Argonne NATIONAL LABORATORY

AUTONOMIE

Vehicle System Simulation to Support NHTSA CAFE Standards for the Draft TAR

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Washington DC, NHTSA

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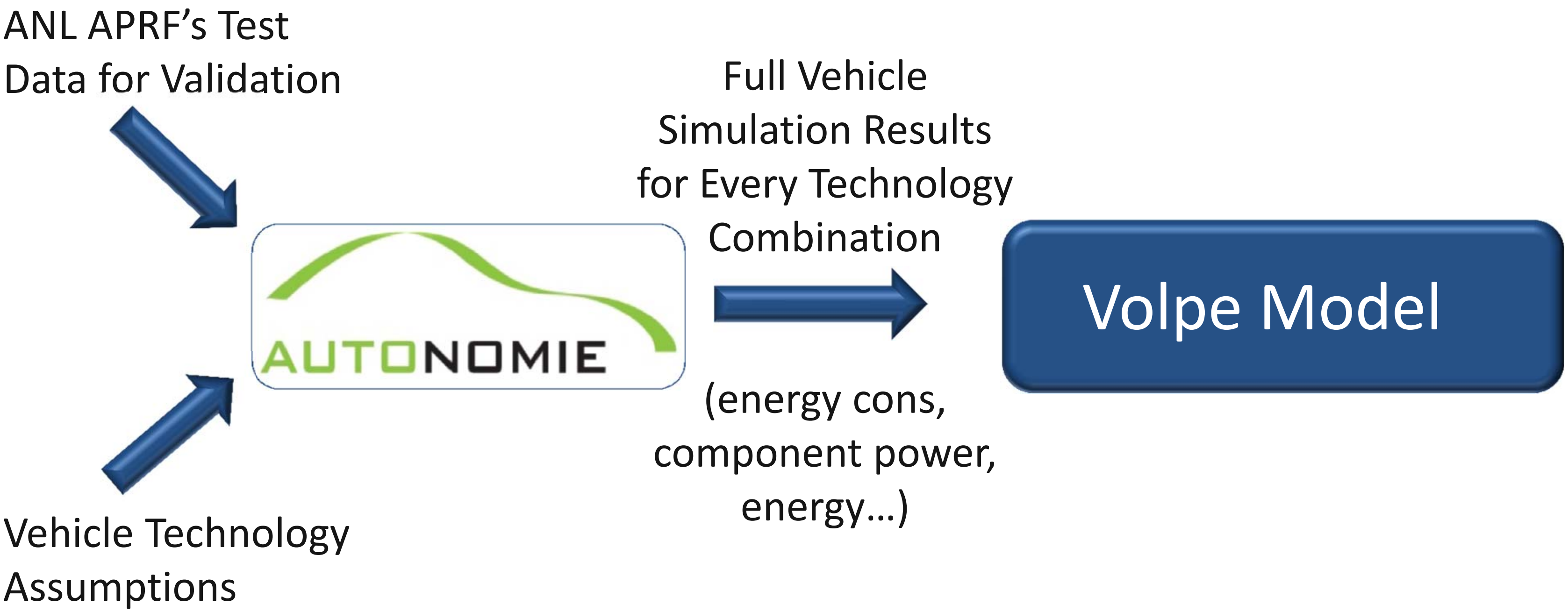
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

U.S. DEPARTMENT OF ENERGY

Overall Process Overview



ANL APRF’s Test Data for Validation

Vehicle Technology Assumptions

AUTONOMIE

Full Vehicle Simulation Results for Every Technology Combination

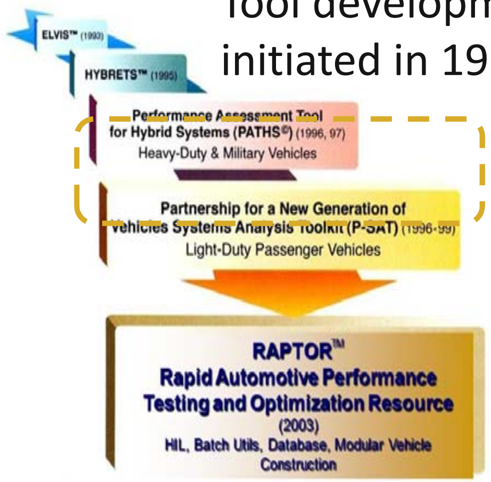
(energy cons, component power, energy…)

