TRADE-OFF ANALYSIS AND SYSTEMATIC OPTIMIZATION
OF HEAVY-DUTY DIESEL HYBRID POWERTRAIN

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FEV has developed a system level approach for the selection and sizing of heavy-duty diesel hybrid powertrain components

- A number of studies have quantified the fuel consumption benefits of hybridization in the heavy duty segment

- Limited studies have been done to outline the process of selection and sizing of hybrid powertrain components based on the key trade-offs as shown in the plot below

![Graph showing trade-offs between MPG, Initial Cost, Payback Period, Weight, Emission, and AFT Temp.](image)
Applications where HEV attributes align well with needs include vocational applications like urban delivery.
Classification of different hybrid systems by type of hybridization and functionality

- **Micro Hybrid**
  - Limited recuperation
  - Stop-Start
  - up to 5 kW

- **Mild Hybrid**
  - Limited e-drive
  - Electric boost
  - ICE operating point shift
  - Recuperation
  - Stop-Start
  - up to 20 kW

- **Full Hybrid**
  - e-drive within short range
  - Boost
  - ICE operating point shift
  - Recuperation
  - Stop-Start
  - 20 kW and more

Focus of this Study

- Electric Power
- Voltage

12V

48V + 12V

High Voltage + 12V
Classifications of hybrid electric vehicle architecture according to the coupling type

**Series**
- Fuel tank → IC engine → Generator → Transmission → Electric motor
- Battery → Power converter (elec. coupler)

**Parallel**
- Fuel tank → IC engine → Mech. coupler → Transmission
- Battery → Power converter → Electric motor

**Series–Parallel**
- Fuel tank → IC engine → Mech. coupler → Generator → Transmission → Electric motor
- Battery → Power converter (elec. coupler)

**Complex**
- Fuel tank → IC engine → Mech. coupler
- Battery (elec. coupler) → Power converter → Electric motor

Focus of this Study
Baseline engine and vehicle specifications from a class 6-7 vocational applications were used for this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Type</td>
<td>Class 6-7 Urban</td>
</tr>
<tr>
<td>Total Loaded Vehicle Mass</td>
<td>25000 lb</td>
</tr>
<tr>
<td>Engine Displacement</td>
<td>6.7L</td>
</tr>
<tr>
<td>Advertised Rated Power</td>
<td>300 hp @ 2600 rpm</td>
</tr>
<tr>
<td>System Voltage</td>
<td>12V</td>
</tr>
<tr>
<td>Transmission Type</td>
<td>Allison 2000 Series 6</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient</td>
<td>0.009</td>
</tr>
<tr>
<td>Vehicle Frontal Area</td>
<td>10.1 [m^2]</td>
</tr>
<tr>
<td>Aerodynamic Drag Coefficient [-]</td>
<td>0.6</td>
</tr>
</tbody>
</table>
A dynamic one dimensional vehicle model was developed in GT-SUITE to represent the baseline freightliner M2 106 vehicle.

<table>
<thead>
<tr>
<th>Conventional Vehicle Model</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram of vehicle model components" /></td>
<td></td>
</tr>
</tbody>
</table>

- **Engine**
  - Map based engine model
  - BSFC, NOx and PM maps measured on dynamometer

- **Transmission**
  - Lumped model with gear ratios, inertia and efficiency specification

- **Vehicle**
  - Dynamic vehicle model with axle, differential and tire inertia
  - Aerodynamic, rolling and grade resistances modeled
A transient soot model and an SCR mid-bed temperature model was also included in the GT model.

Cycle cumulative PM emissions correlated within 10% for multiple FTP cycles.

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Trade-off Analysis and Systematic Optimization of HD Diesel Hybrid Powertrain - M. Dahodwala / FEV North America Inc
Baseline model shows good correlation with the measured test data

Final mpg numbers correlated within 2% for unloaded vehicle
P2 Hybrid vehicle model setup in GT-SUITE with motor-generator, battery, BMS, engine clutch and a supervisory control strategy

- **Motor-Generator Unit**
  - Generic axial flux BLDC MG unit modeled with map based efficiency including inverter losses
  - MG efficiency as function of power, voltage and max speed

- **Battery**
  - NMC Li ion battery pack comprising of 2.05Ah 18650 cells
  - Cells placed in series and parallel arrangement to vary voltage and capacity

- **Brake Controller**
  - Brake controller implemented to apply limited friction brakes
Efficiency map values were scaled using global factors with changes in operating voltage and maximum MG speed.
1RC Thevenin electrical-equivalent battery model used to model a Li-Ion NMC 18650 battery cell

