Autonomie Plug&Play Software Architecture

2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

June 08, 2010

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Argonne National Laboratory

Sponsored by Lee Slezak

Project ID #VSS009

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

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)

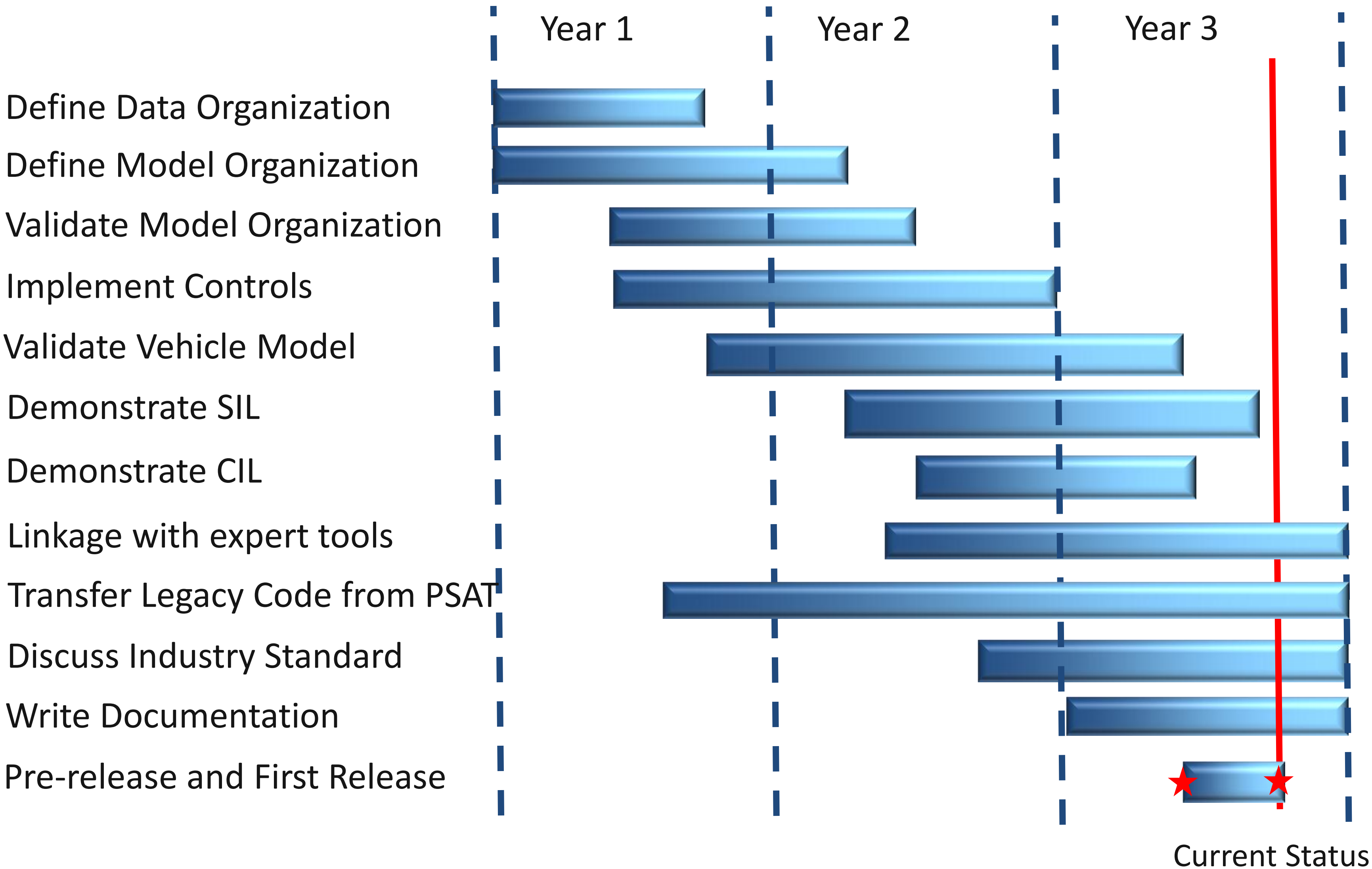
Objective

AUTONOMIE

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

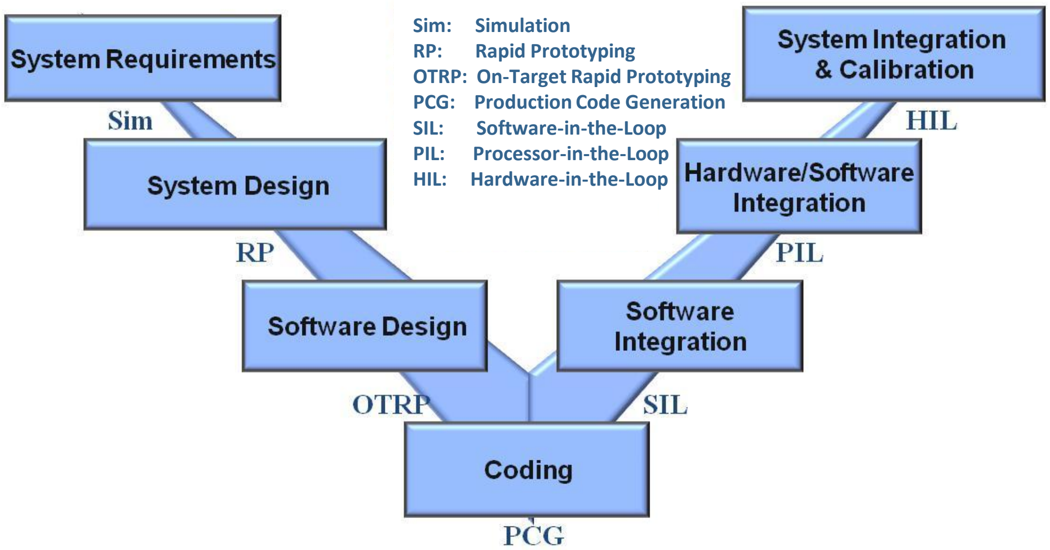


Year 1
Year 2
Year 3
Define Data Organization
Define Model Organization
Validate Model Organization
Implement Controls
Validate Vehicle Model
Demonstrate SIL
Demonstrate CIL
Linkage with expert tools
Transfer Legacy Code from PSAT
Discuss Industry Standard
Write Documentation
Pre-release and First Release
Current Status