Volpe Model

Outline

- Autonomie Overview
- Model Development and Validation
- Process to Estimate Technologies Effectiveness with Full Vehicle Simulation
- Vehicle Powertrain Sizing Algorithms and Validation
- Vehicle Simulation Results Quality Check Process

Autonomie Has a Long History



Tool development initiated in 1995

DOE funding allowed major updates / redesign from 1999 to 2006

Numerous functionalities added through
10 different versions
2 brand new GUI…

In 2006, GM approached Argonne to develop the next generation Plug&Play vehicle simulation tool

Design of a new tool -> Autonomie.
First version released in October 2010

Siemens Selected as Global Partner

AUTONOMIE

- Autonomie’s development has been funded by the U.S Department of Energy (DOE) Vehicle Technologies Office (VTO)
- Models and processes improved over 20+ years based on studies & users’ feedback

Autonomie

Takes Virtual Engineering to a New Level of Efficiency and Productivity

<u>Autonomie's main requirement</u>:

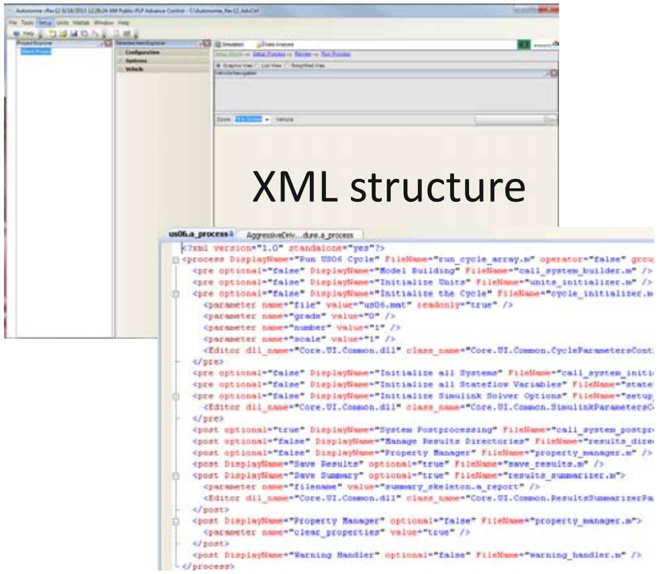
Accelerate the development and introduction of advanced technologies via a Plug&Play modeling architecture and framework through Math-Based Systems Engineering (MBSE).

Autonomie developed under CRADA with GM

Autonomie is Composed of Two Distinct Entities

System Navigation, Integration and Simulation

Empty Interface

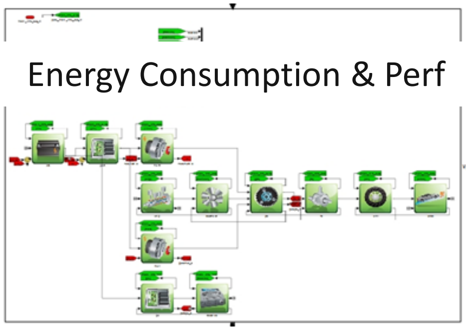


XML structure

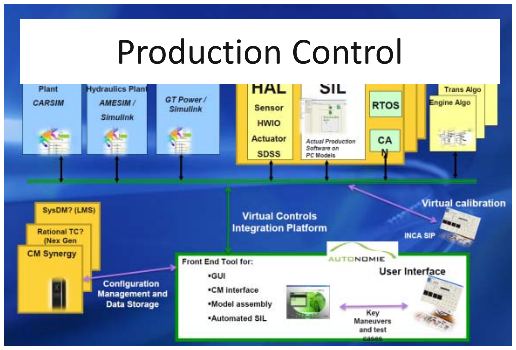
```
<?xml version="1.0" standalone="yes"?>
<process DisplayName="Run US06 Cycle" FileName="run_cycle_array.m" operator="false" grou
  <pre optional="false" DisplayName="Model Building" FileName="call_system_builder.m" />
  <pre optional="false" DisplayName="Initialize Units" FileName="units_initializer.m" />
  <pre optional="false" DisplayName="Initialize the Cycle" FileName="cycle_initializer.m
    <parameter name="file" value="us06.mat" readonly="true" />
    <parameter name="grade" value="0" />
    <parameter name="number" value="1" />
    <parameter name="scale" value="1" />
    <Editor dll_name="Core.UI.Common.dll" class_name="Core.UI.Common.CycleParametersCont
  </pre>
  <pre optional="false" DisplayName="Initialize all Systems" FileName="call_system_initi
  <pre optional="false" DisplayName="Initialize all Stateflow Variables" FileName="state
  <pre optional="false" DisplayName="Initialize Simulink Solver Options" FileName="setup
    <Editor dll_name="Core.UI.Common.dll" class_name="Core.UI.Common.SimulinkParametersC
  </pre>
  <post optional="true" DisplayName="System Postprocessing" FileName="call_system_postpr
  <post optional="false" DisplayName="Manage Results Directories" FileName="results_dire
  <post optional="false" DisplayName="Property Manager" FileName="property_manager.m" />
  <post DisplayName="Save Results" optional="true" FileName="save_results.m" />
  <post DisplayName="Save Summary" optional="true" FileName="results_summarizer.m">
    <parameter name="filename" value="summary_skeleton.a_report" />
    <Editor dll_name="Core.UI.Common.dll" class_name="Core.UI.Common.ResultsSummarizerPa
  </post>
  <post DisplayName="Property Manager" optional="false" FileName="property_manager.m">
    <parameter name="clear_properties" value="true" />
  </post>
  <post DisplayName="Warning Handler" optional="false" FileName="warning_handler.m" />
</process>
```