<table>
<thead>
<tr>
<th>Battery Parameter</th>
<th>Model</th>
<th>Cell Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Capacity</td>
<td>Number of Parallel Cells [#] * Cell Nominal Capacity [Ah]</td>
<td>Formulation</td>
<td>Li-Ion NMC 18650</td>
</tr>
<tr>
<td>[Ah]</td>
<td></td>
<td>Nominal Capacity</td>
<td>2.05 Ah</td>
</tr>
<tr>
<td>Nominal Capacity</td>
<td>Number of Parallel Cells [#] * Cell Nominal Capacity [Ah] * Number of Series Cells [#] * NominalCellVoltage[V]</td>
<td>Ro</td>
<td>0.034 Ω</td>
</tr>
<tr>
<td>[kWh]</td>
<td></td>
<td>R1</td>
<td>0.009 Ω</td>
</tr>
<tr>
<td>Open Circuit</td>
<td>Number of Series Cells [#] * Cell OCV[V]</td>
<td>C1</td>
<td>948 F</td>
</tr>
<tr>
<td>Voltage [V]</td>
<td></td>
<td>Max Charge/Discharge Rate</td>
<td>1C/3C</td>
</tr>
<tr>
<td>SOC (t)</td>
<td>Capacity_{init} − \int_0^t I_{oc}dt / Nominal Capacity</td>
<td>Nominal Cell Voltage</td>
<td>3.8 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max Cell Voltage</td>
<td>4.2 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min Cell Voltage</td>
<td>2.75 V</td>
</tr>
</tbody>
</table>
A rule based strategy was used to determine the torque split between engine and MG based on torque demand and SOC.

- The low load torque curve $T_c$ directly corresponds to the maximum torque curve of motor-generator.
- Torque curve $T_b$ was made a function of motor-generator maximum torque capability.
- $T_{opt}$ and $T_a$ represent the minimum BSFC line and maximum engine torque curve respectively.
Cost and weight functions determined from internal benchmarking

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>$331/kWh</td>
<td>12.8kg/kWh</td>
</tr>
<tr>
<td>Motor</td>
<td>$7.9/kW</td>
<td>0.15kg/kW</td>
</tr>
<tr>
<td>Generator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Electronics</td>
<td>$9.9/kW</td>
<td>-</td>
</tr>
<tr>
<td>Wet Clutch</td>
<td>$700</td>
<td>20kg</td>
</tr>
</tbody>
</table>

### Comments

- Functions implemented in the model to determine total additional cost and weight
- Weight of power electronics considered in the model

### Variable Calculation

**eFuel Economy (MPGe)**

\[
MPGe = \frac{\text{Total miles driven (mi)}}{\text{Total fuel consumed}[\text{gal}]} + \frac{E(\text{battery})[\text{kWh}]}{\text{Diesel Gallon Equivalent}[\text{kWh/gal}]}
\]

**Payback Period (years)**

\[
PP = \frac{\text{Added Electric Powertrain Cost} [\$]}{\left(\frac{\text{Annual Miles Driven}[\text{mi}]}{\text{Conv. Veh MPGe}[\text{mi/gal}]} - \frac{\text{Annual Miles Driven}[\text{mi}]}{\text{Hybrid Veh MPGe}[\text{mi/gal}]\right) \times \text{Diesel Fuel Cost} [\$/\text{gal}]}
\]
400 data points generated with a space filling design algorithm using FEV-XCAL DOE tool based on GP modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG Peak Torque (Nm)</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>MG Max Speed (rpm)</td>
<td>3000</td>
<td>8000</td>
</tr>
<tr>
<td>Battery Voltage (V)</td>
<td>150</td>
<td>760</td>
</tr>
<tr>
<td>Battery Capacity (Ah)</td>
<td>20</td>
<td>100</td>
</tr>
</tbody>
</table>

- MG actual power and torque limited by battery maximum discharge and charge rates
- DOE run on ARB transient cycle since it has the highest weightage in greenhouse gas emission standards for class 6-7 urban vocational vehicle
FC reduction as a function of MG torque and speed (340V/60Ah) and battery capacity and voltage (250Nm/4900rpm max MG speed)
A 4-year payback period/$8000 initial cost was used to determine the optimum layout with 310 kg of added weight.
Overview of the hybrid vehicle control strategy performance on the ARB transient cycle
23% reduction in fuel consumption along with 14% reduction in NOx and significant reduction in PM emissions observed on ARB transient cycle.
Higher SCR midbed temperature observed on hybrid vehicle during warm conditions due to absence of engine idling.
Apart from fuel consumption benefit, package size, cost and weight considerations determined the final solution

- Considering a 4-year payback period and $8000 initial cost a 340V hybrid architecture with a 30kW motor generator (250Nm MG torque, 4900 rpm MG max speed) and a 60Ah battery capacity was found to be optimum

- 23% reduction in fuel consumption observed on ARB transient cycle through engine load shift to higher loads and start-stop operation

- Under warmed up conditions higher SCR mid-bed temperature observed on hybrid vehicle however in cold start conditions, control strategy for hybrid powertrain would require some modifications

- Studies ongoing to optimize torque converter, transmission gear ratios and final drive ratio along with hybrid powertrain components with similar approach as described in this study
Thank you for your attention and would be glad to address any questions or comments

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