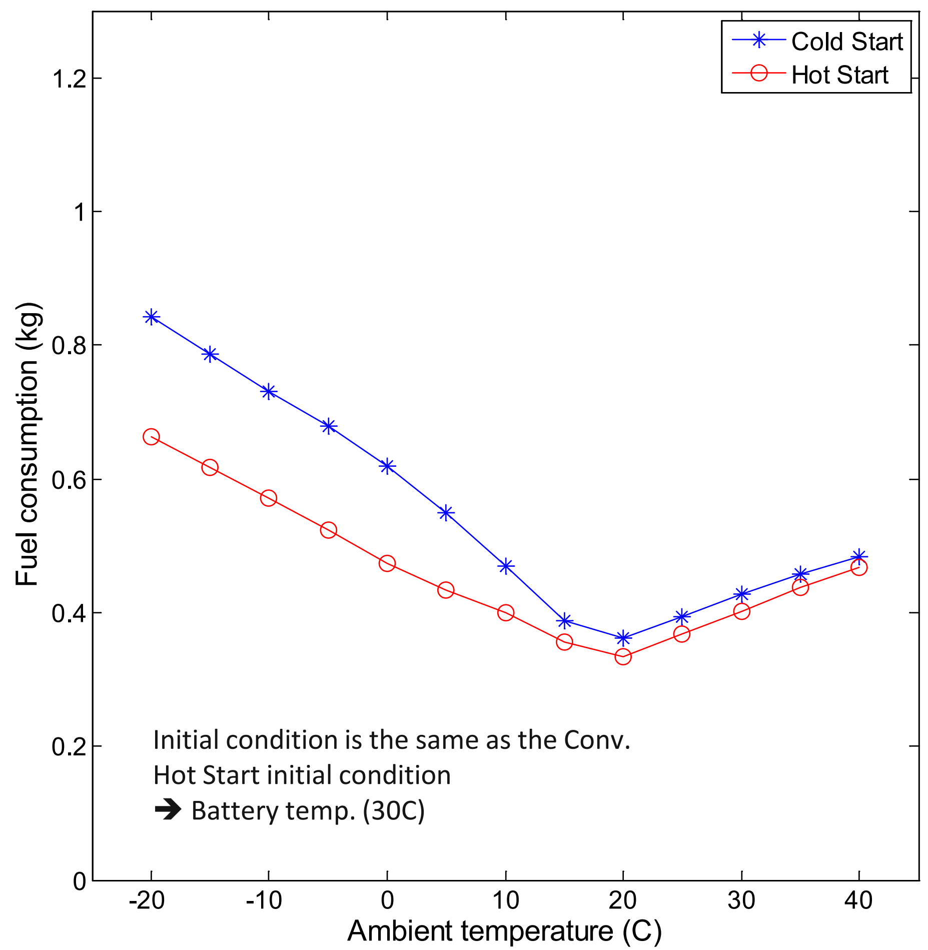
# Technical Accomplishments

## Thermal Impact On Energy Consumption (Conv. & HEV)

Conv.