Approach

Use Model Based Design Approach to Accelerate the Vehicle Development Process

Model Based Design 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

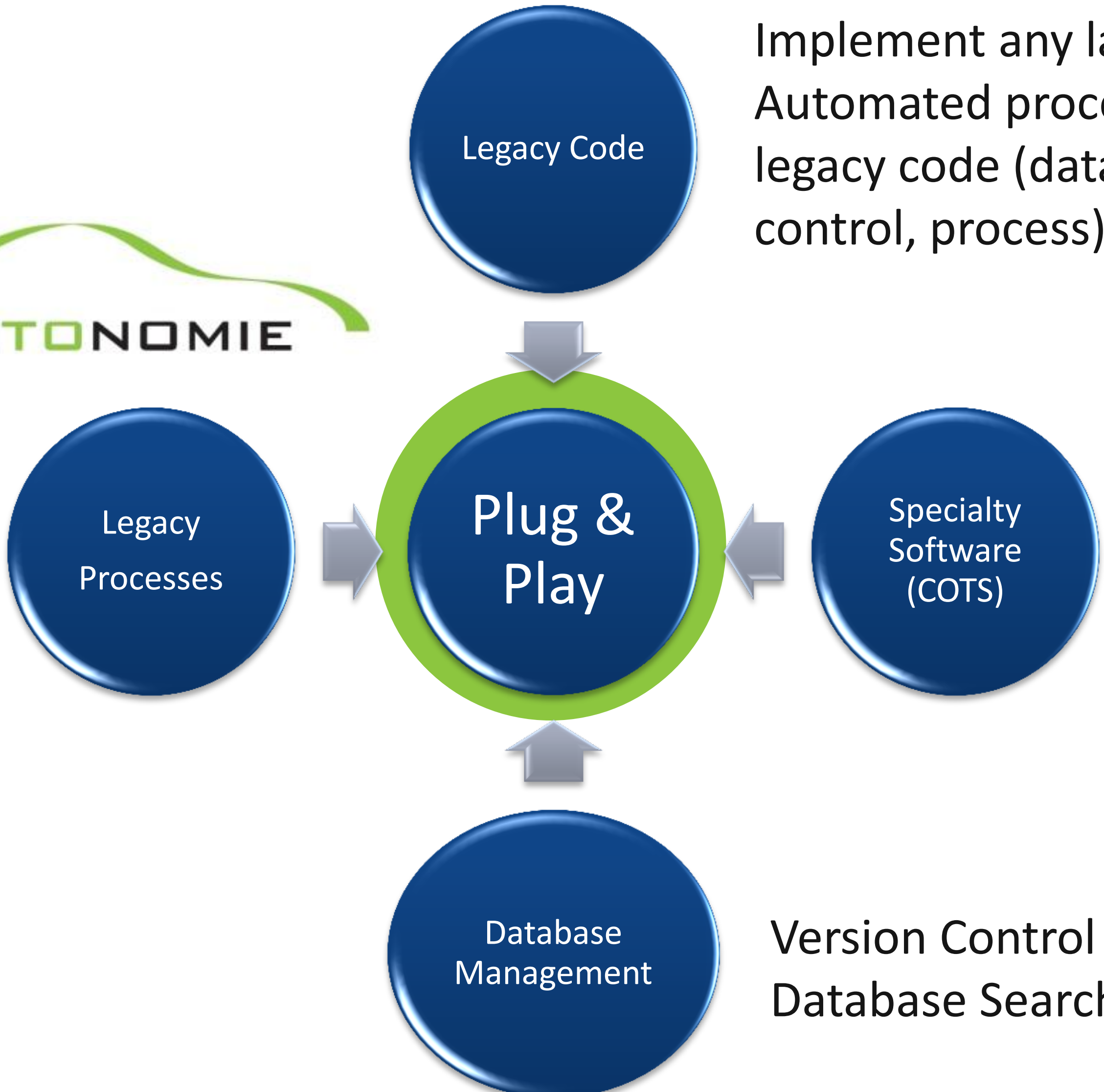
DOE is leading the way with the development of Autonomie

Approach
Maximize Legacy Code Reusability Through Plug & Play

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

AUTONOMIE

Calibration
Validation
Tuning
Drive Quality…



CarSim*
GTPower*
AMESim*…

Version Control
Database Search

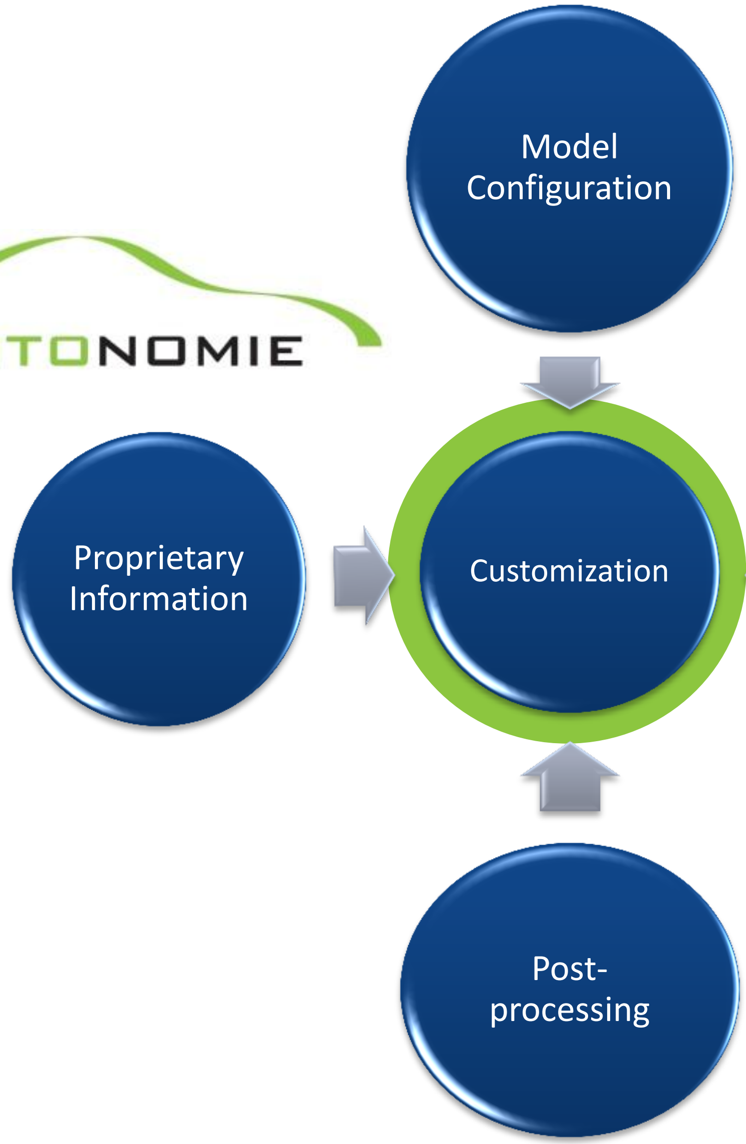
No other tool currently builds the model automatically! Algorithm is patented

* Already linked

Approach
Software Can Be Entirely Customized

Model organization
Single or multiple plants
Controller location

Models
Data
Controls…



Fuel economy
Validation
Drive quality
Control…

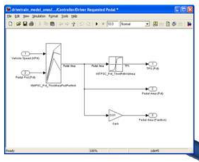
Calculations
Plots
Reports…

Technical Accomplishments

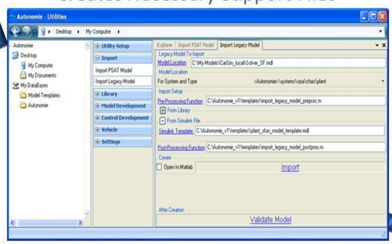
Legacy Code Reusability

Process to Integrate Legacy Code Demonstrated

Legacy Code



GUI Automatically Renames Variables, Creates Necessary Support Files

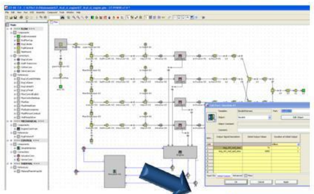


Ready for use in

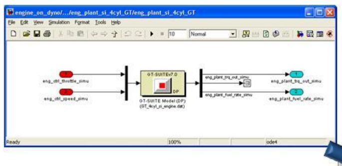
AUTONOMIE

Process to Link Expert Tools (COTS) Demonstrated

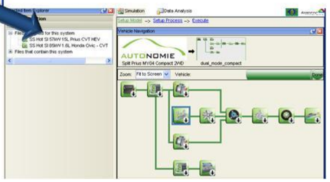
#1 – Develop Model in Native Environment



