Modeling for Market Analysis: HTEB, TRUCK, and LVChoice

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TA Engineering, Inc.

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Annual Merit Review

June 18, 2014

Project ID: VAN012
Overview

<table>
<thead>
<tr>
<th>TIMELINE</th>
<th>FY13</th>
<th>FY14</th>
</tr>
</thead>
<tbody>
<tr>
<td>End Date</td>
<td>Sept. 2013</td>
<td>Sept. 2014</td>
</tr>
<tr>
<td>% Complete</td>
<td>100%</td>
<td>70%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>BUDGET</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total Project Funding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Received for FY13</td>
<td>$141,306</td>
<td></td>
</tr>
<tr>
<td>Funding for FY14</td>
<td>$130,000</td>
<td></td>
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<table>
<thead>
<tr>
<th>COLLABORATIONS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract to ANL, Tom Stephens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collaborations &amp; Interactions:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ANL: Aymeric Rousseau, Anant Vyas, Joann Zhou</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NREL: Aaron Brooker</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ORNL: Zhenghong Lin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EIA: Nicholas Chase, Patricia Hutchins</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21st CTP and SuperTruck program managers &amp; industry partners</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BARRIERS ADDRESSED*</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Program evaluation of: progress against stated goals; program rationale; process; impact; and cost-benefit.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*from 2011-2015 VTP MYPP
Objectives and Relevance

- Overall objective - develop, improve, and apply analysis tools to support program planning, management, evaluation, and reporting, relative to VTO goals to:
  - Reduce energy use and greenhouse gas emissions by enabling development of efficient and clean highway vehicles that are cost and performance competitive.

- HTEBdyn relevance:
  - Estimates benefits of heavy vehicle advanced technologies in terms of fuel consumption reduction;
  - Translates technical targets into vehicle performance benefits.

- HTEB task objectives:
  - Perform analysis in support of VTO GPRA reporting.
  - Maintain quick analysis capability.
  - Improve estimation of:
    - Interactive effects of grade, aerodynamics, and braking;
    - Waste energy availability for recovery technologies; and
    - Impact of duty / drive cycle on benefits.
Objectives and Relevance, Cont.

- **TRUCK; LVChoice relevance:**
  - Estimate market acceptance of advanced vehicle platforms based on performance (fuel economy) and cost;
  - Translate vehicle performance into fleet fuel and emissions savings.

- **TRUCK task objectives:**
  - Perform analysis in support of VTO GPRA reporting;
  - Maintain flexibility of technology specification;
  - Adjust data on truck population to better characterize vehicles targeted by DOE R&D.

- **LVChoice task objectives:**
  - Allow analysis consistent with NEMS methodologies;
  - Improve flexibility of scenario specification, e.g. technologies and size classes;
  - Improve user interface to automate input specification;
  - Perform analysis to support comparison to other models;
  - Analyze sensitivity of results to model structure and parameter specification.
## Milestones FY13-14

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HTEBdyn</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/16/13</td>
<td>Conduct workshop (AMR side meeting); incorporate industry comments</td>
<td>Complete</td>
</tr>
<tr>
<td>4/30/14</td>
<td>Develop user guide and version for review distribution, class 8.</td>
<td>90%</td>
</tr>
<tr>
<td>5/30/14</td>
<td>Model documentation</td>
<td>75%</td>
</tr>
<tr>
<td>7/25/14</td>
<td>Model validation against simulation and test data.</td>
<td>50%</td>
</tr>
<tr>
<td>7/25/14</td>
<td>Journal article submission</td>
<td>0%</td>
</tr>
<tr>
<td>9/30/14</td>
<td>Update class 4-6 characterizations.</td>
<td>0%</td>
</tr>
<tr>
<td><strong>TRUCK</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Update to AEO 2013; subdivide class 4-6.</td>
<td>Complete</td>
</tr>
<tr>
<td><strong>Integrated Analysis – Application of TRUCK and HTEBdyn</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/21/12</td>
<td>SuperTruck benefits analysis final report publication.</td>
<td>Complete</td>
</tr>
<tr>
<td>1/6/14</td>
<td>Complete analysis and documentation for GPRA 2015</td>
<td>Complete</td>
</tr>
</tbody>
</table>
## Milestones FY13-14, Cont.

