Tradeoff Between Powertrain Complexity and Fuel Efficiency

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Namdo Kim, Jason C. Kwon, and Aymeric Rousseau
Argonne National Laboratory, USA
Introduction

- Toyota Prius, and some other hybrids, use a “Power Split” system:
  - Engine speed can be controlled independently from the vehicle speed
  - Relatively low efficiency in the high-speed region
- Combining several EVT modes into one “Multi-mode” hybrid system, thereby increasing the number of MPs and allowing greater operation flexibility
- Dozen of patents on multi-mode EVT design configuration

- EVT efficiency of electro-mechanical power path increases with powertrain (PT) configuration complexity
- EVT mechanical losses also increase with PT complexity

The objective is to evaluate the benefits of several multi-mode powertrain configurations from a fuel consumption and cost point of view.
**What is an EVT?**

- **Electrically Variable Transmission**
- Continuously variable, using gearing and electric motors
- Used with a battery pack in hybrid electric vehicles.
- **Examples:**
  - Single mode w/o FG: Toyota Prius04
  - Single mode w/ FG: Prius10, LS600, HS 250h, Ford Escape,…
  - Two mode w/o FG: Allison EP40 and EP50 bus hybrid
  - Two mode w/ FGs: Saturn Vue HEV, GM Tahoe HEV
  - Three&Four mode w/ FGs: Being developed by OEM

FG = Fixed Gear
Technical Accomplishments
Understand Efficiency Potential of Each Multi-Mode

Note:
- Power ratio = electro-mechanical power / all-input power
- Minimize the power ratio, which is more efficient and transmit more power mechanically
Technical Accomplishments
Understand Efficiency Potential of Each Multi-Mode

Note:
- The efficiency of the multi-mode system has relatively high value
- Additional mode can allow to maintain high efficiency over a wider range

Efficiency (@ W-eng=1500rpm, T-eng=100Nm)

Single Mode

Two Mode (1)

AHS2 FWD

Three Mode

SR, the ratio of W-eng to W-out
Seven Configurations are Considered

**Single Mode**

PRIUS : 2 Electric Motors
- 1 Planetary Gear Set (SPPG)
- no Wet-Plate Clutches

ESCAPE : 2 Electric Motors
- 2 Planetary Gear Set (SPPG)
- no Wet-Plate Clutches

**Single Mode w/ RG**

**Two Mode w/o FG**

P6,478,705 : 2 Electric Motors
- 2 Planetary Gear Sets (only SPPG)
- 2 Wet-Plate Clutches

**AHS2 FWD (Two mode w/ FGs)**

P7,220,203 : 2 Electric Motors
- 2 Planetary Gear Sets (SPPG, DPPG)
- 4 Wet-Plate Clutches

**AHS2 RWD (Two mode w/ FGs)**

P6,953,409 : 2 Electric Motors
- 3 Planetary Gear Sets (only SPPG)
- 4 Wet-Plate Clutches

**Three & Four Mode w/ FGs**

P7,645,206 : 2 Electric Motors
- 3 Planetary Gear Sets (SPPG, DPPG)
- 5 Wet-Plate Clutches

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AHS = Advanced Hybrid System (GM 2 Mode)
Modeled Different Transmissions

Note:
- Transmission models developed in SimDriveline to allow for modeling of detailed losses (Transmission spin loss, Hydraulic oil loss).
- Low level control developed for each transmission

Using Argonne Powertrain System Analysis Toolkit:
- forward-looking powertrain simulation environment
- dynamic plant models
- Matlab/Simulink/Stateflow Based
Multi Mode Leads to Smaller Component Sizes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Engine</th>
<th>Motor(2)</th>
<th>Motor(1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Single w/ RG</td>
<td>99.7%</td>
<td>88.2%</td>
<td>96.7%</td>
</tr>
<tr>
<td>Two w/o FG</td>
<td>95.3%</td>
<td>68.3%</td>
<td>57.5%</td>
</tr>
<tr>
<td>'AHS2 FWD'</td>
<td>94.9%</td>
<td>63.4%</td>
<td>51.8%</td>
</tr>
<tr>
<td>'AHS2 RWD'</td>
<td>95.3%</td>
<td>68.3%</td>
<td>57.2%</td>
</tr>
<tr>
<td>'Three'</td>
<td>93.8%</td>
<td>67.2%</td>
<td>35.7%</td>
</tr>
<tr>
<td>'Four'</td>
<td>93.8%</td>
<td>67.2%</td>
<td>35.7%</td>
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</tbody>
</table>

**Note:**
- Baseline Vehicle Specifications: Small-size 2WD SUV
- Sizing results from **grade** (13% @ 65mph) and **acceleration constraint** (7.8 sec)
- Multi-Mode mode allows **smaller** electric machines
Vehicle Level Controls All Developed Using the Same Control Philosophy

- Controller objective: Find the power split between mechanical components (ICE, MC2, MC1) that meets the driver request for the current speed of the vehicle, while maintaining acceptable battery SOC and minimal fuel consumption
- Controller has to decide on engine ON/OFF, mode and 2 other degrees of freedom
- The SOC correction and engine ON/OFF conditions are properly defined.
- Mode selection rule is defined by maps which are computed in an offline optimization code to find the optimal engine speed and torque.

Note: Basic control concepts/constraints provided by the validation works
AHS2 FWD system provides the highest fuel economy for the vehicle application considered on the small-size SUV specification.
Component Average Efficiency (%)
Single mode has the highest transmission efficiency

The energy loss results of the transmission under UDDS and HWFET

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<td>Energy Loss, Wh</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Transmission Spin</td>
<td>50</td>
<td>150</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>250</td>
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<tr>
<td>Hydraulic Oil</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
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Transmission Losses - HWFET

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Note: Transmission eff. refers only to mechanics including final reduction gearset eff.
Impact of Powertrain on Operation

**UDDS:**

- Single mode system has relatively lower system efficiency in primary operating region
- As transmission reaches higher overdrive, electro-mechanical power increases sharply.

**HWFET:**

- Single mode system has relatively lower system efficiency in primary operating region
- As transmission reaches higher overdrive, electro-mechanical power increases sharply.
Conclusion

- The fuel efficiency potential of several multimode systems (1 to 4 modes) has been defined.
- Detailed transmission models, including spin losses and hydraulic oil losses have been developed along with their low level controllers.
- Vehicle level control strategies have been defined for several multi-mode systems.
- For the small SUV application considered, the results show impact on component sizing and component operating conditions.
- Multi-mode system has more fuel economy advantage during high speed cycle. When the cycle is more aggressive, multi-mode with FG has advantage.
- **Future work will focus on:**
  - Additional vehicle classes (e.g., compact, midsize car, midsize SUV...)
  - Take into account additional Vehicle Technical Specifications (i.e., towing, passing...)
  - Other configurations options (e.g., for series, compare series vs. GM Volt...)
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Contact / Website

Namdoo Kim, nkim@anl.gov
Aymeric Rousseau, arousseau@anl.gov
http://www.autonomie.net/
Argonne National Laboratory, 9700 South Cass, Argonne IL 60439, USA