#2 – Integrate Model in Simulink

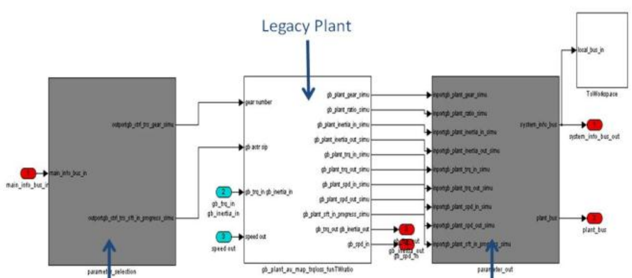


#3 – Use Model in Autonomie



Automatic Building of Any Model

Legacy Plant



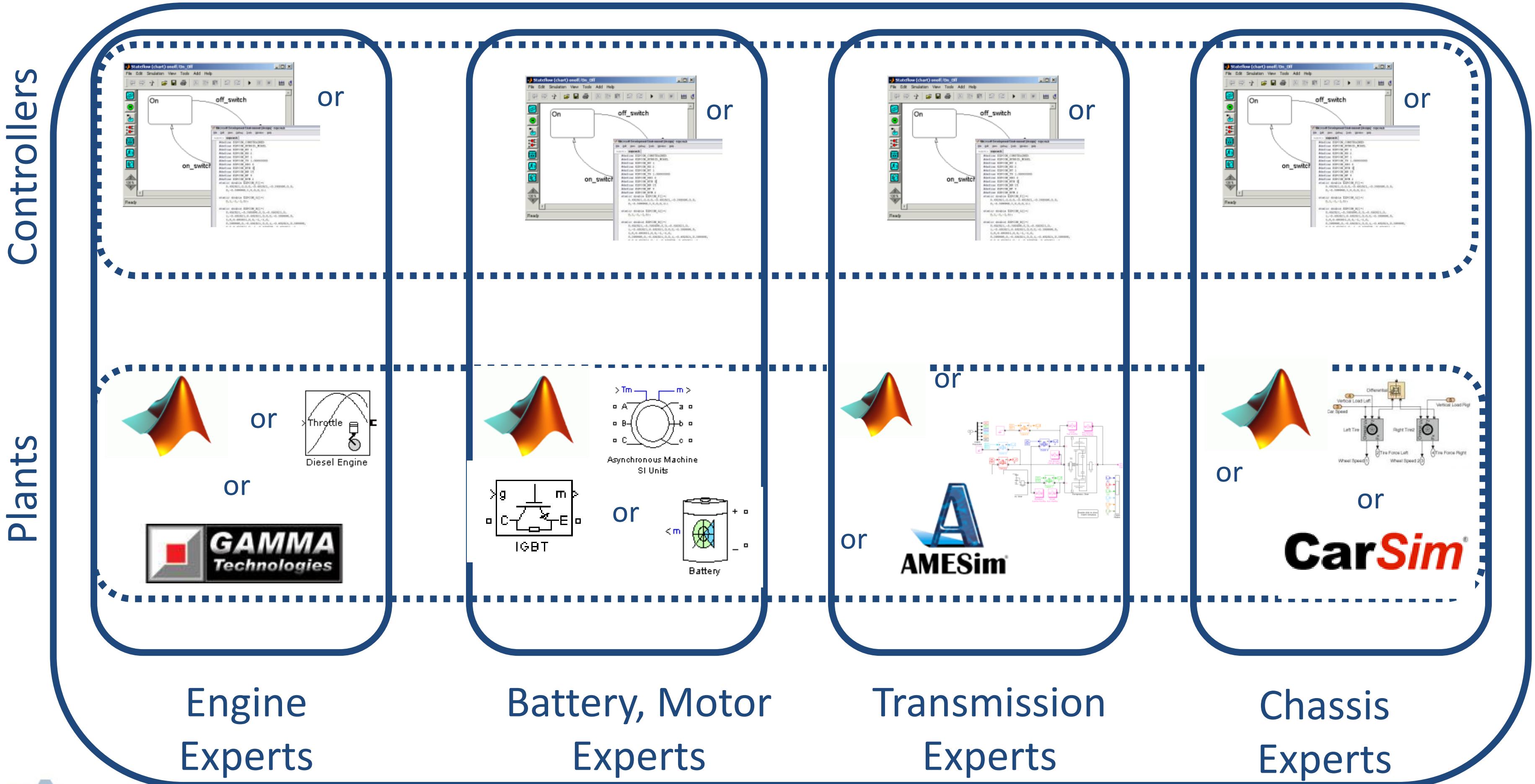
First block **automatically built** to select the required input parameters, change units and data type