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone / Go-No Go</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/14/13</td>
<td>Milestone</td>
<td>Alter model to suit VTO analysis needs.</td>
<td>Complete</td>
</tr>
<tr>
<td>7/16/13</td>
<td>Milestone</td>
<td>Develop interface file.</td>
<td>Complete</td>
</tr>
<tr>
<td>9/3/13</td>
<td>Milestone</td>
<td>Add fuel availability and make/model availability algorithms</td>
<td>Complete</td>
</tr>
<tr>
<td>9/9/13</td>
<td>Milestone</td>
<td>Update to AEO 2013 and perform validation.</td>
<td>Complete</td>
</tr>
<tr>
<td>9/9/13</td>
<td>Milestone</td>
<td>Perform preliminary analysis of common inputs with sensitivity.</td>
<td>Complete</td>
</tr>
<tr>
<td>5/30/14</td>
<td>Milestone</td>
<td>Update to AEO 2014.</td>
<td>0%</td>
</tr>
<tr>
<td>6/13/14</td>
<td>Milestone</td>
<td>Final analysis of common inputs with sensitivity.</td>
<td>0%</td>
</tr>
<tr>
<td>9/30/14</td>
<td>Milestone</td>
<td>Analysis and refinement of FA and MMA algorithms; analysis of calibration factors.</td>
<td>10%</td>
</tr>
</tbody>
</table>
HTEB Approach

- Apply approach from legacy model that estimated power demand based on average drive cycle statistics.
- For a specified drive cycle, calculate required engine brake power $P_b$ at each time step as a function of system losses/demands:
  \[
  P_b = P_{drive} + P_{mech} + P_{elec} + P_{tran}
  \]
  \[
  P_{drive} = P_{aero} + P_{rr} + P_{accel} + P_{grade}
  \]
- Calculate fuel consumption rate as a function of brake power, engine friction loss, and engine indicated efficiency:
  \[
  \hat{F} = \frac{P_b + P_f}{\eta_i}
  \]
- Reduce engine power demand for:
  - Hybrid system contribution (regenerative braking)
  - Mechanically coupled waste heat recovery (turbo-compounding and ogranic Rankine cycle).
- Use simplified relationships that capture the performance characteristics of component systems; “black box” approach rather than detailed component modeling / simulation.
HTEBdyn Accomplishments FY13-14

- Initial development of “dynamic” formulation completed in FY13.
- Presented at 2013 workshop (AMR side meeting); incorporated industry feedback:
  - Added time lag to heat available to ORC recovery.
  - Adjusted regenerative brake recovery algorithm.
  - Hybrid system simplified and parameterized to maximize energy recovery and use; avoids attempt to design power management system.
- Improved estimation when vehicle is unable to meet the drive schedule:
  - Estimated loads are recalculated through one iteration.
  - Added schedule smoothing options to minimize harsh acceleration demand, vehicle under-speed results, and associated power imbalance.
- Improved engine friction definition and estimation.
- Added transmission options, characterized by gear ratios and shift points (rpm).
- Improved user interface:
  - Basic operation from one input worksheet using default engine parameters and default transmission.
  - User options for custom input.
- Validation in progress (Autonomie simulations, NREL fleet tests).
HTEB Accomplishments: Validation against Autonomie Simulation

Comparison to simulation results documented in ANL 2009 report for NAS.
Difference between runs is strictly drive cycle or hybridization.
Estimates of fuel consumption are within 1% for conventional truck and 3% for hybrid truck.
HTEBdyn estimates higher benefits for hybrid; model is parameterized to maximize use of energy recovered.

