Engine Design, Sizing and Operation in Hybrid Electric Vehicles

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Question to Engine Experts: “Are your days numbered?”

“Are you ready to switch to electric vehicles? It is my dream to see our roads with at least 90% EVs so that there’s more efficient use of our energy and resources. The internal combustion engine is one of the most wasteful machines ever invented and we all should prepare the world for the energy crisis we will face when crude oil extraction enters the decline phase.”

- Ricardo Parker, reader blog, Seattle PI
Answer: No

EVs Can Not Be The Primary Household Vehicle. Consumer Acceptance is Limited (with current technology)
Hybrid Vehicle Sales Going Up! Predicted to Top 4 Million by 2015.

- Consumer Reports: 39 percent are considering a hybrid or electric power type for their next new car
- Other analysts say “~50 HEV models by year 2015,” “10% of sales”
Engine Design, Sizing and Operation in HEVs

Discussion Outline

- **Introduction**: Powertrains and Hybrids
- **Engine Start and Re-start**: Emissions and fuel concerns
- **Peak Efficiency**: Engine maps, transmissions, load points (*CVTs*, *EVT*)
- **Sizing**: Downsizing for hybrids?
- **HEVs and Thermal State**: Reducing fuel use with thermal management
- **PHEVs**: Unique operation and challenges (*blended, not blended, US06, EREV engines*)
Introduction
Powertrains, Hybrids, Operation
Argonne State-of-the-Art Laboratory for Research in Vehicle Systems Analysis

Advanced Powertrain Research Facility (APRF)
- Custom multi-input data acquisition specific to hybrid vehicle instrumentation
- Staff at cutting edge of test procedures for new advanced vehicles
- Inventing new and novel instrumentation techniques
Powertrains: Torque and Speed to Drive at the Wheel

Prius
Veh Wt: 3250 lbs
Road Load Force
\[ F = A + Bv + Cv^2 \]
A = 25
B = 0.139
C = 0.0164

Mismatch is only a problem for engines. Motors can in fact be designed to satisfy wheel demands.
Compare Wheel Requirements to Engine Capability
Compare Wheel Requirements to Engine Capability

Transmission and Brake System

Varied Drive Ratios Needed

Launch Mechanism Needed

Braking Torque Device Needed
## Terminology for “Electrified Vehicles”

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Electric Power</th>
<th>Electric Storage</th>
<th>Grid Connected</th>
<th>Electric Driving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild HEV</td>
<td>Low</td>
<td>Low</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Full HEV</td>
<td>Med</td>
<td>Low</td>
<td>No</td>
<td>Very limited</td>
</tr>
<tr>
<td>Blended PHEV</td>
<td>Med</td>
<td>Med</td>
<td>Yes</td>
<td>Limited</td>
</tr>
<tr>
<td>Intermediate PHEV</td>
<td>Med+</td>
<td>Med</td>
<td>Yes</td>
<td>UDDS cycle</td>
</tr>
<tr>
<td>E-REV PHEV</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
<td>Full Performance</td>
</tr>
<tr>
<td>BEV</td>
<td>High</td>
<td>High</td>
<td>Yes</td>
<td>Full Performance</td>
</tr>
</tbody>
</table>
Hybrid Architectures

Power-Split
- Toyota Prius
- Ford
- GM complex 2-Mode has fixed gear capability

Honda System
- Insight, Civic, CR-Z

Hyundai System
- Sonata “1-motor”
- Nissan has slightly different 1-motor design
## Hybrid and Advanced Powertrain Operational Features

<table>
<thead>
<tr>
<th>Method</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Idle Stop</td>
<td><img src="non-hybrid" alt="Mazda 3" />  eAssist (all hybrids)  <img src="non-hybrid" alt="Prius" /></td>
</tr>
<tr>
<td>Best Line in Map</td>
<td><img src="EVT" alt="Prius" />  <img src="CVT" alt="Insight" />  <img src="CVT" alt="CVT" /></td>
</tr>
<tr>
<td>Engine Downsizing (electric assist)</td>
<td>Hybrids: Engine smaller or Performance Up</td>
</tr>
<tr>
<td>Low-Load Electric Driving</td>
<td><img src="Power-split" alt="Prius" />  <img src="Power-split" alt="Fusion" />  <img src="Parallel" alt="Sonata" /> (full hybrids)</td>
</tr>
<tr>
<td>Regenerative Braking</td>
<td>All Hybrids (Full HEV recovers most)</td>
</tr>
<tr>
<td>Transient Smoothing</td>
<td>All Hybrids (more power = more torque authority)</td>
</tr>
</tbody>
</table>
Engine Start and Re-Start

Emissions and Fuel Concerns
THS Initial Engine-Start Strategy

“Cold-Start” UDDS

- Hill 1 of UDDS requires low driving loads. Motor handles driving while engine employs controlled warm-up strategy.
- Conservative cold-start strategy employed in 2001 Prius. No shut-down between hills 1 and 2.
- 2004 Prius delays engine start after key start
- 2004 Prius shuts down engine between hills 1 and 2
Cold Hybrid Engine Start Strategy Analysis

MY 2010 Prius uses a unique cold-start/catalyst warm-up strategy

- Fast catalyst warm-up with minimal fueling
- Reduced engine speed variability during vehicle warm-up
Hybrid Operation Different Between Mild and Full Hybrids
- Different trade-offs in achieving low emissions and high fuel efficiency

2006 Civic Hybrid

2001 Prius Hybrid
Hybrid Engine Thermal Conditions Also Different

- In transient driving, full hybrid engines spend considerable time OFF.
- Cylinder, head/port temperatures, fueling strategies different
- Catalyst temperature management strategies different
Prius exhaust-to-coolant heat exchanger for improved warm-up.

