Heavy Duty Hybrid Powertrain Testing
Objectives

• Compare Hybrid vs. Non-hybrid emission results
• Compare Chassis to Engine dynamometer testing
• Contribute to knowledge base for regulatory development
Heavy-Duty Test Cell #1 Schematic
## The instruments

<table>
<thead>
<tr>
<th>Compound</th>
<th>Analysis Method</th>
<th>Instrument</th>
<th>Sample Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>Non-Dispersive Infrared Detection (NDIR)</td>
<td>HORIBA Model AIA-210 LE</td>
<td>Continuous Collection</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>Non-Dispersive Infrared Detection (NDIR)</td>
<td>HORIBA Model OPE-115</td>
<td>Continuous Collection</td>
</tr>
<tr>
<td>Oxides of Nitrogen (NOₓ)</td>
<td>Heated Chemiluminescence Detection</td>
<td>California Analytical Instruments Model 400-HCLD</td>
<td>Continuous Collection</td>
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<tr>
<td>Nitric Oxide (NO)</td>
<td>Heated Chemiluminescence Detection</td>
<td>California Analytical Instruments Model 400-HCLD</td>
<td>Continuous Collection</td>
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<tr>
<td>Total Hydrocarbons (THC)</td>
<td>Heated Flame Ionization Detection (FID)</td>
<td>California Analytical Instruments Model 300M-HFID</td>
<td>Continuous Collection</td>
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<tr>
<td>Particulate Matter (PM)</td>
<td>Gravimetric Procedure</td>
<td>Sartorius M5P-00V001</td>
<td>70mm Emefab Filters</td>
</tr>
<tr>
<td>Particulate Matter (PM)</td>
<td>Gravimetric Procedure</td>
<td>1065-CFR Standard Sampling Cabinet</td>
<td>47 mm Teflon Filters</td>
</tr>
</tbody>
</table>
The dynamometer

- 500HP DC motor **2200rpm max speed**
- Trunnion mounted
- Load cell torque measurement.
- 5000 pulses per revolution rpm measurement
- Regenerative drive
## Testing Parameters

<table>
<thead>
<tr>
<th></th>
<th>Hybrid Active Vehicle</th>
<th>Hybrid Inactive Vehicle</th>
<th>Hybrid Active Vehicle for Just the HD GHG transient with peak speed truncated to dyno speed limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>m (kg)</td>
<td>6450</td>
<td>5883</td>
<td>6450</td>
</tr>
<tr>
<td>A (N)</td>
<td>506.1</td>
<td>506.1</td>
<td>506.1</td>
</tr>
<tr>
<td>B (N/(m/s))</td>
<td>7.345</td>
<td>7.345</td>
<td>7.345</td>
</tr>
<tr>
<td>C (N/(m/s)^2)</td>
<td>1.960</td>
<td>1.960</td>
<td>1.960</td>
</tr>
<tr>
<td>Tire Radius</td>
<td>0.498</td>
<td>0.498</td>
<td>0.498</td>
</tr>
<tr>
<td>Final Drive</td>
<td>4.57</td>
<td>4.57</td>
<td>5.57</td>
</tr>
</tbody>
</table>
The setup

[Diagram showing components of a hybrid system, including Battery, Inverter/Controls, Engine, Auto Clutch, Motor/Generator, Transmission, Hybrid Control Module, Patented Hybrid System Software, and Dynamometer.]

Brake Information
Connection to Dynamometer

• Typical EC Engine testing: Dyno connected to engine, controlling engine speed and torque
• Hybrid Power Pack Testing: Dyno connected to transmission output
• Testing Engine, Electric motor and Automated Manual Transmission configured as a Hybrid Vehicle
• Simulating road speed: differential gear ratio and tire size simulated to get correct transmission output speed
• Given: tire radius, diff gear ratio, vehicle mass and $A+Bv+Cv^2$ Road Load, cycle as time vs. speed
• Clutch and automated manual transmission allowed to operate by Eaton controller
Change in Dyno Control

• Typical Engine testing Dyno controls torque (or speed), engine controls opposite, speed (or torque), cycle is speed and torque vs. time

• EPA determined shifting was harsh using this type of control due to disconnection of load while transmission shifts, so Dyno controller set up similar to EPA system

• Change Engine Dyno Software to behave like a chassis dyno and use speed vs. time cycle

• Use throttle to control Hybrid, speed following cycle

• Reacted to changes in torque to determine what dyno speed should be
Dyno Cycle Control Modes

- 4 modes of operation, modeled from EPA’s experience:
  - Stopped: zero torque
  - Launch: accelerating from a stop; must exceed static RL Force before moving, dyno speed set at zero
  - Braking: throttle at minimum; brakes not simulated, regeneration cannot cause braking too fast, dyno speed setpoint is cycle speed, torque cannot build to unrealistic levels (modulate braking on/off)
  - Accelerating/Cruising: remaining simulation; dyno speed set according to measured force and vehicle parameters
Additional Setup Considerations

