Autonomie
Plug&Play Software Architecture

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

Project ID #VSS009
Project Overview

Timeline
- Start – July 2007
- End – July 2010
- 90% Complete

Barriers
- Bring technologies to market faster
- Support technology evaluation
- Support requirements definition

Budget
- Three year Project
  - 50% DOE
  - 50% GM
- DOE
  - FY08 $ 500k
  - FY09 $ 500k
  - FY10 $ 500k + $400k (legacy transition)

Partners
- General Motors
- MathWorks
- Gamma Technology (GTPower)
- LMS (AMESim)
- Mechanical Simulation (CarSim)
Autonomie’s objective is to accelerate the development and introduction of advanced technologies through a Plug&Play architecture that will be adopted by the entire industry and research community.

- Reduce cost and time to production by minimizing hardware iterations through Math-Based environment
- Enterprise wide solution through database management maximize model and process reusability
Milestones

Year 1
- Define Data Organization
- Define Model Organization
- Validate Model Organization
- Implement Controls
- Validate Vehicle Model
- Demonstrate SIL
- Demonstrate CIL
- Linkage with expert tools
- Transfer Legacy Code from PSAT
- Discuss Industry Standard
- Write Documentation
- Pre-release and First Release

Year 2
- 

Year 3
- 

Current Status
**Approach**

*Use Model Based Design Approach to Accelerate the Vehicle Development Process*

**Problem:**
- Heavy reliance on hardware leads to high cost and longer development time
- Integration of new technologies in a system lowers its true benefit

**Result:**
Wasted Opportunities, Time, and Resources (People & $)

**Solution:**
OEMs are moving towards an increasing reliance on modeling to accelerate the introduction of advanced technologies

DOE is leading the way with the development of Autonomie
Approach
Maximize Legacy Code Reusability Through Plug & Play

Implement any language Automated process to import legacy code (data, model, control, process)...

Plug & Play

Legacy Code

Legacy Processes

Specialty Software (COTS)

Database Management

Version Control Database Search

Calibration Validation Tuning Drive Quality...

No other tool currently builds the model automatically! Algorithm is patented

* Already linked
Approach
Software Can Be Entirely Customized

Model organization
Single or multiple plants
Controller location

Model Configuration

Customization

Processes

Calculations
Plots
Reports...

Post-processing

Fuel economy
Validation
Drive quality
Control...

Proprietary Information

Models
Data
Controls...
Technical Accomplishments
Legacy Code Reusability

Process to Integrate Legacy Code Demonstrated

- GUI Automatically Renames Variables, Creates Necessary Support Files
- Process to Integrate Legacy Code Demonstrated

Process to Link Expert Tools (COTS) Demonstrated

1. Develop Model in Native Environment
2. Integrate Model in Simulink
3. Use Model in Autonomie

Automatic Building of Any Model

First block automatically built to select the required input parameters, change units and data type

Last block automatically built to change units (SI) and data type before sending the information to a bus to make them available to other systems
Technical Accomplishments

Software Customization

The Entire Model is Automatically Built Allowing Users to Reuse Expert Systems and Select Appropriate Level of Modeling

Controllers

Plants

- Engine Experts
- Battery, Motor Experts
- Transmission Experts
- Chassis Experts
- Vehicle Experts
Technical Accomplishments
Software Customization

The Model Can Be Organized to Exactly Match the Hardware Setup

Each System is Optional

Example: GM 2 Mode HEV Transmission Plant

Any System can have Subsystems To Accurately Represent Hardware
Software Customization Allows a Single Tool to Be Used Throughout the Vehicle Development Process

**Model-in-the-Loop**

- Algorithm or Controller Model
- Plant Model

**Software-in-the-Loop**

- Algorithm or Controller Model
- Compiled C-code S-Function
- Plant Model
- Code Generation
- Execution on Host Computer
- Non Real Time
- No I/O

**Hardware-in-the-Loop**

- Algorithm or Controller Model
- Plant Model
- Code Generation
- Embedded Target
- I/O
- PC with I/O Boards

**Component-in-the-Loop**

- Algorithm or Controller Model
- Plant Model
- Code Generation
- Rest of Vehicle is Emulated
- Entire System is Hardware

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Model-in-the-Loop (MIL) Examples Supporting Current DOE R&D Activities

Evaluation of Fuel Consumption Benefits of Advanced Powertrains (VSS_010)

Evaluation of Fuel Consumption Benefits of Advanced Controls

Global Optimization

Rule Based

Instantaneous Optimization

Heuristic Optimization

2 Mode HEV

Control Development

Vehicle Analysis

Evaluation of Fuel Consumption Benefits of Advanced Technologies (VSS011)

