MODELING ELECTRIFIED VEHICLES UNDER DIFFERENT THERMAL CONDITIONS

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Temperature Has a Significant Impact on the Energy Consumption of Electrified Vehicles

Test Data on the Urban drive Cycle from Argonne’s Advanced Powertrain Research Facility

- **EREV (CD mode)**
  - -7°C: +94% + α%  
  - 21°C: 0%  
  - 35°C: +41%

- **PHEV (CS mode)**
  - -7°C: +92%  
  - 21°C: 0%  
  - 35°C: +59%

- **HEV**
  - -7°C: +74%  
  - 21°C: 0%  
  - 35°C: +59%
Entire Vehicle Models (incl. Thermal) Were Developed From Test Results

Dyno test data from APRF (Argonne)

Control and Performance Analysis
- Engine operation target
- Heat capacity estimation
- Mode behaviors

Model Validation

Test data
- °C
  - 0
  - 7
  - 21
  - 35

Simulation data

Model Development (Autonomie)

SOC

Engine on/off demand

Battery power demand

Motor 2 torque demand

Driver power demand

Mode decision (Engine on/off)

Energy management (SOC balancing)

Thermal conditions

Controller

Battery

Engine

Motor

Coolant loop

Heatercore loop

Fan

Valve

Radiator

Engine room

Engine coolant loop

Temperature

Vehicle speed

Engine speed

Engine torque

Fuel consumption

SOC (%)

Time (s)
Validation Completed 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**
Component Validation
Engine Thermal Model

\[ m_{\text{eng}} C_{\text{eng}} T_{\text{eng}} = Q_{\text{fuel}} - P_{\text{work}} - Q_{\text{exhaust}} - Q_{\text{coolant}} - Q_{\text{air}} - Q_{\text{heating}} \]

- \( Q_{\text{fuel}} = H_l \cdot \dot{m}_{\text{fuel}} \)
- \( P_{\text{work}} = S_{\text{eng}} \cdot T_{\text{eng}} \)
- \( Q_{\text{exhaust}} = \dot{m}_{\text{eg}} C_{\text{eg}} \Delta T_{\text{eg}} \)
- \( Q_{\text{air}} = \alpha A (T_{\text{eng}} - T_{\text{eng\_room}}) \)
- \( Q_{\text{heating}} = f_{\text{heating}}(T_{\text{cabin}}) \)

\( Q_{\text{fuel}} \): Heat generated by fuel
\( P_{\text{work}} \): Power converted to mechanical power
\( Q_{\text{exhaust}} \): Heat exhausted by exhaust gas
\( Q_{\text{coolant}} \): Heat rejected by coolant
\( Q_{\text{air}} \): Heat transfer to engine room
\( Q_{\text{heating}} \): Heat given to cabin (cold only)

Engine, battery, cabin, wheel, motor, and gearbox models have been developed
Component Efficiency Depends on Temperature

- Engine Fuel Efficiency
- Wheel torque loss
- Battery Internal Resistance

\[ 0.00795x^2 - 1.12x + 67.1 \]
Engine waste heat is provided for HEV if the engine is turned on.
At the component level, thermal models are validated with test data.
Vehicle Control
Cooler Engine Leads to Engine Being ON for Warm-Up

**Engine is turned ON if the coolant temperature is low**

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

(b) Not turned off

**The engine is not turned OFF if the coolant temperature is low.**

Prius HEV
Engine Control Is Significantly Affected by Temperature Conditions

**Cold engine:** warm-up and idling

**In between:** produces torque, but left on at low power

**Hot Conditions:**
Engine has many ON/OFF, High Torque when ON

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**Prius HEV**

- Coolant temperature (hot)
- Coolant temperature (medium)
- Coolant temperature (cold)
Engine May also Starts to Warm-up the Cabin (no Electrical Heater)

Prius HEV

Waste heat provided for the cabin
For the Prius PHEV too, Engine Is Used for Cabin Heating

Prius PHEV under -7C ambient temperature
Vehicle Validation and Analysis
Vehicle level control is validated with test data, such as engine On/Off, SOC balancing, and operating torque.
Models Are Validated within Test to Test Uncertainty Under Different Ambient Temperature

**Conv.**

-7°C, 22°C, 35°C

Test: 1.0, 0.8, 0.8
Simulation: 1.0, 0.8, 0.8

**HEV**

-7°C, 22°C, 35°C

Test: 0.5, 0.3, 0.5
Simulation: 0.6, 0.3, 0.6

**PHEV (CS)**

-7°C, 22°C, 35°C

Test: 0.8, 0.4, 0.4
Simulation: 0.8, 0.4, 0.4

**EREV (CS)**

-7°C, 22°C, 35°C

Test: 0.7, 0.5, 0.5
Simulation: 0.7, 0.5, 0.5
Models Are Validated within Test to Test Uncertainty Under Different Ambient Temperature

**Conv.**

-7°C, 22°C, 35°C

**HEV**

-7°C, 22°C, 35°C

**PHEV (CS)**

-7°C, 22°C, 35°C

**EV**

-7°C, 22°C, 35°C

Fuel consumption (kg)

Fuel consumption (kg)

Fuel consumption (kg)

Electrical consumption (kWh)
Thermal Impact On Energy Consumption Is Analyzed Based on Simulation Models (Conv. & HEV)

**Conv.**

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

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

**HEV**

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

**Graphs**

- Ambient temperature (C) vs. Fuel consumption (kg) for Cold Start and Hot Start conditions.
Thermal Impact On Energy Consumption Is Analyzed Based on Simulation Models (PHEV & EV)

PHEV

The same initial condition as HEV
Engine should be turned on for heating the cabin.

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

EV

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

There is a drastic change of the pattern by the engine on threshold for Cold Start
Real-World Scenario with Thermal Impact

ASSUMPTIONS from multi-resources

REAL WORLD
Temp. Conditions

Cycle synthesizing

Drive Cycles: UDDS
0 200 400 600 800 1000 1200 1400
0
10
20
30
40
50
60
Time

Drive Cycles: HWFET
0 200 400 600 800 1000 1200 1400 1600
0
10
20
30
40
50
60
Time

Drive Cycles: US06
0 100 200 300 400 500 600
0
10
20
30
40
50
60
Time

Drive Cycles: SC03
0 100 200 300 400 500 600
0
10
20
30
40
50
60
Time

AUTONOMIE on high performance computing

Conv.

PHEV

E-REV

HEV

Energy distribution

Comparative studies

ANALYSIS by database tool

Distribution of Vehicle Mass (Conventional Vehicle (Automatic))

Vehicle Mass (kg)

Number of appearance

1420 1440 1460 1480 1500 1520 1540 1560 1580
0
500
1000
1500

Cycle synthesizing

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Summary

- Electrified vehicles are more affected by ambient temperature than conventional vehicles.
- Models of entire xEVs were built in Autonomie and validated using data from chassis dynamometer with thermal chamber.
- Models can be used for:
  - More accurate energy consumption prediction
  - Control optimization
- Future work:
  - Control optimization with thermal impacts
  - Estimation of energy consumption in a real-world scenario