Applications

Energy Consumption & Perf



Production Control



Nuclear Waste Processing

…

Benefits

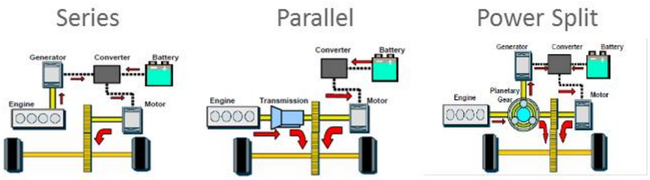
- Uses a common platform to:
  - Simulate individual components as well as complex system
  - Share and integrate models from different languages and complexity levels
- Supports “industrialization” of models, processes and post-processing
- Supports current standards (e.g., Functional Mockup Interface)
- Links/integrates third party tools for:
  - Plant models (i.e., Modelica, LMS AMESim, GT Power, SimScape…),
  - Economic and environmental models (i.e., component cost, LCD, GHG…),
  - Processes (i.e., optimization, parallel and distributed computing, x2x…),
  - Model management
- Fully customizable: architecture, models, configurations, use cases, post-processing…
- Large number of validated low frequency models and controls for a wide range of powertrain configurations (CO2 application)

Autonomie Is Recognized by the Community

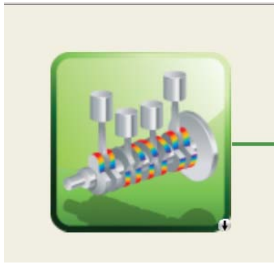
- More than 175 companies, research organizations and universities are currently using Autonomie, including:
  - **Light duty vehicle manufacturers**: GM, Ford, Chrysler, Hyundai, Mercedes-Benz, PSA Peugeot Citroen, Toyota, Tata…
  - **Heavy duty vehicle manufacturers**: Cummins, John Deere, Daimler, PACCAR/Kenworth, Ashok Leyland…
  - **Suppliers**: Johnson Control, Delphi, Allison Transmission, Magna, Siemens, ArvinMeritor, Roush, LG Chem, Samsung SDi …
  - **Regulatory / Research organizations**: DOT, DOD, NREL, ORNL, KATECH, CATARC …
  - **Universities**: >30 US Universities (University of Michigan, MIT, Purdue..), Mines Paris, Tsinghua Univ., Beijing Institute of Technology, Seoul National Univ., Sunkyunkwan Univ., Kookmin Univ, Hanyang Univ, Chungnam Univ…

Autonomie Vehicle Energy Consumption & Performance Application

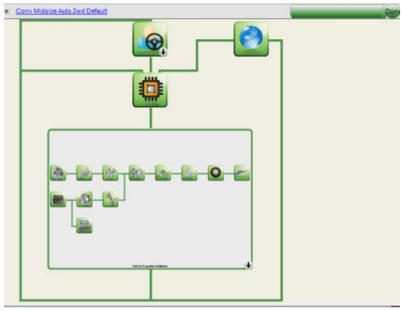
>100 **Powertrain Configurations**



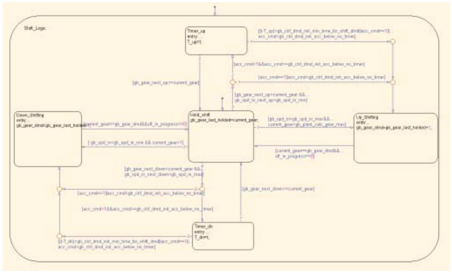
Dozens of **plant models** and >100 **initializations**