HCCI Fuel Savings vs PI According to Hybridization Degree

Definition of Component Requirements for Program Goals

Unadjusted Fuel Consumption Ratio

Hybridization Degree (%)

HCCI Potential

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>EOL (End of Life)</th>
<th>High Power Energy Rating Battery</th>
<th>High Energy Power Rating Battery</th>
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</thead>
<tbody>
<tr>
<td>Reference System Mass Range</td>
<td>kWh</td>
<td>100</td>
<td>48</td>
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<tr>
<td>Peak Power Discharge Power -2 Sec / 10 Sec</td>
<td>kWh</td>
<td>20</td>
<td>15</td>
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<tr>
<td>Peak Range Power (10 sec)</td>
<td>kWh</td>
<td>30</td>
<td>15</td>
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<tr>
<td>Available Energy for C2 (Charge Depleting) Mode, 10 kV Rate</td>
<td>kWh</td>
<td>3.6</td>
<td>11.6</td>
</tr>
<tr>
<td>Available Energy for C1 (Charge Sustaining) Mode</td>
<td>kWh</td>
<td>5.1</td>
<td>6.3</td>
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<tr>
<td>Minimum Endurance Energy Efficiency (US IHC BEV Cycle)</td>
<td>%</td>
<td>88</td>
<td>89</td>
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<td>Cold starting power at -30°C, 2 sec, 3 Pulses</td>
<td>kW</td>
<td>7</td>
<td>7</td>
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<tr>
<td>CD Life / Discharge Throughput</td>
<td>Cycle/MWh</td>
<td>5,000 / 17</td>
<td>5,000 / 10</td>
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<td>CI HEV Cycle Life, 50 Wh Profile</td>
<td>CYcles</td>
<td>200,000</td>
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<tr>
<td>Calendar Life, 50 Wh</td>
<td>CYcles</td>
<td>12</td>
<td>12</td>
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<tr>
<td>Minimum System Weight</td>
<td>kg</td>
<td>90</td>
<td>110</td>
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<tr>
<td>Minimum System Volume</td>
<td>Cubic</td>
<td>40</td>
<td>80</td>
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<td>Minimum Operating Voltage</td>
<td>VDC</td>
<td>360</td>
<td>360</td>
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<tr>
<td>Minimum Operating Voltage</td>
<td>VDC</td>
<td>-60 to 55</td>
<td>-60 to 55</td>
</tr>
<tr>
<td>Maximum Self-discharge</td>
<td>%</td>
<td>84</td>
<td>84</td>
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<tr>
<td>System Efficiency Rate at 30°C</td>
<td>kW</td>
<td>1.4 (120V/10A)</td>
<td>1.4 (120V/10A)</td>
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<tr>
<td>Unassisted Operating &amp; Charging Temperature Range</td>
<td>°C</td>
<td>-30 to 62</td>
<td>-30 to 62</td>
</tr>
<tr>
<td>Survival Temperature Range</td>
<td>°C</td>
<td>-46 to 68</td>
<td>-46 to 66</td>
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<tr>
<td>Maximum System Production Price @ 10th minute</td>
<td>$</td>
<td>51,700</td>
<td>53,400</td>
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</tbody>
</table>
Software-in-the-Loop (SIL) Example to Develop Low Level Engine Control

Real Time Operating System (RTOS) ensures call of functions at specific intervals (such as CAN)

Sends and receives CAN signals

New algorithm(s) to be tested

Production Code

Hardware input/output
Component-in-the-Loop (CIL) Example to Evaluate Non-Modeled Phenomena for DOE

Example #1: Impact of battery cold start on PHEVs Fuel Consumption (VSS012)

Example #2: Impact of emission and engine cold start on PHEVs Fuel Consumption (VSS014)

Example #3: Engine and Battery are Coupled

Rest of the Vehicle Modeled

ANL is DOE’s lead laboratory for Automotive Component-in-the-Loop

Commands
(Battery, ABC150, equipment..)

Sensors

Commands
(ICE, Dyno, equipment..)

Sensors

Battery behaves as if in vehicle

Engine behaves as if in vehicle
Autonomie Designed to Be Used For All Steps in the Development Process

Build and compare large number of technology, powertrain, options

Ensure simulation traceability, model compatibilities

Easy selection & implementation of data, models, control or cycles

Run batch mode + Distributed computing

Generic Processes

Database Management

Analyze and compare test and simulation data

Enables MIL, SIL, RCP, HIL, CIL
Collaborations

Source: GM
Collaborations

- Provide inputs on “best practices”
- Implementation of MathWorks developed models and algorithms to support studies
- Provide technical support to automate the integration of GTPower (engine modeling) into Autonomie
- Provide technical support to automate the integration of AMESim (transmission modeling) into Autonomie
- Provide technical support to automate the integration of CarSim and TruckSim (vehicle dynamics modeling) into Autonomie
Future Activities

