Heavy Duty Vehicle Modeling and Simulation

2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review
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Sponsored by Lee Slezak

Project ID #VSS020
Project Overview

Timeline
- Start October 2009
- Finish September 2010
- 80% Complete

Budget
- FY08 - $200K
- FY09 - $200K
- FY10 - $300K

Barriers
- Evaluate the potential fuel efficiency gains for Medium & Heavy Duty
- Provide DOE R&D guidance

Partners
- Allison
- ArvinMeritor
- Cummins
- John Deere
- PACCAR
- U.S. EPA
Objectives

- Evaluate benefits of DOE technology on medium and heavy duty vehicles
- Develop heavy duty version of Autonomie to support DOE R&D activities
- Integrate specific data, models, controls for heavy duty
- Validate several heavy duty vehicle classes
- Integrate specific features for heavy duty
Milestones

- Specific Shifting
- Line Haul Validation EPA
- Class 4 Validation EPA
- Line Haul Validation PACCAR
- Agricultural Tractor John Deere
- HEV Control ArvinMeritor
- Fuel Consumption Analysis

Current Status
Approach
Work Directly with Companies

Component Data
Fuel Consumption Analysis
Validation Data
Drive Cycles
Control Strategy
Technical Accomplishments
Reference Vehicles for Different Applications

Pickup Class 2b
Parcel and Delivery Class 4
Utility Class 6
Line Haul Class 8
Transit Bus
Refuse Truck
Technical Accomplishments
Specific Shifting Algorithms Defined

- A generic shifting schedule algorithm was developed based on Allison’s inputs
- Specific torque converter lockup logic was also developed
Technical Accomplishments
Line Haul Conventional Validation with EPA

- The Truck considered was a 2008 Navistar Prostar with the following specifications:
  
<table>
<thead>
<tr>
<th>Engine</th>
<th>Cummins ISX 14.9L, 321kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Manual 10 Speed FRM-15210B</td>
</tr>
<tr>
<td></td>
<td>Final Drive Ratio: 2.64</td>
</tr>
<tr>
<td>Tractor + Trailer Mass</td>
<td>31203 kg</td>
</tr>
<tr>
<td>Wheel</td>
<td>Total of 18 wheels (10 for tractor and 8 for trailer)</td>
</tr>
<tr>
<td></td>
<td>Loaded Radius = 0.48 m</td>
</tr>
</tbody>
</table>

- Gear number not recorded in test -> Had to be reconstructed

- Algorithm was developed to select the best gear when the truck is starting in simulation

- Signals comparison showed very close shifting behaviors and engine speeds. Minor differences were seen in vehicle speed.
Technical Accomplishments
Line Haul Conventional Validation with EPA

- Several assumptions had to be made since the sample rate and list of sensors were not appropriate for validation exercise.

Test-to-test Uncertainty Showed High Variations

<table>
<thead>
<tr>
<th>(Consumption in gal/100mi)</th>
<th>Transient</th>
<th>Cruise</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Test Consumption</td>
<td>27.04</td>
<td>12.66</td>
<td>14.47</td>
</tr>
<tr>
<td>Higher Test Consumption</td>
<td>31.94</td>
<td>13.74</td>
<td>17.12</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>17.4%</td>
<td>8.6%</td>
<td>18.3%</td>
</tr>
</tbody>
</table>

Fuel Consumption Results Comparison

<table>
<thead>
<tr>
<th>(Consumption in gal/100mi)</th>
<th>Transient</th>
<th>Cruise</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Test Iteration Fuel Consumption</td>
<td>27.04</td>
<td>13.04</td>
<td>15.42</td>
</tr>
<tr>
<td>Simu Fuel Consumption</td>
<td>25.95</td>
<td>13.40</td>
<td>16.14</td>
</tr>
<tr>
<td>Difference (%)</td>
<td>-4.03%</td>
<td>+2.75%</td>
<td>+4.68%</td>
</tr>
</tbody>
</table>
Technical Accomplishments
Line Haul Conventional Validation with PACCAR

- Validation of a Kenworth T660 Line Haul Truck with the following specifications:

<table>
<thead>
<tr>
<th>Engine</th>
<th>Cummins ISX 14.9L, 317kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Manual 18 Speed Fuller RTLO-18918B</td>
</tr>
<tr>
<td></td>
<td>Final Drive Ratio: 3.55</td>
</tr>
<tr>
<td>Tractor + Trailer Mass</td>
<td>29800 kg</td>
</tr>
<tr>
<td>Wheel</td>
<td>Total of 18 wheels (10 for tractor and 8 for trailer)</td>
</tr>
<tr>
<td></td>
<td>Loaded Radius = 0.477 m</td>
</tr>
</tbody>
</table>