HEV



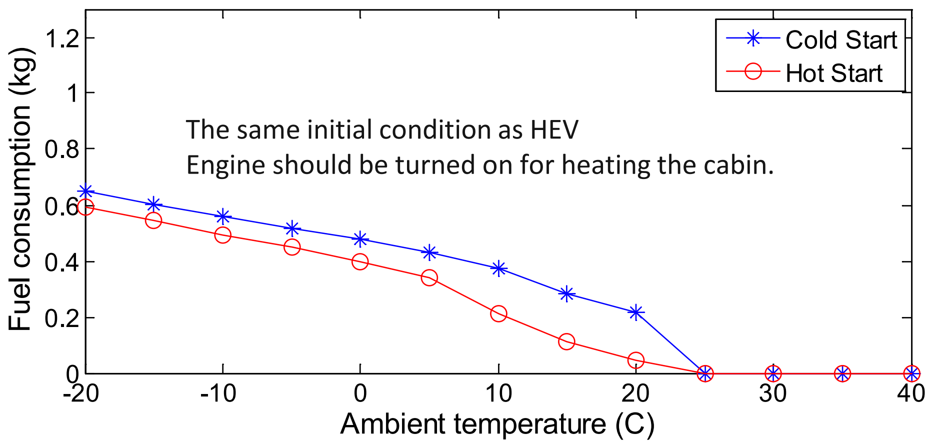

Cabin is sized, so that all vehicles have the similar hvac power consumption

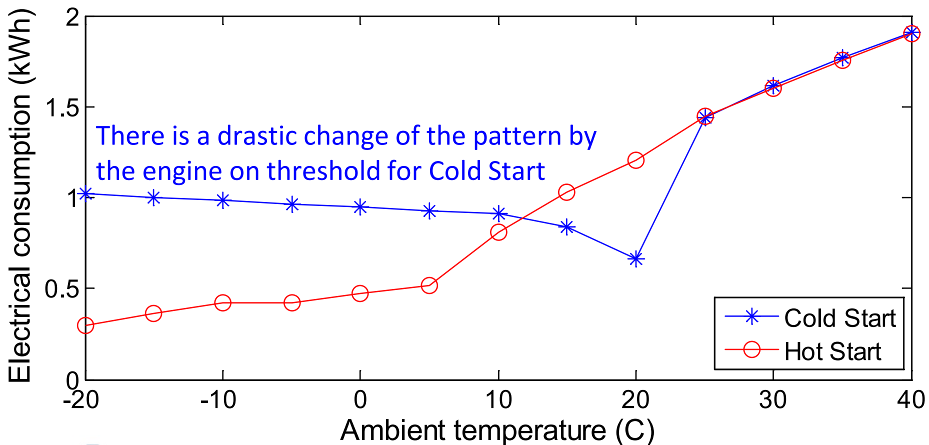
# Technical Accomplishments

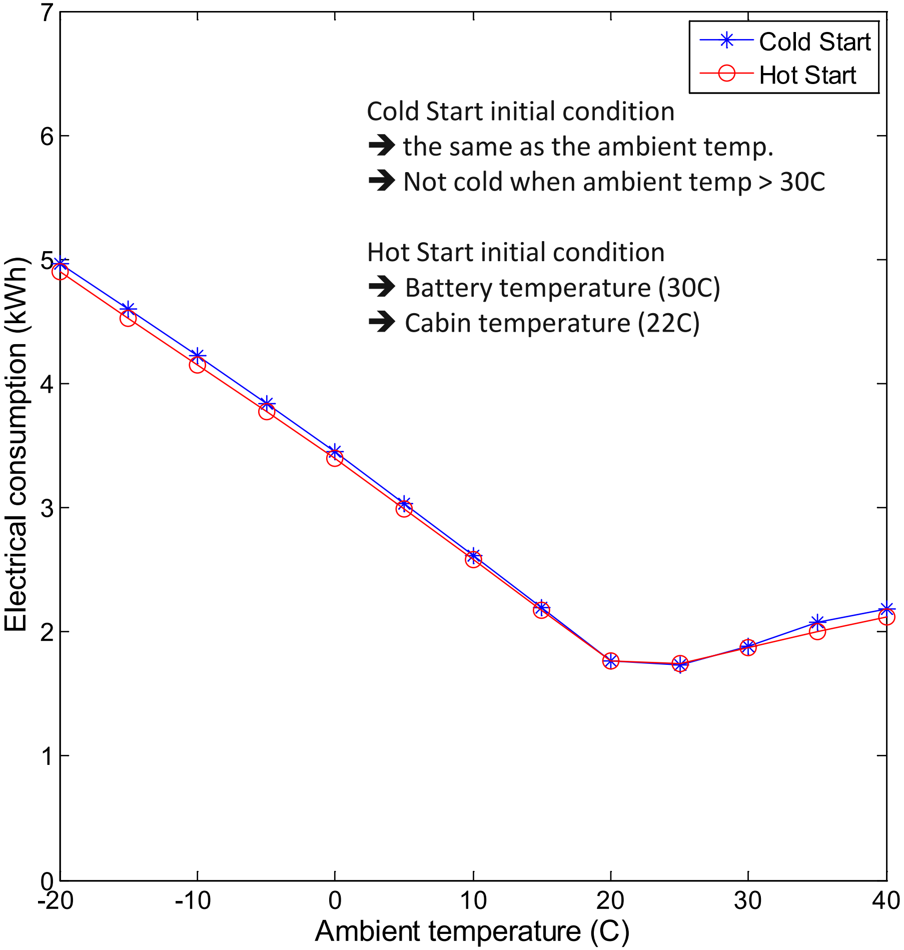
## Thermal Impact On Energy Consumption (PHEV & EV)