<table>
<thead>
<tr>
<th></th>
<th>UDDS Cycle</th>
<th></th>
<th>HHDDT65 Cycle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANL</td>
<td>HTEB</td>
<td>% diff</td>
<td>ANL</td>
</tr>
<tr>
<td><strong>Conventional</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Avg Efficiency</td>
<td>36.4%</td>
<td>36.7%</td>
<td>0.94%</td>
<td>40.5%</td>
</tr>
<tr>
<td>Consumption (gal/100 mi)</td>
<td>22.7</td>
<td>22.9</td>
<td>0.97%</td>
<td>16.1</td>
</tr>
<tr>
<td><strong>Hybrid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Avg Efficiency</td>
<td>38.0%</td>
<td>37.8%</td>
<td>-0.64%</td>
<td>40.9%</td>
</tr>
<tr>
<td>Brake Recovery @ wheel</td>
<td>74.6%</td>
<td>74.1%</td>
<td>-0.69%</td>
<td>57.8%</td>
</tr>
<tr>
<td>Consumption (gal/100 mi)</td>
<td>16.2</td>
<td>15.8</td>
<td>-2.68%</td>
<td>15.3</td>
</tr>
<tr>
<td><strong>Hybrid Fuel Savings</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gal/100 mi</td>
<td>6.5</td>
<td>7.2</td>
<td>10.1%</td>
<td>0.80</td>
</tr>
<tr>
<td>%</td>
<td>29%</td>
<td>31%</td>
<td>9.03%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>
TRUCK Approach

- Estimate market penetration of fuel saving or alternative fuel heavy trucks based on technology cost and value of fuel savings.
  - Fuel price projection from latest AEO.
  - Determine estimated payback period within each of eleven mileage cohorts based on VIUS data for new trucks (≤ 2 yrs).
  - Estimate adoption rate of based on distribution of required payback period (ATA Return on Investment Survey, 1997).
  - Separate calculations for four classes (3-6 gasoline, 3-6 diesel, 7&8 Single Unit, 7&8 Combination) and two refueling strategies (central, non-central).

- Compete up to 3 platforms against a baseline
  - All four vehicles may use any transportation fuel included in AEO.
  - Baseline must have the lowest vehicle purchase price.

- Include capability to consider technology preferences that are not reflected in costs (e.g., fuel availability, risk aversion, imperfect information, technical features, etc.).

- Separate model for class 4-6 trucks (vs. 3-6) for GPRA 2015.
The high annual mileage driven by Class 7&8 CU trucks (tractor trailers) results in higher annual fuel savings and shorter payback periods.

Market shares are % of annual class VMT. Shares as % of trucks will be lower since higher mileage trucks are more likely to adopt.
Due to lower mileage of single unit (SU) class 7 & 8 trucks and long payback periods, market shares for advanced technologies are limited. As a result, combination unit (CU) truck fuel economy is projected to far exceed SU fuel economy.
LVChoice Approach / Strategy

- LVChoice model developed for NPC and adapted to suit VTO analysis needs:
  - Nested multi-nominal logit structure and coefficients from NEMS, including calibration coefficients;
  - Include subset of NEMS size classes and technologies according to interest of VTO.

- To facilitate comparison to other VC tools: develop an interface Excel file using VBA code to translate “flat” input file:
  - Compatible with original model; model can still be run independently;
  - Accessible and transparent.

- Maximize flexibility in interface file: allow user to map model technologies and size classes to any input values in the flat file:
  - Accommodates any future changes to source program (Autonomie) and availability of new source program data;
  - User may include all or a subset of both technologies and classes;
  - Not all specified inputs need to be applied in a given run.

- Maximize flexibility in interface file: specify all utility factor and fuel economy calculation parameters in the interface file.
- Include specification of all possible inputs, including those unique to LVChoice.
LVChoice Accomplishments: Benchmark Comparison to AEO

- LVChoice projects a higher overall fleet fuel economy due to differences in the car market
  - Initially due to higher TDI sales
  - In 2030-2040 timeframe, LVChoice projects higher market share for HEVs, PHEVs, and EVs.