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



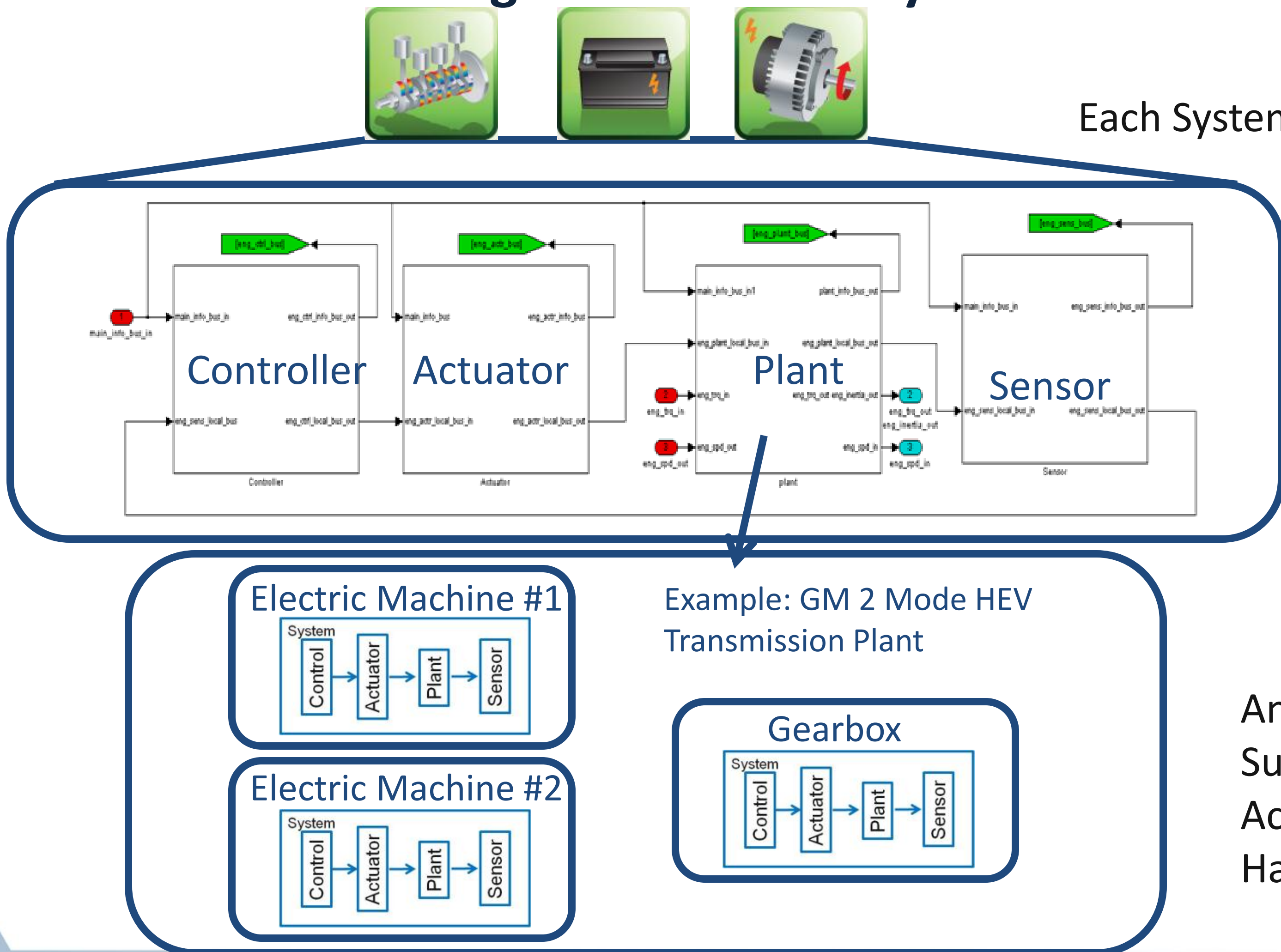
Vehicle Experts

Technical Accomplishments

Software Customization

The Model Can Be Organized to Exactly Match the Hardware Setup

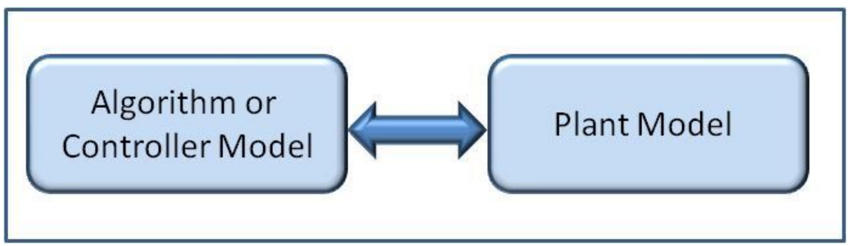
Each System is Optional



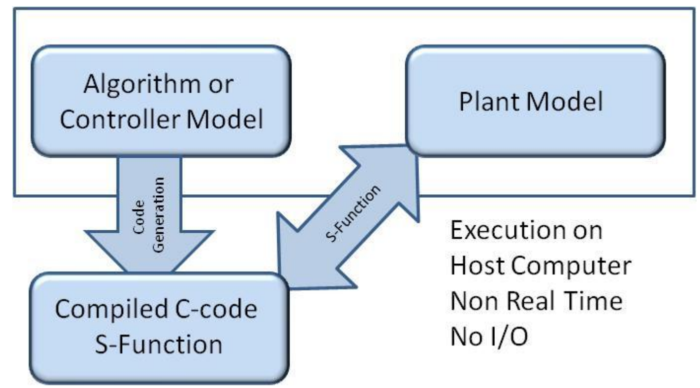
Any System can have Subsystems To Accurately Represent Hardware

Software Customization Allows a Single Tool to Be Used Throughout the Vehicle Development Process

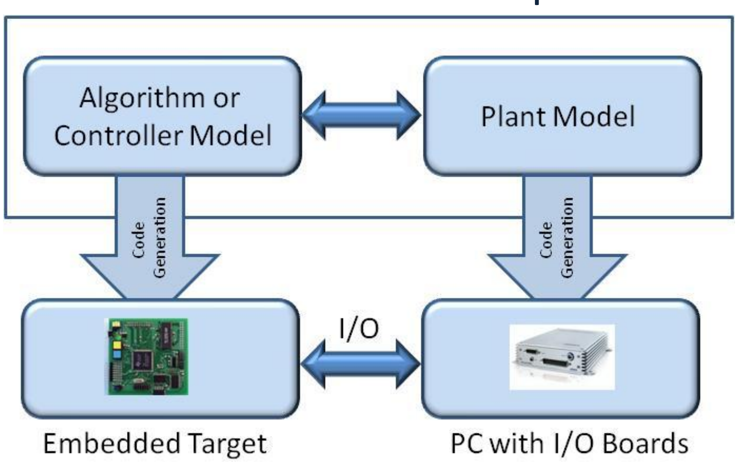
Model-in-the-Loop



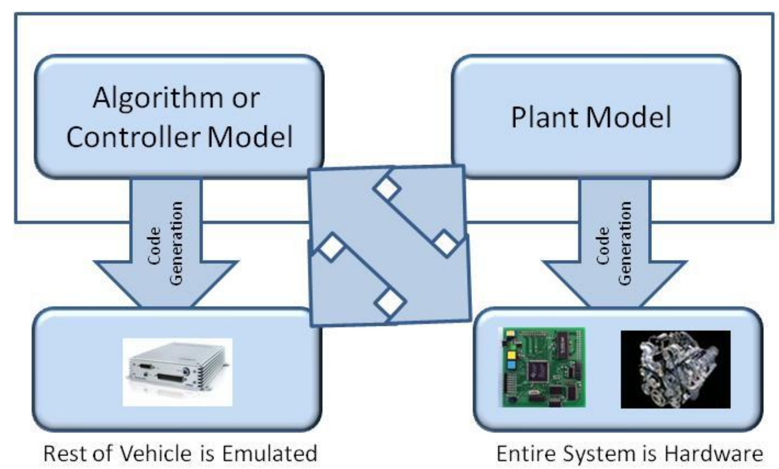
Software-in-the-Loop



Hardware-in-the-Loop

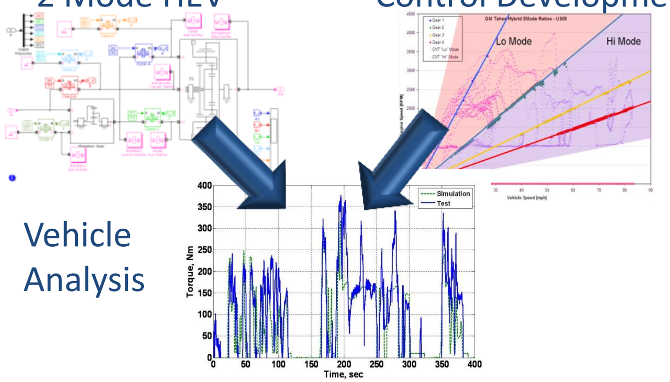


Component-in-the-Loop

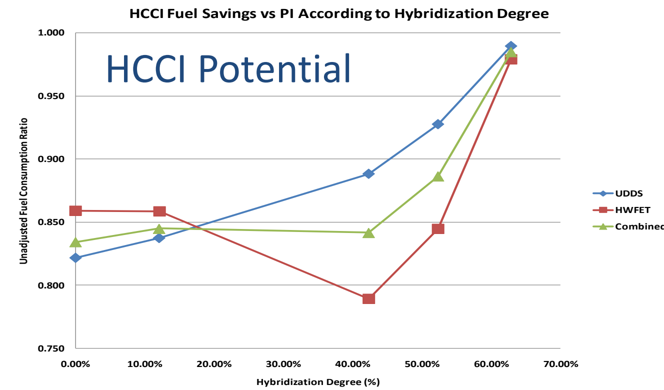


Model-in-the-Loop (MIL) Examples Supporting Current DOE R&D Activities

Evaluation of Fuel Consumption Benefits of Advanced Powertrains (VSS_010)

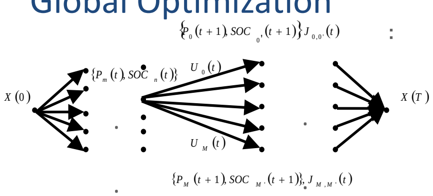


Evaluation of Fuel Consumption Benefits of Advanced Technologies (VSS011)

