Control of Engine for Hybrid Vehicle Emissions

SAE 2011 Electronic Systems for Vehicle Propulsion Symposium
Troy, Michigan, USA
Nov 8-9, 2011

Presenter: Michael Duoba
Contributors: H. Lohse-Busch, E. Rask
Argonne National Laboratory
Contributors: Richard Carlson
Idaho National Laboratory

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Benchmarking Program: Provide Best Vehicle Test Data Using Advanced Sensors and Testing Methods

Advanced Powertrain Research Facility (APRF)
- Custom multi-input data acquisition specific to hybrid vehicle instrumentation
- Expert staff developing test procedures for new advanced vehicles
- Inventing new and novel instrumentation techniques
Engine Operation for Charge-Sustaining Hybrids
Hybrid Operation - “start-stop”
- Different trade-offs in achieving low emissions and high fuel efficiency

2006 Civic Hybrid

2001 Prius Hybrid
Evolution of HEV Engine Control - Cold-Start
Balancing Emissions Constraints with Low Fuel Consumption

Gen 1 Prius

Crank at key start

Continued operation

Key Start

Gen 2 Prius

Button Start

2001 Prius

2004 Prius
Hybrid Assist Offers New “Levers” for Controlling Engine Start and Warm-up Emissions

Charge-sustaining operation

transients taken by battery
Hot-Start UDDS, Evolving Engine-Stop Strategy

12 Stops

Key Start

veh mph

eng rpm/100

Time [s]

2 Stops

Key Start

veh mph

eng rpm/100

Time [s]

2001 Prius Hybrid

2010 Prius Hybrid
Prius Warm-up Operation

- Prius decouples engine during catalyst warm-up (~50s), then slightly increased fuel use for ~300 seconds of cold operation
Fusion Warm-up Operation

- Fusion uses additional fueling and reduced engine off during initial ~200 seconds of cold operation.
Energy Management Comparison

- 2010 Prius charges at hills 1 and 2, while 2004 Prius stays balanced.
- 2010 Prius engine off more during hills 3 – 5.
- 2010 Prius has a larger energy swing than 2004 Prius, but has same ave RMS current (14.6) current during cycle.
Emissions Comparison “cold-start UDDS”

- Restarts are a contributor to total emissions
- Restart HC emissions not significant
- Restart NOx problematic
  - Most NOx come from restarts in Camry hybrid
- Hill 1 engine load more decoupled as time progressed
- Restart challenge for Hill 3
  - THS keeps engine unfired and spinning above 40 MPH
  - Blowing cool air through catalyst
  - Before shut-down, a short combustion event
Restart Emissions
“hot-start UDDS”

- HC emissions mostly occur at initial warm-up period
- Restarts in the last three hills in the “505” have the highest NOx
- 2010 Prius has no restarts in hill 2, however has similar NOx spikes as if there were
- In latter half of UDDS, 2010 Prius has no NOx spikes, but does have small HC spikes
PHEV Energy Management and Engine Operation
Two Types of PHEV Operation During Testing

**EREV**: Defined as having the ability to drive all-electric under driving style (max power in electric)

**Blended**: Does not have a “full performance” electric drive system. Engine operation needed during some or all test cycles. Although small electric drive, blended PHEVs can displace a significant amount of fuel use.
Characteristic Engine Demands Differ by degree of Electric Power

- EREV
- Intermediate “Urban-Capable”
- Blended

- Both electric-capable in this cycle

- Wheel kW
  - 20 kW
  - 35-40 kW
  - 70 kW

- US06 and Max Accel [kW]
  - 20 kW
  - 35-40 kW
  - 70 kW

- Wheel kW
  - 10 kW
  - 20 kW
  - 30 kW
  - 40 kW
  - 50 kW
  - 60 kW
  - 70 kW
  - 80 kW
Aftermarket Conversion Prius PHEV
- Engine Must Assist E-Drive = “Blended Operation”

