Plug-in Hybrid Powertrain Configuration Comparison Using Global Optimization

2008 ASME Dynamic Systems and Control Conference,
Ann Arbor,
October 21st, 2008

Dominik A. Karbowski, Karl-Felix Freiherr von Pechmann, Sylvain Pagerit, Jason Kwon
Argonne National Laboratory

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Outline

- Introduction
- Vehicle Sizing
- Global Optimization Algorithm
- Simulation Results
- Conclusion
PHEVs Come in Various Powertrain Configurations: How to Compare Them?

- Plug-in Hybrid Electric Vehicles (PHEVs) combine:
  - long range, high power density and easy energy refill
  - low tailpipe emissions, high fuel displacement (on short daily trips)
- Various hybrid powertrain configurations are possible: *how do they compare in a PHEV context?*
- Prototypes exist, but built upon different requirements, sizes, electric ranges, etc.

*Simulation tools must be used for a fair comparison!*

**Chevrolet (GM) Volt (Series)**

**Toyota Prius PHEV (Power-Split)**

**Mercedes Sprinter PHEV (Parallel Pre-Transmission)**
Choosing the Most Suitable Simulation Tool

- Argonne’s PSAT
  - Forward-looking model
  - Includes Transients
  - Rule-based control

- Global Optimization
  - Backward-looking model
  - Steady-state model
  - Control is an output

Global optimization allows a “fair” comparison
Study Process

1. Define Vehicle Requirements
   - Industry standards
2. Size Vehicles
   - PSAT + Automated Sizing
3. Optimally Simulate Vehicles
   - Different cycles, Different distance
4. Analyze data

Implement optimization code for various configurations
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## Requirements and Assumptions

<table>
<thead>
<tr>
<th>Type</th>
<th>Requirement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-electric Range</td>
<td>10 mi (16 km) on the UDDS</td>
<td>90% to 30% SOC</td>
</tr>
<tr>
<td>Grade</td>
<td>6%@65 mph (105 km/h)</td>
<td>@GVWR, w/o using the battery</td>
</tr>
<tr>
<td>0-60 mph (97 km/h)</td>
<td>9.3s</td>
<td>@ 30% SOC</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>&gt;100 mph (160 km/h)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glider mass</td>
<td>1142 kg</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.28</td>
</tr>
<tr>
<td>Frontal area</td>
<td>2.3 m²</td>
</tr>
<tr>
<td>Rolling resistance</td>
<td>0.009</td>
</tr>
<tr>
<td>Wheel Radius</td>
<td>0.332 m</td>
</tr>
</tbody>
</table>

Comparable to Toyota Camry, Chevrolet Malibu
Automated Sizing Routine

- Motor and battery power sized for the UDDS
- Engine power sized for the grade
- Engine (and motor in series config.) size increased if 0-60 mph requirements not met
- Battery energy sized to meet the AER requirements
- Mass is function of components characteristics
- Based on PSAT simulations
Sizing Results

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>1782</td>
</tr>
<tr>
<td>Power-Split</td>
<td>1824</td>
</tr>
<tr>
<td>Series</td>
<td>1793</td>
</tr>
</tbody>
</table>
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Global Optimization Uses a Backward Model, Based on Look-up Tables

- **Parallel Pre-Transmission**
- **Power-Split**
- **Series**

- Engine (ICE), electric machines (MG) : input power (thermal or electric) is function of output torque and speed
- Battery voltage and resistance is function of SOC
Optimization Problem

- **State:** Battery State-of-charge (SOC)
- **Command** $u$:
  - gear and engine **torque** (Parallel)
  - generator **power** (Series)
  - engine **power** (Power-split)
- **Link between state and command:**
  \[
  \frac{dSOC}{dt} = - \frac{I_{ess}(P_{ess}(u, SOC))}{Q_{ess}}
  \]
- **Initial and final conditions:** initial SOC between 90 and 30% , final SOC=30%,
- **Cost function to minimize:**
  \[
  J(SOC, u) = \int_0^{t_{end}} (P_{fuel}(SOC, u) + P_{pen}) dt
  \]
- **Constraints:**
  - Vehicle follows drive trace
  - Keep ICE and EM speed/torque within limits
  - Keep battery current within limits
  - Series & power-split: torque and speed such that for a given power ICE operates optimally
- **Method:** application of Bellman’s principle
Algorithm Outputs Results for Different \( \Delta \text{SOC} \)

1 vehicle
1 cycle
1 distance
1 run

\begin{align*}
\text{Plug-to-Wheel Wh/km} & \begin{array}{c}
0 \\
0.1 \\
0.3 \\
0.5 \\
0.6 \\
\end{array} \\
\Delta \text{SOC} & \begin{array}{c}
0 \\
0.1 \\
0.3 \\
0.5 \\
0.6 \\
\end{array}
\end{align*}
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In Series, Engine Starts “Later” and Is Used More Often To Charge The Battery

- **Power at the Wheels Above Which ICE Is ON 95% of the Time**
- Power-split and parallel follows similar trends
- Series “Engine ON” threshold is higher => ICE is ON less often and at higher loads

**Ratio of ICE Energy Used to Charge the Battery**

- Much more Charging for the Series
In Series Config., ICE is Used at Higher Power for Higher Efficiency

- **Average Engine Power (when ON)**
- Different trends:
  - Series = independent of Wh/km
  - Parallel = higher for higher Wh/km
- Series: ICE power is much higher

**Overall Engine Efficiency**
- Similar trends to average power
- Series = engine operates close to maximal efficiency (36%)
- Parallel = much lower efficiency in CS mode
- Power Split = in between
On The UDDS Power Split Seems to Be the Best Compromise

- Charge-Sustaining: Series config. uses most fuel, due to poor electric transmission efficiency
- Parallel uses the least fuel, as engine-to-wheel path is more efficient
- In electric-only, parallel is penalized by the transmission efficiency
- Power-Split performs well is both situations
Similar Hierarchy When Using Other Cycles

- In charge-sustaining mode, the difference between the series configuration and the two other ones is more important on more energy-intensive cycles (HWY) or aggressive (LA92).
- The difference between parallel and the other ones is less significant on LA92 or HWY.
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Conclusion

- Comparing different powertrains requires a common set of requirements.
- An automated routine using PSAT allows to quickly size vehicles.
- Global optimization can be used to ensure “fair” comparison, because control is optimal.
- Series is potentially more efficient on the “electric-only” side, parallel (pre-tx) is potentially more efficient on the “charge-Sustaining” side, power-split is a good compromise.
- Global optimization is a theoretical tool, and in real-world optimal control is harder to get because:
  - it requires the knowledge of the cycle beforehand
  - real-world must also take into account drivability, safety, etc.
- However it provides the theoretical boundaries, as well as control patterns.
- Future work will use patterns obtained from global optimization to implement adaptive rule-based controls.