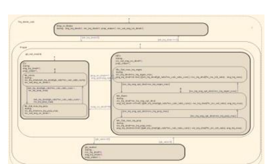


Evaluation of Fuel Consumption Benefits of Advanced Controls

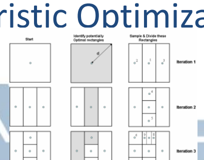
Global Optimization



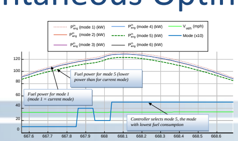
Rule Based



Heuristic Optimization



Instantaneous Optimization



Definition of Component Requirements for Program Goals

Requirements of End of Life Energy Storage Systems for PHEVs

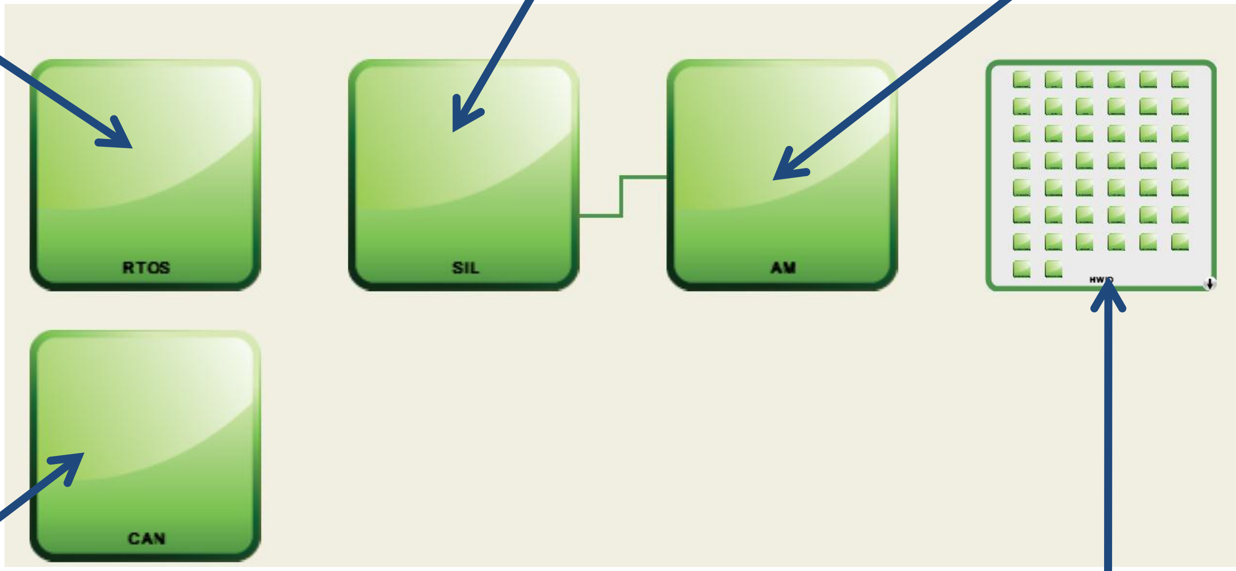
Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Reference Equivalent Electric Range	miles	10	40
Peak Pulse Discharge Power - 2 Sec / 10 Sec	kW	50 / 45	46 / 38
Peak Regen Pulse Power (10 sec)	kW	30	25
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	3.4	11.6
Available Energy for CS (Charge Sustaining) Mode	kWh	0.5	0.3
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	90	90
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	7	7
CD Life / Discharge Throughput	Cycles/MWh	5,000 / 17	5,000 / 58
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000
Calendar Life, 35°C	year	15	15
Maximum System Weight	kg	60	120
Maximum System Volume	Liter	40	80
Maximum Operating Voltage	Vdc	400	400
Minimum Operating Voltage	Vdc	>0.55 x Vmax	>0.55 x Vmax
Maximum Self-discharge	Wh/day	50	50
System Recharge Rate at 30°C	kW	1.4 (120V/15A)	1.4 (120V/15A)
Unassisted Operating & Charging Temperature Range	°C	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

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

Rest of the Vehicle Modeled

AUTONOMIE

Commands (Battery, ABC150, equipment..)

Sensors

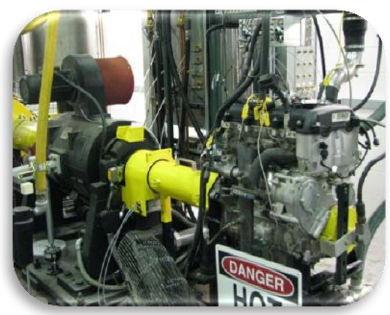
Battery behaves as if in vehicle

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

Example #3: Engine and Battery are Coupled

Commands (ICE, Dyno, equipment..)

Sensors



Engine behaves as if in vehicle

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

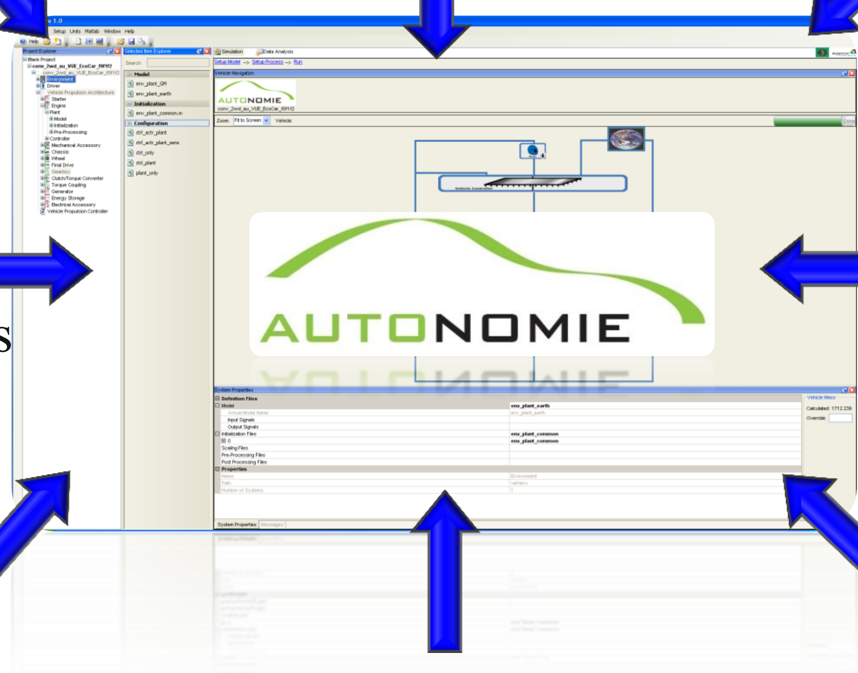
ANL is DOE's lead laboratory for Automotive Component-in-the-Loop