- Some reasons for differences:
  - LVChoice does not include manufacturer decision-making to meet CAFE regulations.
  - LVChoice has different size classes and does not have the full NEMS technology suite.
  - “True” comparison would require a NEMS run matching these inputs.
LVChoice Accomplishments: Sensitivity Analysis

- Base run with zero calibration coefficients and exogenous fuel availability (FA).
- All runs with endogenous make / model availability (MMA) and no early year market limits.
- Sales share of advanced vehicles is highly sensitive to calibration coefficient and FA.
Response to Previous Year’s Comments

- This project was not reviewed in previous years.
Collaboration and Coordination

- All projects performed under contract to Argonne National Laboratory, project manager Tom Stephens.

- Integrated analysis of heavy vehicles for GPRA:
  - Performed in collaboration with Tom Stephens (ANL);
  - Assistance with AEO inputs provided by EIA (Patricia Hutchins, Nicholas Chase).
  - Coordination of inputs with VTO program managers (Roland Gravel, Ken Howden, Gurpreet Singh).

- HTEBdyn reviews and comments provided by Aymeric Rousseau (ANL) and SuperTruck industry partners (Daimler, Cummins, Navistar, Volvo, Detroit Diesel).

- LVChoice development and analysis, coordinating with:
  - ANL - Tom Stephens, Joann Zhou, Aymeric Rousseau, Anant Vyas, Deena Patel
  - EIA - Patricia Hutchins, Nicholas Chase
  - NREL – Aaron Brooker
  - ORNL – Zhenhong Lin
Remaining Challenges

- **HTEBdyn**
  - Model validation – lack of published test data that includes all necessary model inputs.
    - Coordinating with national labs and with SuperTruck and 21st Century Truck partners.
  - Many possible component and system configurations.
    - Configuration of hybrid and waste heat recovery systems impacts benefits.
    - Model needs to include pre-defined options with flexibility for customization.
  - Requirement to maintain quick run-time limits ability to solve power imbalance when vehicle does not meet schedule speed.

- **LVChoice**
  - Model comparisons complicated by sensitivity to variables that are treated differently among models, particularly fuel availability, make model availability, and calibration coefficients.
Proposed Future Work

- Update all models to latest AEO and perform analysis for GPRA 2016.
  - Analysis complete 2/28/2015
  - Documentation complete 4/30/2015.

- HTEB development:
  - Continue model validation;
  - Improve characterization of engines;
  - Characterization of gasoline engines for class 4-6;
  - Conversion of calculations to VBA or other platform to solve for vehicle speed when system is under powered;
  - Electrical coupling of TuCo and ORC systems; and
  - Add class 3 characterization.
Proposed Future Work, cont.

- TRUCK development:
  - Research and analyze data (population distribution by annual mileage) for class 3 commercial trucks.

- LVChoice development:
  - Analysis of fuel availability and make model availability algorithms and validation of results.
  - Model restructuring to increase flexibility; i.e. easily accommodate changes to technology suite.
    - Generic technologies with automated mapping to logit nests.
    - Fuel specification flexibility.
  - Add integrated model of producer decision-making to allow consideration of CAFE and ZEV mandates.
    - Endogenous calculation of new vehicle fuel economy and price.
## Summary

<table>
<thead>
<tr>
<th>RELEVANCE</th>
<th>HTEBdyn, TRUCK, and LVChoice provide a toolset to support VTO program planning, management, evaluation, and reporting. Models translate program technical targets into future fuel consumption and greenhouse gas reduction benefits.</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPROACH</td>
<td>Build on legacy models/tools; Use methodologies based on engineering fundamentals, market data, and consumer behavior theory; and Maximize flexibility and ease of use.</td>
</tr>
<tr>
<td>ACCOMPLISHMENTS FY13-14</td>
<td>Tools refined to increase ease of use, add flexibility, add features, and enhance quality of analysis results. Model validation / calibration / comparison is in progress.</td>
</tr>
<tr>
<td>COLLABORATIONS</td>
<td>Work conducted in collaboration / consultation with experts at DOE, EIA, national labs, and industry partners</td>
</tr>
<tr>
<td>FUTURE WORK</td>
<td>Expand the scope of the models to enhance coverage of the technologies and applications in the VTO R&amp;D portfolio as well as spillover benefits in other applications.</td>
</tr>
</tbody>
</table>
Technical Backup
TRUCK Methodology