- Various 10 Hz test data available
  - Real World driving with grade in the Seattle area
  - Test Track driving

- Special attention given to
  - Accurately model shifting behavior, especially gear skipping
  - PACCAR has already developed a successful **distance-based driver** model which they will share with ANL for development in Autonomie. The drive cycle will be speed vs. distance when the truck is moving and time-based when the truck is stopped.
Technical Accomplishments
Class 4 P&D Validation with EPA

- The FedEx Truck is a 2008 Freightliner MT45 Chassis with a Ford Utilimaster Body

<table>
<thead>
<tr>
<th>Engine</th>
<th>Cummins ISB 6.7L, 149kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Automatic 5 Speed Allison 1000 Series</td>
</tr>
<tr>
<td>Final Drive Ratio:</td>
<td>4.1</td>
</tr>
<tr>
<td>Vehicle Mass</td>
<td>5883 kg</td>
</tr>
<tr>
<td>Wheel</td>
<td>Loaded Radius = 0.4 m</td>
</tr>
</tbody>
</table>

Vehicle Speed on a Highway Cycle

<table>
<thead>
<tr>
<th>Highway Cycle</th>
<th>Test</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Economy (mpg)</td>
<td>13.8</td>
<td>14.3</td>
</tr>
<tr>
<td>Fuel Consumption (gal/100miles)</td>
<td>7.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Delta Fuel Consumption (%)</td>
<td></td>
<td>-3.5%</td>
</tr>
</tbody>
</table>

Preliminary results
Technical Accomplishments
Agricultural Tractor Study with John Deere

- Model Development of a Conventional John Deere 7530 tractor and a Hybrid version

<table>
<thead>
<tr>
<th>Engine</th>
<th>Diesel John Deere 6.8L, 154kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Manual 20 Speed split in 5 different groups</td>
</tr>
<tr>
<td>Vehicle Mass</td>
<td>8000 kg</td>
</tr>
<tr>
<td>Wheel</td>
<td>Loaded Radius Front = 0.7 m</td>
</tr>
<tr>
<td></td>
<td>Loaded Radius Rear = 0.9 m</td>
</tr>
</tbody>
</table>

- The gearbox is split in 5 groups of 4 gear ratios, each specific to a vehicle application
- PTO and accessory loads are time varying and can request high amounts of torque
- Engine operations are governed by PTO device (Specific engine speed has to be used for PTO work, e.g. 2100 RPM)
- The Hybrid main goal is to assist the engine in transient operations (other than PTO)
- Modeling work was done to build the two configurations in Autonomie, include varying high torque mechanical accessory, and develop a generic hybrid model before more data is available.
- No Test data and drive cycle available yet. Thus no validation has been achieved.
Technical Accomplishments
Line Haul Hybrid Control Development with ArvinMeritor

- ArvinMeritor has been developing a hybrid transmission for Class 8 Line-Haul trucks ("Dual-Mode Hybrid Drivetrain")
- ArvinMeritor provided:
  - Configuration type
  - Ratios and component efficiencies
- Argonne implemented:
  - Implemented specific configuration in Autonomie
  - Implemented high- and low-level hybrid control
  - Provided ArvinMeritor with complete vehicle model
- ArvinMeritor is going to use Autonomie for their vehicle simulations to support future design and control
Technical Accomplishments
Evaluating Fuel Consumption of Advanced Technologies

Impact of Aerodynamics for Different Line Haul Applications

Impact of Mild and Full HEV for Line Haul Applications

The Sum of the Combined Technologies < The Sum of Each Technology
Collaborations

- Collaboration with OEMs critical in
  - Accelerating the development of the control code (e.g., shifting logic, torque converter lock up...)
  - Gathering state of the art component data
  - Gathering state of the art vehicle data
- Value of data obtained through partnerships valued at several million dollars
Future Activities

- Complete on-going activities
  - Validation of conventional vehicles for Class 4 (EPA) and Line Haul (PACCAR).
  - Development of HEV control strategies

- Expand collaborations
  - Validate additional classes (e.g., bus) and configurations (e.g., HEVs) working with OEMs, government agencies and ANL’s APRF (testing of Class 4 with several powertrain)
  - Continue to develop specific heavy duty features, including driver, shifting, accessories
  - Evaluate fuel consumption benefits of advanced technologies on both standard and real world drive cycles

- Support future Medium and Heavy Duty regulations
Summary

- Requirements were added to Autonomie to ensure specific needs of Heavy Duty Trucks
- Features were implemented:
  - Models and data
  - Control strategies...
- Several vehicle classes correlated using proprietary OEM’s data.
- Evaluation of advanced technologies on-going.
- Leveraged several millions of dollars of proprietary OEM data (both component and vehicle testing)