- Torque determined from accelerated system inertia and measured dyno torque: $T_{shaft} = \alpha I_{dyne} + T_{dyne}$
- Dyno controller provided brake signal to ECM (Engine Control Module) input, ECM generated CANBus signal for Hybrid Regenerative braking, OK to put into Drive, etc.
- Eaton provide firmware change so that “I’m alive” CANBus signal from ABS module did not need to be generated
- Speed sensor installed on input side of transmission for dyno controller to monitor and ensure clutch and AC motor speed would not exceed max limit
Speed Set Point Formula

• For Engine Speed Control, the speed set point was calculated:
  
  \[ \text{CycleSpeed}_{m/s} = f_n(\text{time, cycle}) \]
  
  \[ \text{Rpm} = 60 \times \text{Ratio}_{\text{axle}} \times \text{CycleSpeed}_{m/s} \times \frac{1}{(2\pi \times \text{Radius}_{\text{tire}})} \]

• Did not use force control: \( F_{\text{setpoint}} = ma + A + Bv + Cv^2 \)

• For Dyno Speed Control, measured force determines the speed at 100 Hz rate:
  
  \[ \text{Force}_{\text{simulated}} = \text{Torque}_{\text{shaft}} \times \frac{\text{Ratio}_{\text{axle}}}{\text{Radius}_{\text{tire}}} \]
  
  \[ \text{Force}_{\text{acceleration}} = \text{Force}_{\text{simulated}} - (A + Bv + Cv^2)_{\text{roadload}} \]
  
  \[ \text{Accel}_{\text{setpoint}} = \frac{\text{Force}_{\text{acceleration}}}{\text{Mass}} \]
  
  \[ \text{NewSpeed}_{\text{setpoint}} = \text{PreviousSpeed}_{\text{setpoint}} + dt \times \text{Accel}_{\text{setpoint}} \]
Target Loading and Cycle Verification

• For cycle verification the measured test speed was compared to the cycle target speed

• Test force was compared to calculated cycle target force:

\[ a_{\text{target}} = \frac{(v_{\text{cycle},i} - v_{\text{cycle},i-1})}{dt} \]

\[ F_{\text{target}} = ma_{\text{target}} + A + Bv + Cv^2, \ v \text{ is the cycle speed} \]
Dyno System Considerations

• Max Dyno speed limited choice of differential ratios; could not simulate lower ratios, so higher engine speeds used; use our higher speed dyno in the future
• Assistance from Eaton was invaluable, always willing to work through a problem, provided parts and equipment to keep the project moving ahead
• Several months of active software changes and trials required before able to run tests
Cycles

- **ss55ss65**
  - Cycle Time (s) vs. Trace Speed (kph)
  - Samples at 55 Mph and 65 Mph

- **CILCC**
  - Cycle Time (s) vs. Trace Speed (kph)
  - Phases 1 and 2

- **vFTP**
  - Cycle Time (s) vs. Trace Speed (kph)

- **WHVC**
  - Cycle Time (s) vs. Trace Speed (kph)
Cycles

GHG Transient

Cycle Time (s)

Trace Speed (kph)
Results

![Graph showing CO2 emissions [g/mile] for different scenarios.](image)

- **C02 Emissions [g/mile]**
- **55 MPH**
- **65 MPH**
- **CILCC**
- **GHG**
- **GHG - EPA's 5.57 FD**
- **vFTP**
- **WHVC**

Legend:
- ENGINE - Active Hybrid
- CHASSIS - Active Hybrid
- ENGINE - EPA - Active Hybrid
- ENGINE - Inactive Hybrid
- CHASSIS - Inactive Hybrid
- ENGINE - EPA - Inactive Hybrid
Results

**Fuel Consumption [L/100km]**

<table>
<thead>
<tr>
<th>55 MPH</th>
<th>65 MPH</th>
<th>CILCC</th>
<th>GHG</th>
<th>GHG - EPA's 5.57 FD</th>
<th>vFTP</th>
<th>WHVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENGINE - Active Hybrid</td>
<td>ENGINE - Inactive Hybrid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHASSIS - Active Hybrid</td>
<td>CHASSIS - Inactive Hybrid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results

NOx Emissions [ g/mile ]

- ENGINE - Active Hybrid
- CHASSIS - Active Hybrid
- ENGINE - EPA - Active Hybrid
- ENGINE - Inactive Hybrid
- CHASSIS - Inactive Hybrid
- ENGINE - EPA - Inactive Hybrid