- Adoption rate (AR) determined from one of three curves (user selected).
- Most “aggressive” represents stated preferences.
- Two remaining curves represent levels of risk aversion.

- AR curve is neutral to magnitude of incremental cost.
- Willingness to adopt is limited by availability of capital and perception of risk.
- AR is reduced with increasing cost.
HTEBdyn Methodology: Engine Friction

- Engine friction includes all losses that vary with engine speed and is calculated from the friction mean effective pressure (fmep):

\[
fmep = k_0 + k_1 \cdot \omega + k_2 \cdot \omega^2
\]

\[
P_f = \frac{1}{2} \cdot fmep \cdot D \cdot \omega
\]

- \( k_0 \): boundary friction; power varies with \( \omega \)
- \( k_1 \): viscous (hydrodynamic) losses; power varies with \( \omega^2 \)
- \( k_2 \): losses due to turbulence; power varies with \( \omega^3 \)

- Includes losses due to:
  - Rubbing and reciprocating friction (crankshaft, valve train, etc.);
  - Engine auxiliaries (oil, water, fuel pump); and
  - Pumping losses due to gas exchange and fluid flows.

- Method is from PERE and consistent with Heywood (1988).
LVChoice Methodology: Nested Multi-nominal Logit Formulation

- Market share of advanced vehicle $i$ (AV$_i$) within a size class is the probability of purchase based on relative utility:

$$P_i = \frac{e^{\sum_j \beta_{j} \cdot x_{i,j}}}{\sum_i^N e^{\sum_j \beta_{j} \cdot x_{i,j}}}$$

- Where
  - $x_{i,j} = \text{value of attribute } j \text{ for AV}_i$
  - $\beta_{i,j} = \text{coefficient on attribute } j$
  - Utility from selecting vehicle $i$ is: $U_i = \sum_j \beta_{j} \cdot x_{i,j}$
  - $N = \text{total number of vehicle technologies}$

- Note that the coefficients differ among size classes.
### LVChoice Methodology: Vehicle Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Price</td>
<td>Specified or calculated from production cost</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>Per GGE</td>
</tr>
<tr>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Battery Replacement Cost</td>
<td>Cost currently = 0</td>
</tr>
<tr>
<td>Acceleration, 0-60 mph</td>
<td></td>
</tr>
<tr>
<td>Home Refueling for EVs</td>
<td>Dummy (1,0)</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td></td>
</tr>
<tr>
<td>Luggage Space</td>
<td></td>
</tr>
<tr>
<td>Fuel Availability Coefficient 1</td>
<td>% of stations; exogenous or endogenous = f(est. stock)</td>
</tr>
<tr>
<td>Fuel Availability Coefficient 2</td>
<td>Utility due to FA is an exponential function</td>
</tr>
<tr>
<td>Make/Model Availability</td>
<td>Index to conv.; Exogenous or endogenous = f(3-yr avg share)</td>
</tr>
<tr>
<td>Technology Set Gen. Cost</td>
<td>Calculated per NEMS</td>
</tr>
<tr>
<td>Multi-Fuel Gen. Cost</td>
<td>Calculated per NEMS</td>
</tr>
<tr>
<td>Calibration coefficient</td>
<td>Specified annually per NEMS or static value</td>
</tr>
</tbody>
</table>

- LVChoice uses the same attributes as NEMS; coefficients are based on NEMS.
- Endogenous FA and MMA calculations based on NEMS algorithms.