MODELING AND INTEGRATION OF CONVENTIONAL AND HYBRID TRUCK SYSTEMS

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Outline

- Introduction
- Variable fidelity and complexity
- New component and control modules - VNT
- Hybrid Electric Truck Study
  - Sub-system and component models
  - Performance and fuel economy results for the Class VI truck
- Conclusions
Objectives

- **2X-3X fuel economy:**
  - Optimize advanced diesel powerplants
  - Explore where hybridization makes sense
  - Improve the match between the powertrain and the vehicle
  - Improved accessories, e.g. electric pump

- **Reduce emissions:**
  - New technologies for improved NOx/PM trade-off, e.g. VNT+EGR, HCCI …
  - Electric powertrain components
  - Fuel cell

- **Active Safety:**
  - Rollover warning and prevention
  - Differential braking, engine braking
  - Intelligent Transportation – truck “platooning”
Key Modeling Issues

- Variable complexity and fidelity of engine, driveline and vehicle dynamics modules, depending on overall vehicle simulation goal
- Development of advanced component models
- Feed-forward system for realistic transient response and control
- Integration in different computing environments: flexibility vs. computational speed trade-off
Integrated Simulation in SIMULINK – Vehicle-Engine SIMulation
Previous and Ongoing VESIM Applications

- Extensively tested under variety of very dynamic conditions
- Validated against experimental data
- High fidelity version used by International and UM for mobility and driveability studies
- Reduced complexity version developed for target cascading

Vehicle Specifications: International 4700 Series

- GVWR: 7950 Kg
- Wheelbase: 3.7 m
- CG Location: 2.2 m from front
- Frontal Area: 5 m²
- Air Drag Coefficient (C_D): 0.8
- 4 Speed Automatic Transmission
- Rear Wheel Drive - 4x2
- V8 DI Diesel
  - Turbocharged, Intercooled
  - Displacement: 7.3 liters
  - Bore: 10.44 cm
  - Stroke: 10.62 cm
  - Compression Ratio: 17.4
  - Rated Power: 155 kW@2400 rpm

Validation: 0 - 60 mph
Current Emphasis

- Increase the fidelity and add new components for studies of critical driveability and emissions issues
  - New system engine configurations for advanced diesels
  - Novel turbomachinery models
  - Exploring matching and control strategy

- Develop integrated HEV simulation:
  - Evaluate modeling options
  - First generation models of electric components
  - Basic power controller
  - Initial fuel economy study
Model Complexity = f (Simulation Goals)

<table>
<thead>
<tr>
<th>Conventional</th>
<th>Hybrid</th>
<th>HIGH-SPEED</th>
<th>HIGH-FIDELITY</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Mobility, fuel economy over driving cycles,</td>
<td>Critical transients (e.g. launch), driveability,</td>
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<td>subsystem matching, optimization</td>
<td>control, component matching, emissions</td>
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<tr>
<td></td>
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<td>Mobility, fuel economy, energy management,</td>
<td>Critical transients (e.g. starting-stopping),</td>
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Engine System Models in SIMULINK

High-Fidelity

High-Speed
Motivation for the Application of VNT to a Diesel Powertrain

**Mobility:**
- Improved response and acceleration performance

**Emissions:**
- Control pressure difference across the engine for EGR application to heavy duty diesels

<table>
<thead>
<tr>
<th>Standard</th>
<th>Test Cycle</th>
<th>Emissions Limits [g/bhp.h]</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>NOx</td>
</tr>
<tr>
<td>US'98 1998</td>
<td>US-FTP</td>
<td>4.0</td>
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<tr>
<td>US'02 2002</td>
<td>US-FTP</td>
<td>2.5</td>
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</table>
EGR System - Options and Implications

- EGR – external:
  - short route (manifold to manifold)
  - long route
  - pumped EGR

- EGR – internal:
  - variable valve timing (camless)

- In every case, negative pressure drop needed across engine
Neural Network for Compressor Modeling

ANN model

Train NN

Speed
Pressure Ratio
Mass Flow Rate
Efficiency

Corrected Mass Flow Rate
Corrected Air Flow (lbs/min)
Pressure Ratio
1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4
0 1 0 2 0 3 0 4 0 5 0 6 0 7