Autonomie Designed to Be Used For All Steps in the Development Process

Build and compare large number of technology, powertrain, options

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

Run batch mode + Distributed computing



Ensure simulation traceability, model compatibilities

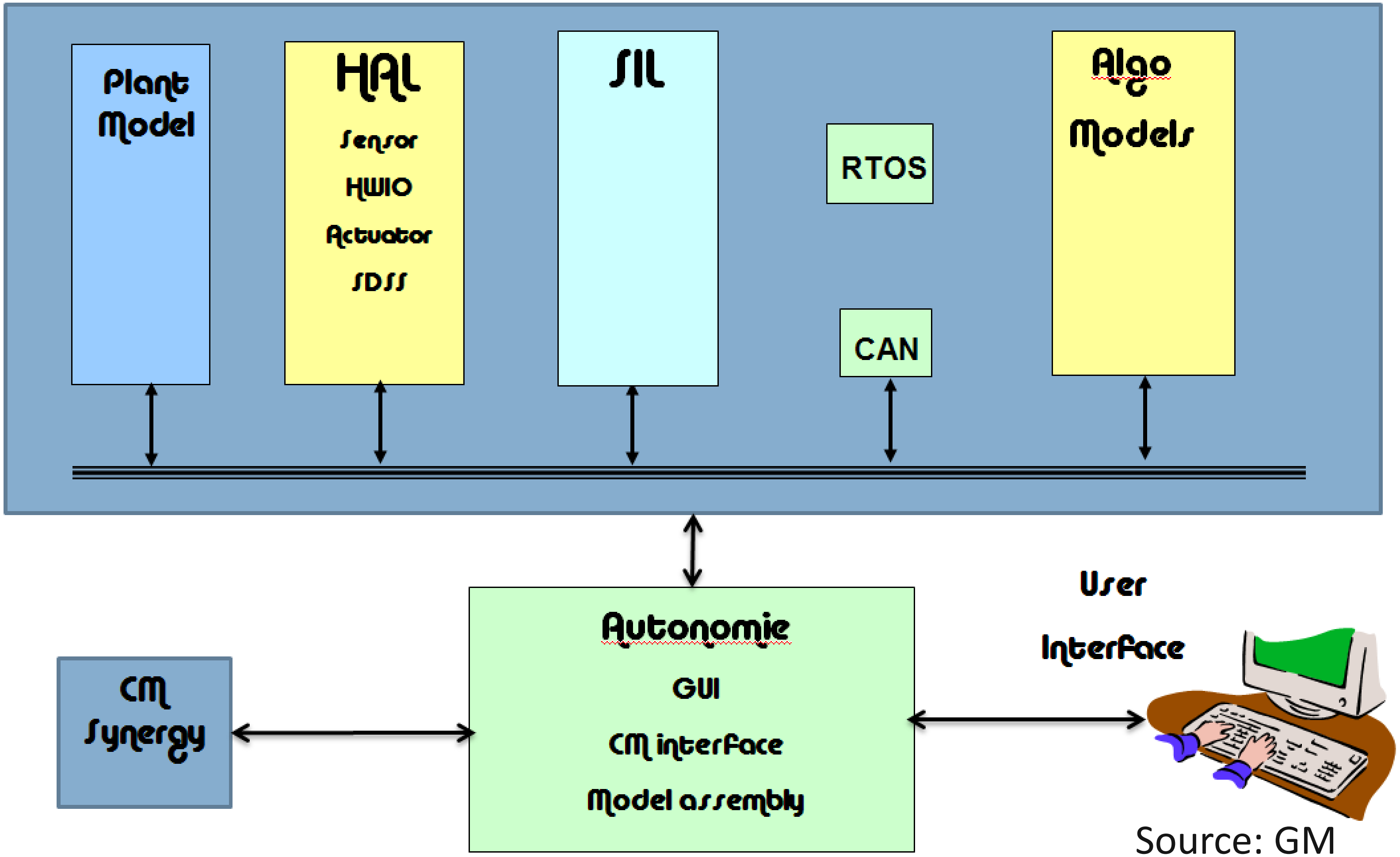
Analyze and compare test and simulation data

Database Management

Generic Processes

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

Gamma Technologies

- Provide technical support to automate the integration of GTPower (engine modeling) into Autonomie

LMS ENGINEERING INNOVATION

AMESim

- Provide technical support to automate the integration of AMESim (transmission modeling) into Autonomie

CarSim® Mechanical Simulation

- 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

Additional Slides

Key Benefits

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

- 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

- 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

Capability	PSAT	PSAT-PRO	Autonomie
Plug & Play Architecture	✓		✓
Hierarchical Architecture Standards (Vehicle, syst…)			✓
Model Reusability through System Experts (Concept to Production)			✓
Establish Standard Interfaces (Industry-wide)			✓

Features

Capability	PSAT	PSAT-PRO	Autonomie
Model/data Customization	✓		✓
Powertrain Configuration Customization			✓
Select Appropriate Level of Modeling	✓		✓
GUI Customization (process, post-processing…)			✓
Database Management			✓