- Continue to provide guidance for DOE R&D activities
- Expand the Autonomie usage throughout DOE to promote Model Based Design approach
- Continue to enhance the tool based on DOE needs and user’s feedback
- Define the industry standard for modeling and simulation to be adopted by the entire industry through SAE
- Discuss potential use of Autonomie to support future Medium and Heavy Duty fuel consumption regulations
Summary - ANL Will Continue to Accelerate Technology Development and Introduction

- Support DOE R&D activities
- Support usage of Autonomie for OEMs, HD Regulation...
- Promote Autonomie as worldwide standard for Automotive modeling & Simulation
- Implement process throughout DOE

[Diagram showing interactions between National Labs, U.S. DOE, Autonomie, and OEMs]
Additional Slides
Key Benefits

Plug & Play
- Flexibility & Reusability
- Customizable architectures
- Common Nomenclature
- Code Neutral

Reduces Cost & Time to Production
- Common Methods to sort technologies quickly to reduce hardware build iterations
- Reduces/eliminates duplicate modeling and analysis work
- Delivers designs that balance Fuel Economy, Emissions and Drivability (FEED) requirements

Enterprise Wide Solution
- Database Management
- Provides common methods and tools for comparing/evaluating technologies

No other tool currently allows the linkage with any legacy code!
## AUTONOMIE/PSAT Comparison

### Architecture

<table>
<thead>
<tr>
<th>Capability</th>
<th>PSAT</th>
<th>PSAT-PRO</th>
<th>Autonomie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plug &amp; Play Architecture</td>
<td>☑</td>
<td></td>
<td>☑</td>
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<tr>
<td>Hierarchical Architecture Standards (Vehicle, syst...)</td>
<td>☑</td>
<td></td>
<td>☑</td>
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<tr>
<td>Model Reusability through System Experts (Concept to Production)</td>
<td></td>
<td></td>
<td>☑</td>
</tr>
<tr>
<td>Establish Standard Interfaces (Industry-wide)</td>
<td></td>
<td></td>
<td>☑</td>
</tr>
</tbody>
</table>

### Features

<table>
<thead>
<tr>
<th>Capability</th>
<th>PSAT</th>
<th>PSAT-PRO</th>
<th>Autonomie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model/data Customization</td>
<td>☑</td>
<td></td>
<td>☑</td>
</tr>
<tr>
<td>Powertrain Configuration Customization</td>
<td>☑</td>
<td></td>
<td>☑</td>
</tr>
<tr>
<td>Select Appropriate Level of Modeling</td>
<td>☑</td>
<td></td>
<td>☑</td>
</tr>
<tr>
<td>GUI Customization (process, post-processing...)</td>
<td>☑</td>
<td></td>
<td>☑</td>
</tr>
<tr>
<td>Database Management</td>
<td></td>
<td></td>
<td>☑</td>
</tr>
</tbody>
</table>
# AUTONOMIE/PSAT Comparison

## Usage*

<table>
<thead>
<tr>
<th>Capability</th>
<th>PSAT</th>
<th>PSAT-PRO</th>
<th>Autonomie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluate Fuel Consumption Benefits (technology, size, powertrain configuration...)</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Evaluate and Balance FEED in Simulation (Fuel Economy, Emissions &amp; Drivability)</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Develop Component Requirements</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Simulate Single Component</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Develop System/Subsystem Requirements</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Develop Vehicle Level Control</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Develop System/Subsystem/Component Control</td>
<td>✔</td>
<td></td>
<td>✔</td>
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<tr>
<td>Component-in-the-Loop</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Software-in-the-Loop, Hardware-in-the-Loop...</td>
<td>✔</td>
<td></td>
<td>✔</td>
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</tbody>
</table>

*Final usage depends on the level of details of the models available*
Define Component Requirements

Component Data from R&D Teams

Battery

Electric Machine

2004 Prius

Vehicle Simulations

Vehicle Classes

Sizing & Simulation

Vehicle Testing

DOE / USABC Requirements

Battery RCP

JCS VL41M

Vehicle Requirements

Accessories

Camry A/C Power

Prius A/C Power

Model

Testing

Vehicle

Simulations

Validation

Component Data from R&D Teams

Battery

Electric Machine

2004 Prius

Vehicle Simulations

Vehicle Classes

Sizing & Simulation

Vehicle Testing

DOE / USABC Requirements

Battery RCP

JCS VL41M

Vehicle Requirements

Accessories

Camry A/C Power

Prius A/C Power

Model

Testing
Validate Vehicle Models to Ensure Studies Integrity

Collect Test Data

Analyze Data

Develop Control

Validate Model

Engine Torque

Understand Gearbox

Model Gearbox

Example of GM 2 Mode Tahoe
Develop Vehicle Control to Maximize Fuel Displacement

Global Optimization

Backward model

Bellman Principle

Optimal Control, Minimal Fuel Cons.