Predicted
Measured

Pressure Ratio
Corrected Mass Flow Rate

0 1 0 2 0 3 0 4 0 5 0 6 0 7
3.5 3 2.5 2 1.5 1.0
Variable Nozzle Turbine (VNT)

VNT allows modification of turbine flow characteristics for best performance:

- “small” flow area (nozzles partially closed) for low engine speed and load
- “large” flow area (nozzles open) for high speed and high load
Neural Network Model of VNT Turbine

Discrete number of maps for fixed blade (nozzle) positions

Train ANN

ANN model

Nozzle Position
Speed
Pressure Ratio
Mass Flow Rate
Efficiency

Predictions for any blade position

Corrected Turbine Mass Flow Rate (Normalized) vs. Turbine Expansion Ratio (Normalized) for different blade positions.
Application of VNT: Control Strategy for Maximum Mobility

- Nozzle Position signal varies from 0 – 1:
  - If boost pressure below corresponding steady-state values obtained with the conventional turbocharger NP=0
  - If boost pressure is above corresponding steady-state values obtained with the conventional turbocharger and below a set target level NP varies between 0 and 0.7
  - If boost pressure is above the target value NP between 0.7 and 1
VNT: The Effect on Engine and Vehicle Response

Vehicle launch and acceleration from 0 - 60 mph
VNT: Nozzle Position Signal and Turbocharger Speed

Start of the transient
VNT: Turbine Operating Points During Vehicle Acceleration

0~60 acceleration with VGT
VNT: Compressor Operating Points During Vehicle Acceleration

0~60 acceleration with VGT

"***": Starting Point

"o": Ending Point
VNT: Manifold Pressure and the Response of the Fuel Controller

![Graph showing intake manifold pressure and fuel injected over time for VGT and CT settings.](image-url)
VNT: Changing the Control Strategy to Affect Pressure Ratio Across the Engine

By increasing the target value we increased not only the average boost level at high engine speed, but also the negative pressure difference across the engine ($P_{\text{exhaust}} - P_{\text{intake}}$).
Future Directions – VNT and High Fidelity Engine System

- Improved component modules for advanced diesel and hybrid electric systems, e.g. EGR sub-system components, camless valvetrain
- Explore various system configurations for EGR application
- Explore engine control strategies for improved response and reduced emissions – utilize predictive spray, combustion and emissions models
- Validate component and system predictions
VESIM-HEV Case Study

- HEV Class VI Truck:
  - Proper modeling
  - Performance
  - Fuel economy over a driving cycle
Drivetrain

- TC
- Trns
- Propshafts
- Driveshaft
- D-R
**Vehicle Dynamics**

- Nonlinear 3D kinematics
- Aerodynamic and rolling resistance losses
- Nonlinear tire traction forces
# Proper Model: Definition

## Characteristics
- Minimum complexity
- Physical parameters
  - Geometry
  - Material
- Specified level of accuracy

## Advantages
- Computational efficiency
  - Design insight
- Physically meaningful
  - Direct design decisions
- Clear interpretation of model predictions

Can meet model objectives
Proper Models

- Need proper models for:
  - System evaluation
  - Design/Sensitivity studies

- Ad-hoc modeling approach:
  - Require experience to build and interpret models.
  - Require excessive time to:
    - Develop model
    - Compute model
  - Lack systematic approaches to generate models of appropriate:
    - Complexity
    - Accuracy
Automated Modeling Algorithms

Overly-complicated models are:

- Difficult to compute
- Difficult to:
  - Do design optimization, controller design, etc.
  - Gain physical insight into the system behavior

Automated modeling algorithms addresses the model complexity in a systematic and quantitative approach:

- Frequency-based MODA - Linear systems
- Energy-based MORA - Nonlinear systems
Proper Models for Fuel Economy

**Drivetrain**
- Rigid Propshafts
- Rigid Driveshaft
- Quasi-Static Lookup Tables
- Gear Ratios
- Blending Functions

**Vehicle Dynamics**
- Longitudinal
  - Total Vehicle Mass
  - Aerodynamic Drag
- Heave
  - Wheel Inertia
  - Wheel Slip
  - Rolling Resistance
  - Suspension
  - Unsprung Mass
  - Flexible Tire
  - Road Excitation