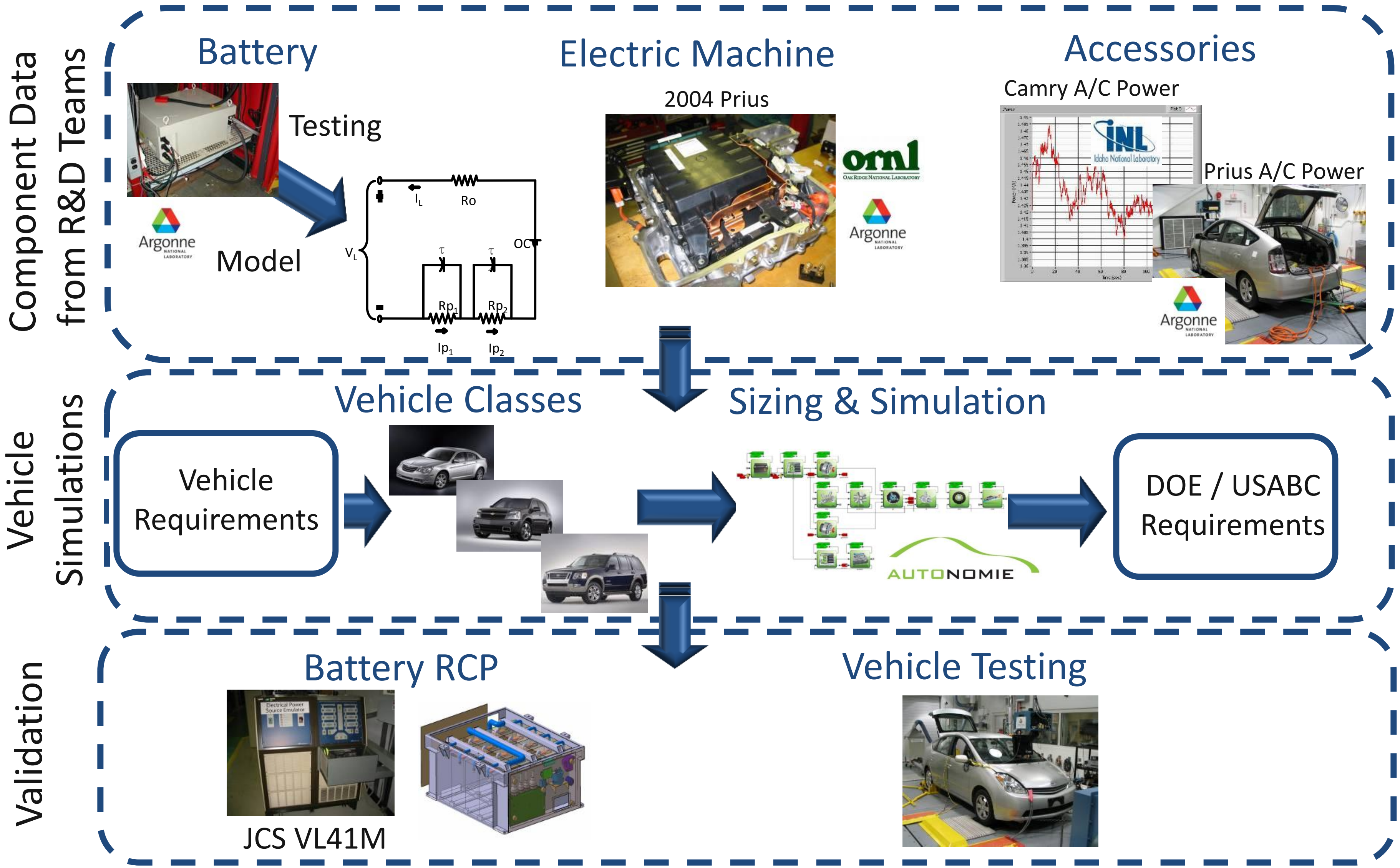
AUTONOMIE/PSAT Comparison

Usage*

Capability	PSAT	PSAT-PRO	Autonomie
Evaluate Fuel Consumption Benefits (technology, size, powertrain configuration…)	✓		✓
Evaluate and Balance FEED in Simulation (Fuel Economy, Emissions & Drivability)			✓
Develop Component Requirements	✓		✓
Simulate Single Component			✓
Develop System/Subsystem Requirements			✓
Develop Vehicle Level Control	✓		✓
Develop System/Subsystem/Component Control			✓
Component-in-the-Loop		✓	✓
Software-in-the-Loop, Hardware-in-the-Loop…			✓

*Final usage depends on the level of details of the models available

Define Component Requirements

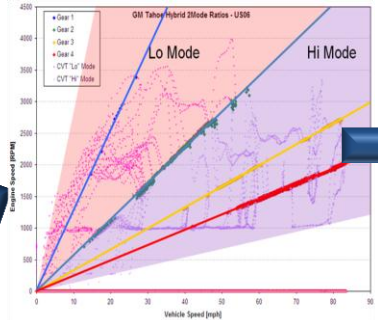


Validate Vehicle Models to Ensure Studies Integrity

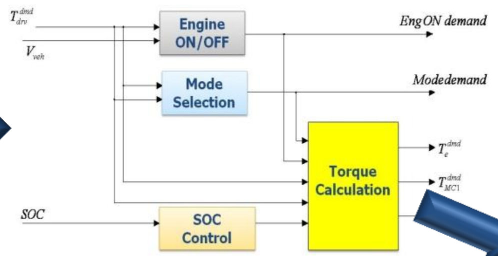
Collect Test Data

APRF

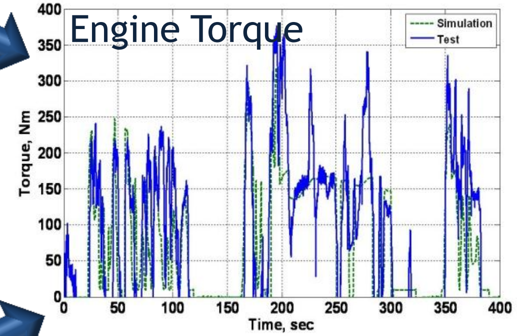
Analyze Data



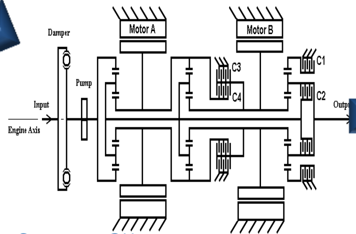
Develop Control



Validate Model

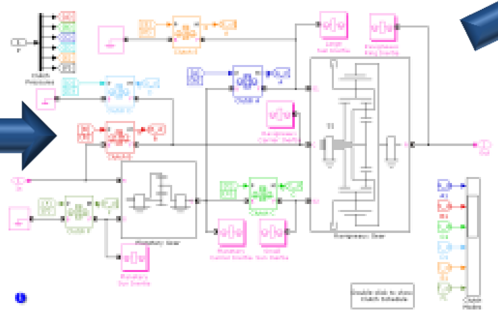


Understand Gearbox



Source : GM

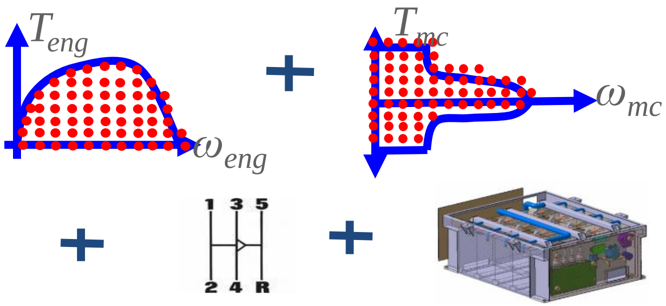
Model Gearbox



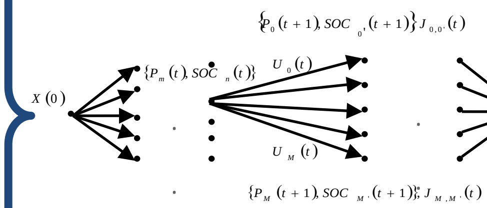
Example of GM 2 Mode Tahoe

Develop Vehicle Control to Maximize Fuel Displacement

Global Optimization



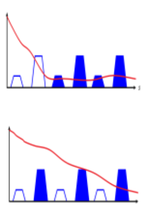
Backward model



Bellman Principle

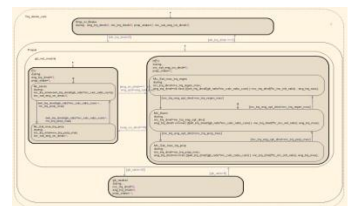
Optimal Control, Minimal Fuel Cons.

Control Design



Various Control Principles

AUTONOMIE +

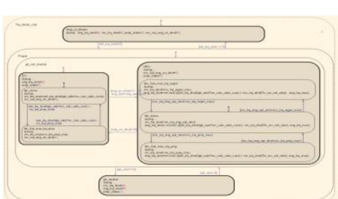


Rule-Based Control Design

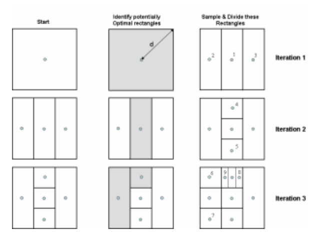
Various Control Strategies

Heuristic Optimization

AUTONOMIE +



Existing Control Logic



DIRECT Algorithm

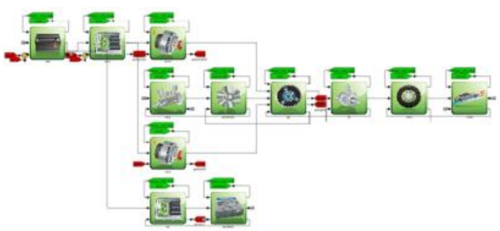
Optimally tuned Parameters

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



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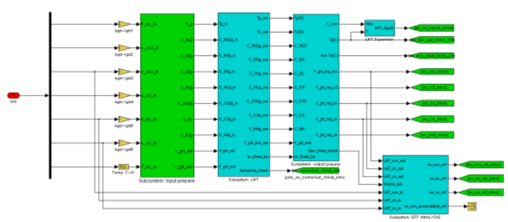
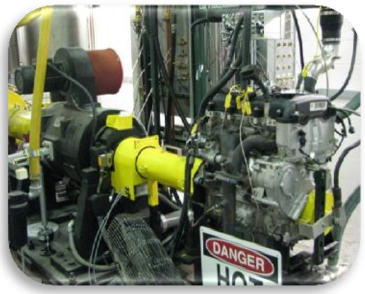
Detailed After-Treatment Model