55 MPH 65 MPH CILCC GHG GHG - EPA's vFTP WHVC
CFR86 TPM Emissions [mg/mile]

1065 TPM Emissions [mg/mile]
Particulates

CPC (hybrid)  
CPC (hybrid inactive)
Jun 14 test

~9:40, 55 mph
5 min stabilization
5 min sampling

~9:55, 65 mph
5 min stabilization
5 min sampling

~10:20, 55 mph
5 min stabilization
5 min sampling

~10:35, 65 mph
5 min stabilization
5 min sampling

~11:03, 55 mph
5 min stabilization
5 min sampling

~11:10, 65 mph
5 min stabilization
5 min sampling

Jun 19 test

~13:25, 55 mph
5 min stabilization
5 min sampling (may start at sampling)

~13:35, 65 mph
5 min stabilization
5 min sampling

~14:20, 65 mph
5 min stabilization
5 min sampling

~14:35, 65 mph
5 min stabilization
5 min sampling

~15:03, 65 mph
5 min stabilization
5 min sampling
Challenges

- Physical & system limitations
- Control system
- Complexity of the system:
  - Wiring
  - Additional Sensor (speed)
  - J1939 signals
  - Hybrid control Module required software update to bypass J1939 ABS signals & chassis signal in order to provide regenerative braking
- Simulating chassis testing on an engine dynamometer (simulating driver AND vehicle)
- Signal Simulation (parking brake, braking, etc)
- Required involvement of the manufacturer
- Active Regeneration
- Additional software requirements (J1939, Eaton’s Service Ranger)
Suggestions

- Establishing a standard for active regeneration
- If this testing method is to become standard:
  - Manufacturer’s involvement will be required (high voltage, wiring information, J1939 signals, etc)
  - Due to the increased set-up time, a cost/benefit ratio will have to be evaluated vs chassis testing
  - Equipment upgrade may be needed due to higher speed testing due to the inclusion of the transmission
  - The acceptance criteria 2mph/speed regression is challenging to meet
Special Thanks

- Environment Canada – Emissions Research & Measurement
  - Jacek Rostkowski
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  - Shannon Furino

- Eaton
  - Jeff Bosscher
  - Greg Nowel

- EPA
  - James Sanchez

- Cummins
  - Morgan Andrea
  - John O’Brien
## Summary CO₂ Results

<table>
<thead>
<tr>
<th>Hybrid Inactive</th>
<th>Cycles</th>
<th>EPA vs EC Powertrain</th>
<th>EPA Powertrain vs Chassis</th>
<th>EC Powertrain vs Chassis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>55 mph</td>
<td>15.5%</td>
<td>-0.6%</td>
<td>15.0%</td>
</tr>
<tr>
<td></td>
<td>65 mph</td>
<td>12.1%</td>
<td>4.9%</td>
<td>16.3%</td>
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<tr>
<td></td>
<td>EPA GHG</td>
<td>-3.4%</td>
<td>4.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>CILCC</td>
<td>-0.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid Active</td>
<td>55 mph</td>
<td>14.7%</td>
<td>-2.6%</td>
<td>12.4%</td>
</tr>
<tr>
<td></td>
<td>65 mph</td>
<td>9.3%</td>
<td>6.7%</td>
<td>15.4%</td>
</tr>
<tr>
<td></td>
<td>EPA GHG</td>
<td>2.8%</td>
<td>6.5%</td>
<td>9.0%</td>
</tr>
<tr>
<td></td>
<td>CILCC</td>
<td>-1.8%</td>
<td>3.9%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>
• Added brake force.
  – Allows the vehicle model not to have additional states to handle vehicle braking
  – Allows for simulation of foundation brakes

\[ v_{i,\text{ref}} = \left( FR_{\text{meas,}i-1} - \left(A + B \cdot v_{i,\text{ref-1}} + C \cdot v_{i,\text{ref-1}}^2 \right) - F_{\text{brake,}i-1} \right) \frac{t_i - t_{i-1}}{M} + v_{i,\text{ref-1}} \]

• Putting models into Matlab and Simulink to easily:
  – add details to the vehicle model like component inertia and efficiency
  – add components to simulate vehicle accessories
Improvements to Driver Model

• Moving to a feed forward driver model that uses vehicle parameters to predict required wheel torque to follow cycle
• Now includes brake pedal position rather than just on/off
• Cycle speed look ahead
Conclusion

- CO₂ powertrain results for the transient cycles compare very well between labs.
- The difference in CO₂ emissions for the steady-state cycles can be explained by the final drive ratio being different between the two labs.
- Offset between powertrain and chassis dyno results are likely due to the lack of accessory loads, cooling system and wheel slip.
- Differences in NOₓ emissions could be due to difference in preconditioning and soak time. Since CO₂ was the main emission of interest, these parameters were not closely controlled.