Control Design

Various Control Principles

Rule-Based Control Design

Various Control Strategies

Heuristic Optimization

Existing Control Logic

DIRECT Algorithm

Optimally tuned Parameters
Develop Vehicle Control Taking into Account Non Modeled Parameters

Example: Impact of Vehicle Level Control on Engine Emissions for PHEVs (collaboration with ORNL)

Step #1 – Evaluate Different Controls in Simulation

Step #2 – Verify the Trends with Engine-in-the-Loop
Match Technologies, Configurations to Specific Applications

Impact of Aerodynamics for Different Line Haul Applications

Comparison of Aerodynamic Fuel Savings for Drive Cycles vs Steady States

- HTUF Class 6
- UDDS Truck
- HHDDT Cruise
- HHDDT High Speed

50% load

Impact of Mild and Full HEV for Line Haul Applications

Impact of All Technologies on Fuel Consumption

The Sum of the Combined Technologies < The Sum of Each Technology
Evaluate Uncertainties Through Monte Carlo Analysis

- Uncertainty is modeled by a probability density function (pdf)
- How is the uncertainty propagated?

- PHEV 10 miles All Electric Range (AER) midsize used as reference case

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Sampling</th>
<th>Results</th>
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<tbody>
<tr>
<td>Cd</td>
<td>Monte Carlo (MC),</td>
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<tr>
<td></td>
<td>Latin hypercube (LHS),</td>
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</tr>
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<td></td>
<td>Median Latin hypercube (MLHS)</td>
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<td>FA</td>
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<tr>
<td>Crr</td>
<td></td>
<td></td>
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<tr>
<td>Weight</td>
<td></td>
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</tbody>
</table>
Address Previous Reviewers Comments

- **Question 1:** Does this project support the overall DOE objective of petroleum displacement? Why or why not?

  The project supports the overall DOE objective of petroleum displacement by allowing a faster introduction of advanced technologies in the market, while reducing cost. One of the main advantage is that it benefits all technologies, rather than focusing on a single one. The process also allows all companies, small and large, to implement the process.

- **Question 2:** What is your assessment of the approach to performing the work? To what degree are technical barriers addressed? Is the project well-designed, feasible, and integrated with other efforts?

  The requirements of the software have been developed with the support of General Motors. GM has highlighted several technical barriers that were preventing them to take full advantage of Model Based Design approach using existing tools and processes. Working with GM, every requirement was defined, developed and validated using examples. As a result of the project, GM is planning to use Autonomie company wide to support all future control developments. The software has been discussed and reviewed with numerous OEMs and researchers and is used to support numerous current DOE activities.
Address Previous Reviewers Comments

- Question 3: Characterize your understanding of the technical accomplishments and progress toward overall project and DOE goals.

Several Beta versions were provided to GM, starting July 2009. ANL started using Autonomie to support several DOE activities in November 2009. The pre-release version was provided to more than 15 companies to gather feedback in February 2010. The first public version is expected to be released in June 2010.

- Question 4: What is your assessment of the level of collaboration and coordination with other institutions?

The main current collaborations are with GM, MathWorks, Mechanical Simulation, Gamma Technology and LMS. However, several presentations have been provided to numerous OEMs, both light and heavy duty. More than 15 companies are been evaluating the pre-release and provided feedback. Several institutions have been invited to participate to the SAE committee to define modeling and simulation industry standard. With more than 130 companies and 750 users currently using PSAT, ANL expects to get more feedback after the public release.
Address Previous Reviewers Comments

- Question 5: Has the project effectively planned its future work in a logical manner by incorporating appropriate decision points, considering barriers to the realization of the proposed technology, and, when sensible, mitigating risk by providing alternate development pathways?

Future work currently planned is primarily focused on improving the support to DOE activities. Once the basic features are implemented, future development will be defined based on DOE needs. Further development requested by other users will (a) be funded by them if the needs are specific to their applications or (b) be funded through DOE based upon sponsor approval if it can benefit the entire community.

- Question 6: How sufficient are the resources for the project to achieve the stated milestones in a timely fashion?

The funding used for the project development was sufficient for the development phase. In the future, GM is planning to directly fund the development to support its specific needs. DOE is also planning to support maintenance and further development as it has done previously with PSAT. The level of the future support will depend on how much Autonomie is used within DOE. Part of the development is also included in studies.
List of Publications

- Building Algorithm Patent