Advanced Engine Control Symposium, Tianjin, China, Nov 3-4, 2010
PHEVs Have Varying Depletion Rates

**Prius Conversion #1**
- MPG = 172
- Wh/mi = 157
- 62% Petroleum Displacement
- Depleting Range = 31 miles (4.3 kWh usable)

**Prius Conversion #2**
- MPG = 94
- Wh/mi = 80
- 29% Petroleum Displacement
- Depleting Range = 87 miles (7 kWh usable)
Utility Factor Analysis Favors Rapid Depletion
- Displacing fuel overrides inefficient engine operation

Prius Conversion #1
4.3 kWh usable
MPG = 172
Wh/mi = 157
Range = 31 mi
UF = 54.5%

UF-Weighted MPG = 101.4 MPG

Prius Conversion #2
7 kWh usable
MPG = 93.6
Wh/mi = 79.7
Range = 87 miles
UF = 83.8%

UF-Weighted MPG = 88.2 MPG

- Note that the PHEV with more battery, has lower MPG rating
- Because, faster depletion rate displaces more fuel, more often
Varying Depletion Rates Interact With Engine Load Points

- Favorable efficiency
- Maximum depletion
- Theoretical EV depletion
- Maximum Eng Power
- Eng-On Power (without excess charge)
- Max depletion w/ load-following
- Charge-Sustaining
- SOC
- Time

(a) Max depletion maintaining good Eng efficiency w/o excess charge
(b) Max depletion with Eng assist at favorable efficiency
(c) Absolute maximum depletion
(d) Engine-On Pwr
(e) Charge-balanced operation

Road load power plot

Engine Power
Max EV Pwr Limit
Favorable Eng Efficiency Pwr Levels

SOC (end of depletion)
Max Eng Chrg
PHEV Emissions and Engine-On Strategy
Engine Temperature Never Reaches “Normal” Operating Temp

**Charge Sustaining**
- Early engine temp rise comes from hot coolant purging from storage canister (emissions feature of Gen 2 Prius)
- Normal engine On/Off keeps engine temp low (70-75 C)

**Charge Depleting**
- Late start controls
- Temperature only reaches ~40 C
- Engine is cooling from infrequent operation
Emissions Control Possible After Long Periods of Engine-Off

Normal cold-start emissions

No emissions after long shut-down

>700s (~12min) of EV operation

Normal emission control

Engine speed (/100)

Emissions (HC, CO, NOx)

Advanced Engine Control Symposium, Tianjin, China, Nov 3-4, 2010
Prius PHEV Testing
Max Depletion Mode
UDDS - emissions

- Late start
  - Saves fuel
  - Detrimental to emissions
Prius PHEV Testing
UDDS - Emissions

- Engine operation in 1st hill similar to production Prius
- Following UDDS emissions remain high to infrequent engine operation
Thermal Management Hardware May Be Key to Future PHEV Emissions / Fuel Consumption Trade-Off

2010 Toyota Prius
Exhaust Heat Recovery System

No doubt this system will be helpful in PHEV Prius

Reduced fuel economy penalty between the “warm-start” and “cold-start” EPA City cycles

Engine-Off Percentage for EPA Fuel Economy Test Cycles

Engine-off time is particularly improved at “cold” conditions
Conclusions

- Frequent engine start-stop must be managed
  - Emissions
  - Lower temperatures
- HEV and PHEV can decouple engine from load demands
  - Helps in initial start
  - Transients smoothed
- Prius engine control has evolved noticeably from 2001 to 2010. However, it is hard to assign improvements to any particular change with all the complex system interactions and changing hardware features
- Blended PHEV emissions control requires heating engine before high loads required - lowers ability to deplete
- Once engine is hot, PHEV emission control system still effective for long periods of engine off operation
- Exhaust heat recovery system in the 2010 Prius is well-suited to help warm-up and maintain temperature in blended depleting operation.