PHEV

EV

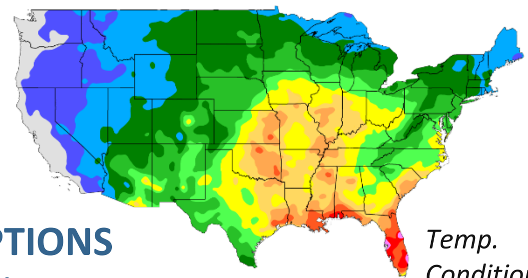


# Ongoing Work
## Real-World Scenario with Thermal Conditions

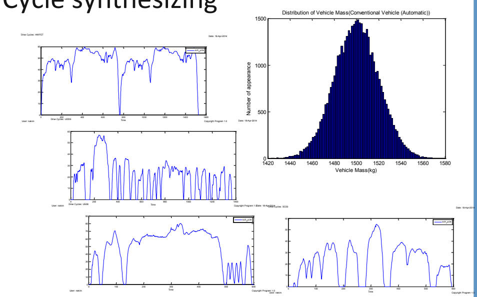
**ASSUMPTIONS**
*from multi-resources*



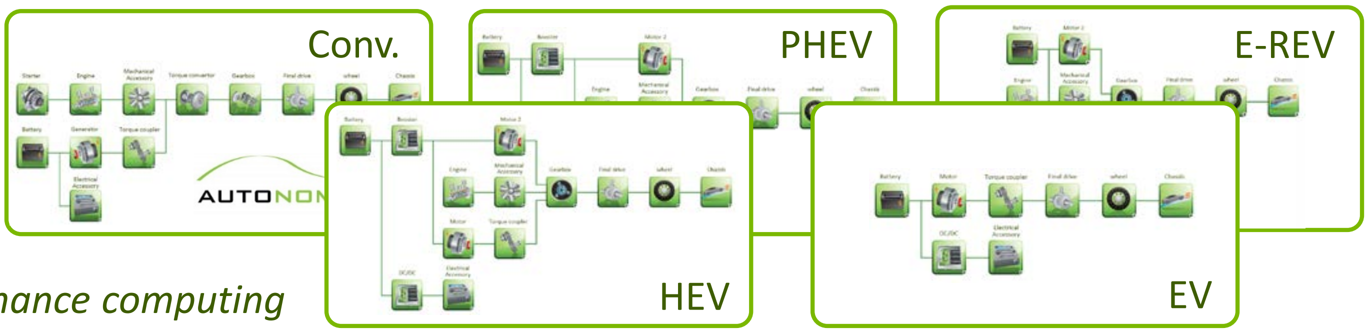
*Temp. Conditions*

*Real World Driving Cycles*

Cycle synthesizing

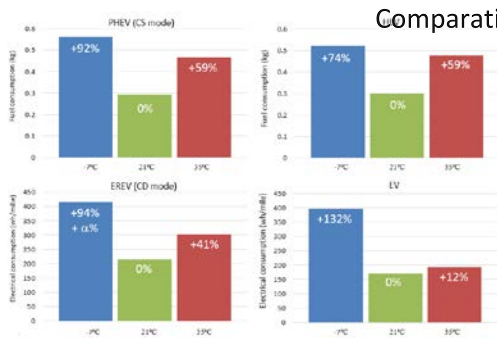


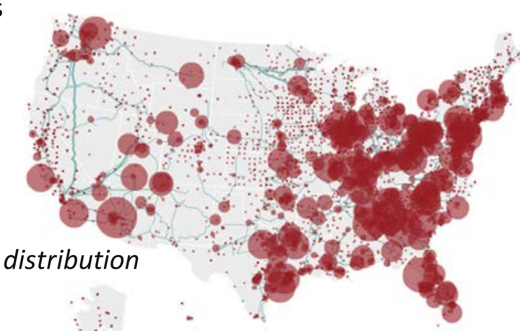

**AUTONOMIE**
*on high performance computing*




**ANALYSIS**
*by database tool*

Comparative studies

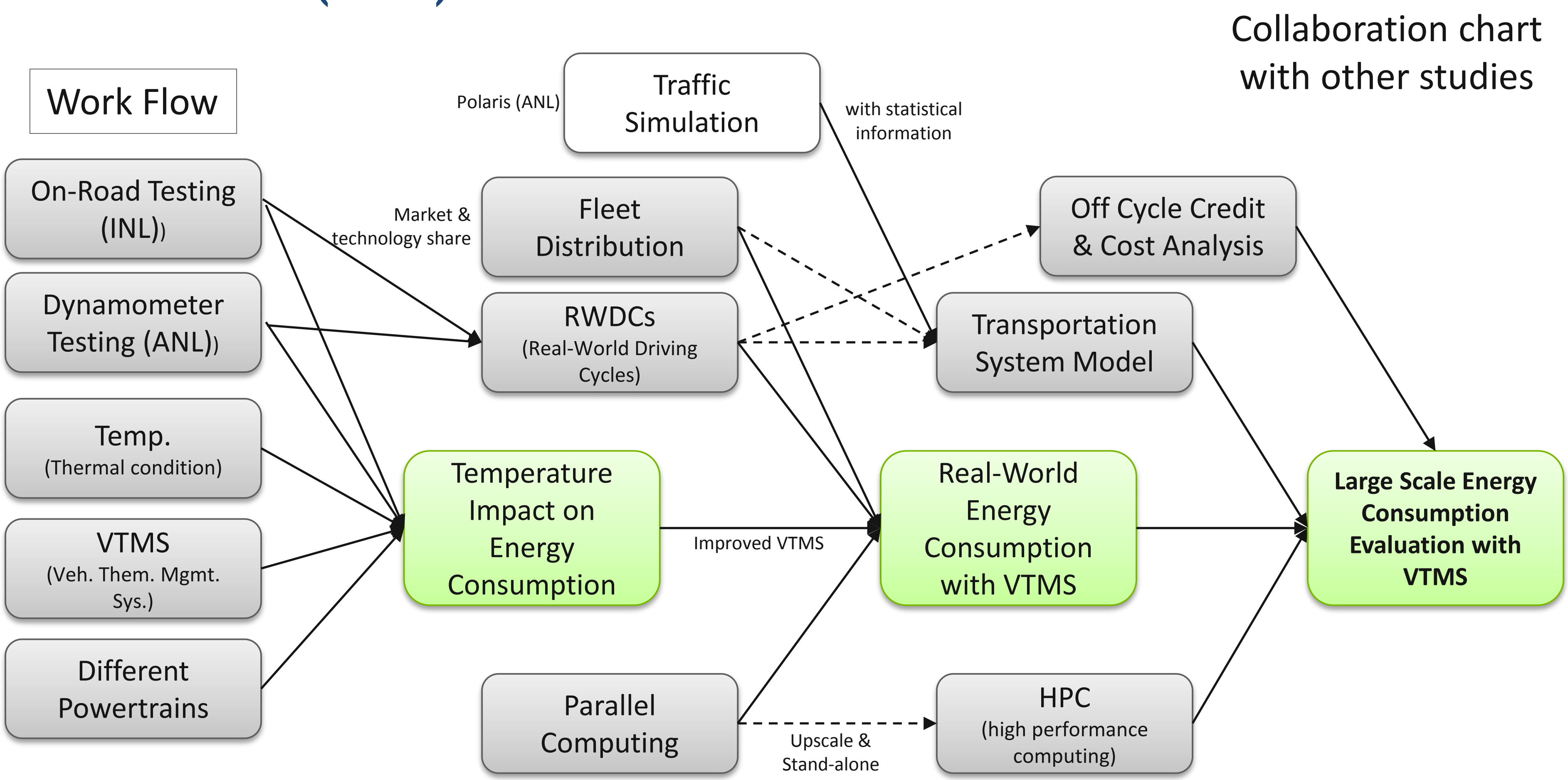


*Energy distribution*

# Multi-year Proposed Work Plan

## Large Scale Energy Evaluation Process to Leverage Road-to-Lab-to-Math (RLM)



# Summary

- Testing results from both on-road and dynamometer testing demonstrate that electrified vehicles are more affected by ambient temperature than conventional vehicles.
- This multi-year effort focuses on developing high fidelity vehicle thermal models for a wide range of powertrain comparison to (1) quantify the impact of temperature under a wide range of conditions in order to (2) mitigate it.
- Argonne continues to develop and validate Vehicle Thermal Management System (VTMS).
  - Using vehicle test data from APRF, multiple vehicle models were developed and validated
  - Thermal component models continue to be improved.
  - Conv., HEV, PHEV, E-REV, and EV models with VTMS are ready for energy analysis.
- Energy consumption with VTMS will be evaluated by
  - Using real-world conditions (RWDC, fleet distribution).
  - Modeling new component technologies to help mitigate thermal impact
  - Optimizing the energy management strategy considering the thermal behaviors.