Autonomie
Plug&Play Software Architecture

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Sponsored by Lee Slezak

Project ID #VSS009
Project Overview

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

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

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

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**
- [Bar chart showing progress]

**Year 3**
- [Bar chart showing progress]

**Current Status**
- [Red star indicating 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)...

Calibration Validation Tuning Drive Quality...

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

* Already linked

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

Database Search

Version Control

Database Management

Legacy Code

Plug & Play

Legacy Processes

Specialty Software (COTS)

CarSim*
GTPower*
AMESim*...
Approach
Software Can Be Entirely Customized

- Model organization
  - Single or multiple plants
  - Controller location

- Fuel economy
  - Validation
  - Drive quality
  - Control...

- Calculations
- Plots
- Reports...

- Post-processing

- Customization

- Proprietary Information

- Processes

- Model organization

- Controllers...

- Models
- Data
- Controls...
Technical Accomplishments
Legacy Code Reusability

**Process to Integrate Legacy Code Demonstrated**

- GUI Automatically Renames Variables, Creates Necessary Support Files
- Ready for use in AUTONOMIE

**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
- Transmission Experts
- Battery, Motor 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
- Plant Model
- Compiled C-code S-Function
- 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
**Model-in-the-Loop (MIL) Examples Supporting Current DOE R&D Activities**

**Evaluation of Fuel Consumption Benefits of Advanced Powertrains (VSS_010)**

- 2 Mode HEV
- Control Development
- Vehicle Analysis

**Evaluation of Fuel Consumption Benefits of Advanced Controls**

- Global Optimization
- Rule Based
- Heuristic Optimization
- Instantaneous Optimization


**Definition of Component Requirements for Program Goals**

**HCCI Fuel Savings vs PI According to Hybridization Degree**

**Unadjusted Fuel Consumption Ratio**

**Requirements of End of Life Energy Storage Systems for PHEVs**

- Characteristics at EOL (End of Life)
- High Power Energy Ratio Battery
- High Energy Power Ratio Battery

- Reference System Operating Range
- Regen Power
- Peak Power
- Peak Regen Power
- Reference Power
- Maximum Regen Power
- Minimum Operating Voltage
- Maximum Operating Voltage
- Minimum Self-discharge
- System Charge Rate at 35°C
- Unassisted Operating & Charging Temperature Range
- Survival Temperature Range
- Maximum System Production Price @ 10k units/yr
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)

Production Code

New algorithm(s) to be tested

Sends and receives CAN signals

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

ANL is DOE’s lead laboratory for Automotive Component-in-the-Loop
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
- Database Management
- Generic Processes
- Run batch mode + Distributed computing
- Analyze and compare test and simulation data
- Enables MIL, SIL, RCP, HIL, CIL
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 the flow of Models & data between National Labs, U.S. DOE, 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>
</tr>
<tr>
<td>Hierarchical Architecture Standards (Vehicle, syst...)</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<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>
</tr>
<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>
</tr>
</tbody>
</table>

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

Component Data from R&D Teams

Battery

Testing

Model

Electric Machine

Vehicle Simulations

Vehicle Requirements

Sizing & Simulation

Vehicle Classes

DOE / USABC Requirements

Accessories

Camry A/C Power

Prius A/C Power

Battery RCP

JCS VL41M

Vehicle Testing

2004 Prius

Model

Cambridge Research Power

Electric Machine

Battery RCP
Validate Vehicle Models to Ensure Studies Integrity

Collect Test Data

Understand Gearbox

Model Gearbox

Analyze Data

Develop Control

Validate Model

Example of GM 2 Mode Tahoe

Source: GM
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

Vehicle Model + Detailed After-Treatment Model → Evaluation of Different Vehicle Control Logic and Tuning

Step #2 – Verify the Trends with Engine-in-the-Loop

Rest of the Vehicle Modeled → Engine behaves as if in vehicle → Analyze Results
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

Impact of Mild and Full HEV for Line Haul Applications

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

Impact of All Technologies on Fuel Consumption

Class 2B Pickup

Percent Fuel Saved

Engine
Transmission
RR
Cd
Weight
Hybrid improvements
Baseline improvements

Each technology (Conv)  Combination (Conv)  Each technology (Hybrid)  Combination (Hybrid)
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

**Inputs**
- Cd
- FA
- Crr
- Weight

**Sampling**
- Monte Carlo (MC),
- Latin hypercube (LHS),
- Median Latin hypercube (MLHS),
- Quasi Monte-Carlo

**Results**
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.
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