* Figures from TMC Prius Manual
Peak Efficiency
Engine maps, transmissions, load points (CVTs, EVT)
Power-Split Design Enables Variable Ratio
Ratio of infinity possible - launch capability

"Best Line" shown on engine efficiency map

Test results using in-situ torque sensor

Source: ANL data
Location of Peak Efficiency

- Electric assist allows engine to operate in high torque region at given speed
  - Minimal “torque reserve”

- For EVT operation, peak system efficiency may not be peak eng eff
  - Assist can keep engine in efficient zones during transients

- No enrichment zone in map
Low Load Electric Driving Eliminates Lowest Efficiency Operation

Interesting Side Note:
Low-load electric driving affects engine sizing
- Honda Insight and Civic (1.3L)
- Prius (1.5-1.8L)
Smaller engines are more efficient at low loads
Engine Sizing
Is smaller = Better?
Conventional Wisdom, smaller always better?

Smaller engine = Higher MPG!

Hybrids allow more engine downsizing while maintaining performance
Downsizing Limits → Baker Grade

- Hybrids boost for seconds, not minutes
- Over-downsized hybrid will be a traffic hazard!
Regen Level Determines Optimum Level of Hybridization

From Toyota.com
Traction Battery Type: Sealed Nickel-Metal Hydride
Power Output: 36 hp (27 kW)
Voltage: 201.6V
Peak Efficiency - Atkinson Cycle
With respect to peak power, Atkinson Cycle is downsizing

- 2011 Prius 1.8L – 142 N-m
- Toyota Matrix 1.8L – 169 N-m
- Honda Civic 1.8L – 174 N-m
Downsizing? In 2010, Prius Engine Got BIGGER!
MPG: 46 → 50
MPG Improvement Comes From Several Changes

- Same power achieved at lower RPM
- Larger high-efficiency window
Plug-In HEVs (PHEV)
More challenges, more departures from “conventional”
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.
Wheel Power Requirements Show When Electric Dive Can Displace Engine Operation

- EREV
- Intermediate “Urban-Capable”
- Blended

Both electric-capable in this cycle

70 kW
35-40 kW
20 kW
-04Prius Full Accel

UDDS Cycle [kW]

US06 and Max Accel [kW]
Engine Temperature Never Reaches Operating Temp

Charge Sustaining UDDS
- 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 UDDS
- Late start controls
- Temperature only reaches ~40 C
- Engine is cooling from infrequent operation
UDDS Emissions Can Suffer from Too Much EV Operation

Engine Operation
- Large emissions spike at first engine operation
- Google staff ironically referred to delayed-start calibration as the “low-emissions” calibration
Emissions Control Possible After Long Periods of Engine-Off

Normal cold-start emissions

No emissions after long shut-down

>700s (~12min) of EV operation

Engine speed (/100)

Emissions (HC, CO, NOx)
Future Engine Technology in Hybrids - Any Synergies?

- Diesels and Hybrids
  - Old Assumption = Diesel or Hybrid, never diesel-hybrid
  - New lesson = Peugeot 3006 full hybrid with diesel engine
- HCCI Engines (and other advanced combustion)
  - Design and control suited for limited operation regime
  - HEV configuration with very controllable load and speeds
- Lean Burn and Other Combustion Strategies
  - Decoupling engine load from driving demands offer more opportunities for care and feeding of advanced after-treatment controls
  - Diesel DPF regen and rich events for lean-burn better controlled
- Less Demanding Engine Design Requirements
  - Turbo lag less important
    - Eliminate expensive anti-turbo-lag technology in modern small turbos
    - Optimize peak efficiency at low loads, less compromises for peak power / liter
- More Demanding Idle-Stop Requirements
  - Emissions concerns in restart
  - DI engines may be better suited for idle-stop
Conclusions

- **Complexity**: Engines are parts of a complex powertrain that are designed, sized, and controlled to meet very specific requirements.

- **Optimization**: By optimizing the whole system, engine design can be better suited for operation that can be very different than for conventional vehicles.

- **Peak Efficiency**: Hybrid assist allow high peak efficiency during normal driving. Efficiency not important at idle and off-idle loads.

- **Engine Sizing**: Downsizing only goes so far in hybrids.

- **Thermal Management**: Attention must be given for keeping engine warm to reduce losses and lower fuel consumption.
For More Information

Google Search:
- Argonne Transportation
- Downloadable Dynamometer Database (open to anyone)
- Advanced Powertrain Research Facility

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