Evaluation of Different Vehicle Control Logic and Tuning

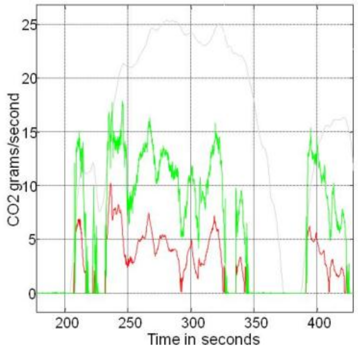
Step #2 – Verify the Trends with Engine-in-the-Loop

Rest of the Vehicle Modeled



Engine behaves as if in vehicle

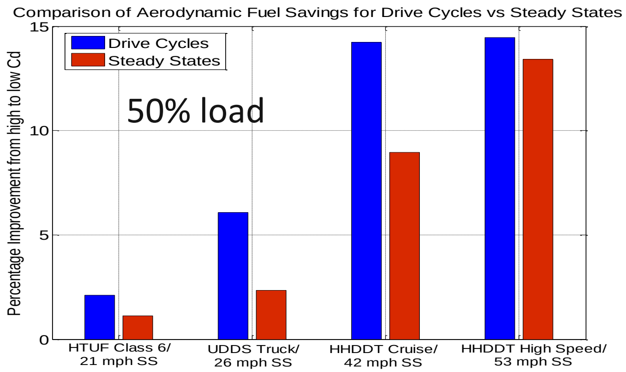
Analyze Results



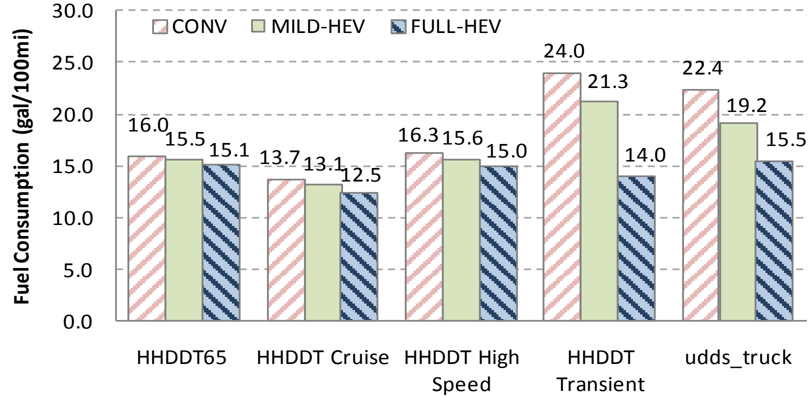
AUTONOMIE

Match Technologies, Configurations to Specific Applications

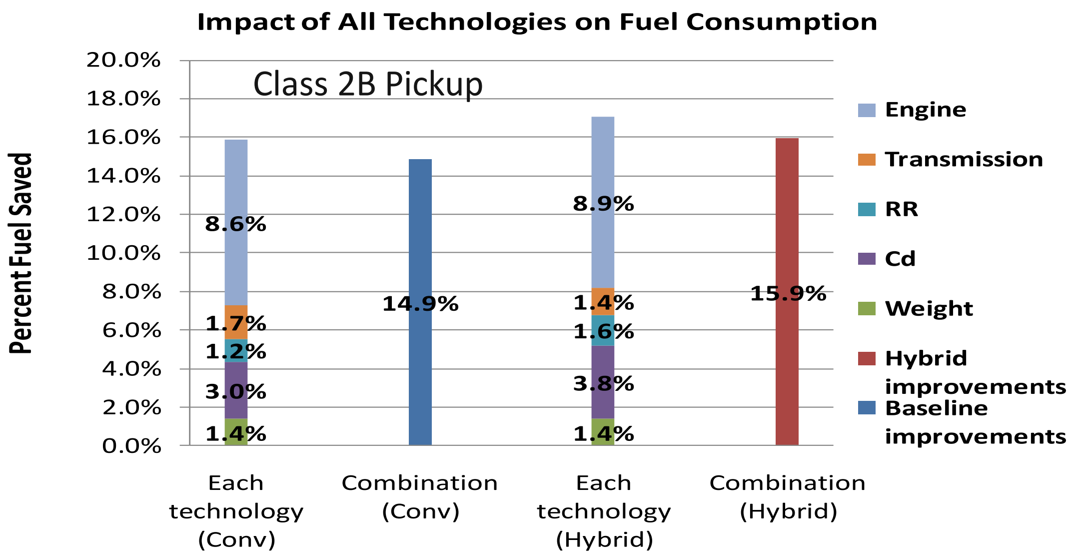
Impact of Aerodynamics for Different Line Haul Applications



Impact of Mild and Full HEV for Line Haul Applications

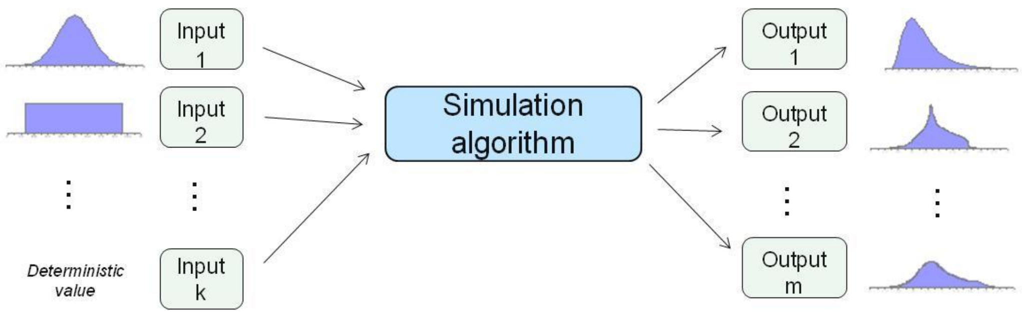


The Sum of the Combined Technologies < The Sum of Each Technology



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

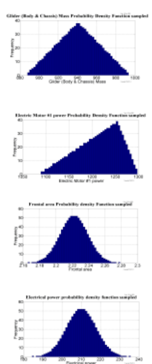
Inputs

Cd

FA

Crr

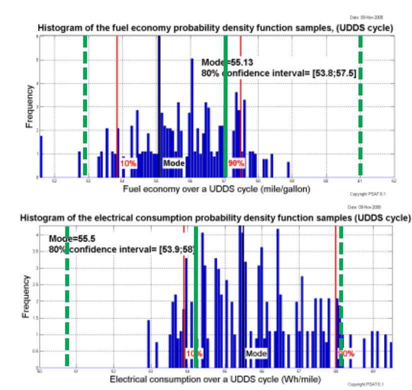
Weight



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.

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- 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.

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- 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

- Halbach, S., Sharer, P., Pagerit, S., Folkerts, C., Rousseau, A., "Model Architecture, Methods, and Interfaces for Efficient math Based Design and Simulation of Automotive Control Systems", SAE 2010-01-0241, SAE World Congress, Detroit, April 2010
- Vijayagopal, R., Shidore, N., Halbach, S., Michaels, L., Rousseau, A., "Automated Model Based Design Process to Evaluate Advanced Component Technologies", SAE 2010-01-0936, SAE World Congress, Detroit, April 2010
- Vijayagopal, R., Kwon, J., Rousseau, A., P. Maloney (MathWorks), "Maximizing Net Present Value of a Series PHEV by Optimizing Battery Size and Control", SAE 2010-01-0037, SAE Convergence, Detroit, November 2010
- Building Algorithm Patent