**Coupling**
Engine Model

- Look-up table for engine output torque as a function of fuel input and speed
- Includes fuel injection controller and engine dynamics
Electric Motor Model

- Permanent magnet DC motor/controller
  - 49 kW Max
  - Max Propulsive Torque: 274.4 N-m
  - Max Reg. Torque: 170 N-m
  - Mass: 60 kg
  - (Source: Advisor 2.2.1)
- Reduce engine size form 157 kW to 117 kW
Battery Model

- Lead Acid Battery
  - Max Capacity: 18 Ah
  - Mass: 165 kg
  - Max Voltage: 412.5 volts

- Battery efficiency, open circuit voltage and internal resistance are function of battery state of charge (SOC)

\[ SOC = \frac{Q_{\text{max}} - Q_{\text{used}}}{Q_{\text{max}}} \]

Equivalent circuit model (Powell and Pilutti, 1993)

\[ R_b C_i \dot{e}_{ib} = \tilde{e}_{ib} - e_{ib} - R_b i_{tb} \]

\[ \tilde{R} C_p \ddot{e}_{ib} = V_{oc} - \left( \frac{R_b + \tilde{R}}{R_b} \right) \dot{e}_{ib} + \frac{\tilde{R}}{R_b} e_{ib} \]
**HEV Power Control Function**

- **Driver Model**
  - $P_{dem}$
- **Power Splitting control module**
  - $P_{eng}$
  - $P_{mot}$
- **Engine/Trans. Control Module**
  - $T_{eng}$
  - Gear #
  - Clutch
- **Motor Control Module**
  - $T_{mot}$
- **Vehicle Model**
- **Shift Logic Control**
- **Motor Only Mode**
- **Engine Only Mode**
- **Hybrid Mode**
- **Charge Sustaining Strategy**
- **Battery Power Limit**
- **Regenerative Braking Control**
HEV Power Splitting Strategy

- Low power → Motor only
  - Prevent the engine from operating at an inefficient region

- Medium power & recharge → Use engine
  - “Engine on” power level
  - “Engine high” power level

- High power → Both engine & motor
  - The motor is used for power assist
VESIM-HEV in SIMULINK
HEV Specifications: Class VI Truck

**ENGINE** size reduced to:
- V6 DI Diesel
- Turbocharged, Intercooled
- Displacement: 5.47 liters (same Bore and Stroke as V8)
- Rated Power: 117 kW @2400 rpm

**ELECTRIC MOTOR:**
- Power: 49 kW
- Max Propulsive Torque: 274.4 N-m
- Max Reg. Torque: 170 N-m
- Mass: 60 kg

**BATTERY:**
- Lead-Acid
- Max Capacity: 18 A-h
- Max Voltage: 412.5 V
- Mass: 165 kg

GVWR: 7950 Kg
Frontal Area: 5 m²
Air Drag Coeff.: 0.8
VESIM – HEV: Performance Test, Acceleration: 0-60mph
VESIM – HEV: FUDS Cycle

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<thead>
<tr>
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<th>Conventional</th>
<th>HEV (Charge Sustaining)</th>
<th>HEV (Charge Depleting)</th>
</tr>
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<tbody>
<tr>
<td>Fuel Economy (mpg)</td>
<td>9.59</td>
<td>12.63</td>
<td>17.75</td>
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</tbody>
</table>
VESIM – HEV: FUDS Cycle,
Time Zoom In: 400 ~ 550 sec

- Engine off at cruising
- Motor starts up
- Regenerative Braking
- SOC hits low limit
- Engine drives vehicle and charges battery
- Engine recharges battery
Engine Operation Points

VESIM - HEV

Use motor to avoid engine inefficient operation

VESIM - Conventional

Shift logic control toward more efficient region
Future Directions - HEV

- Develop improved electrical component models
- Apply proper modeling methodology to other systems
- Use worst-case analysis to generate driving cycle able to reveal possible weaknesses of overall HEV system
- Dynamic energy HEV management strategies
- Support target cascading for HEV vehicle system optimization
- Explore synergisms with other HEV system level codes (e.g. PSAT)