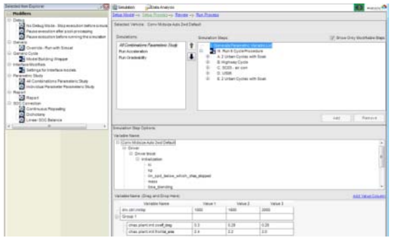
>60 pre-defined LD and MD&HD vehicles



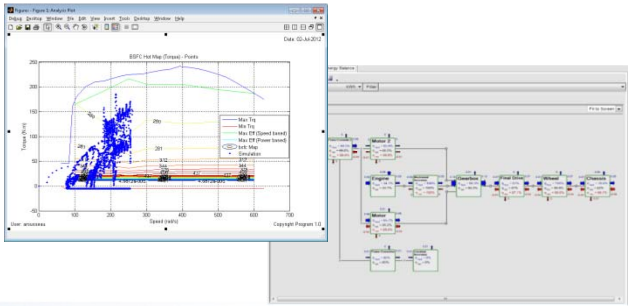
Low level and high level **controls** available for most powertrains



Large Number of **Processes:** drive cycles, parametric study, optimization, batch run, etc.

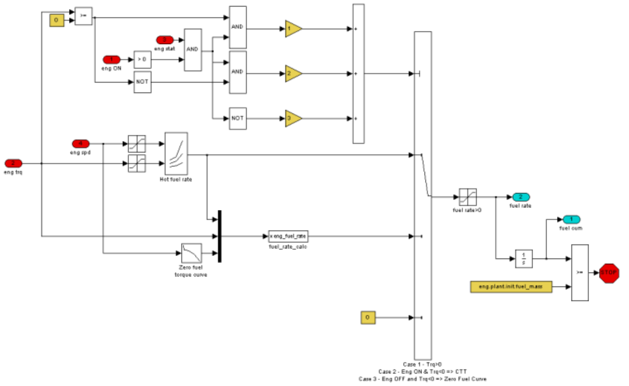


Large Number of **Post-processing** Tools

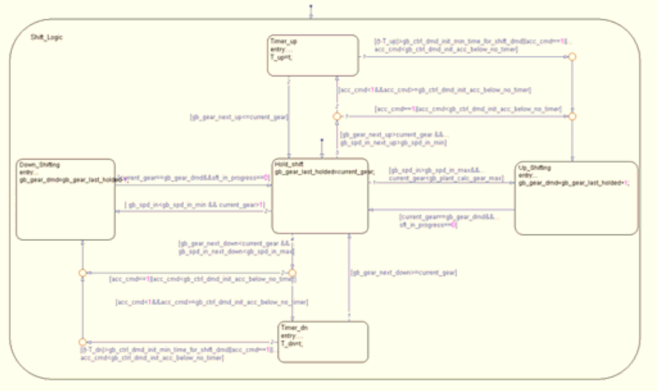


Autonomie is Open (Matlab/Simulink Based)

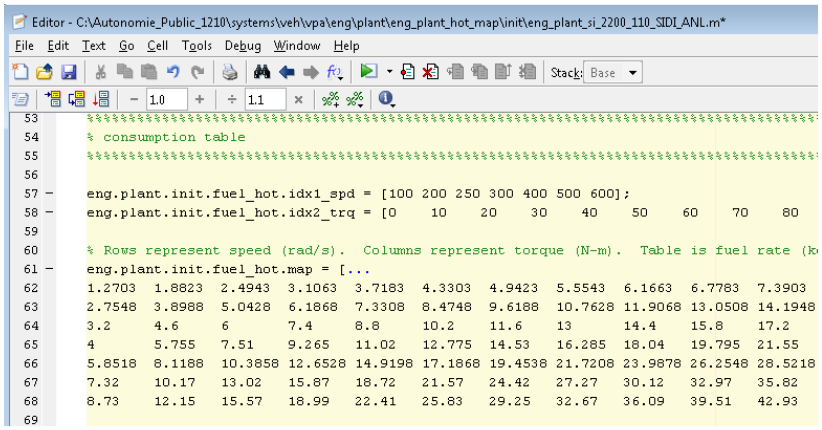
Component Models
in Simulink



Controls
in Simulink / StateFlow

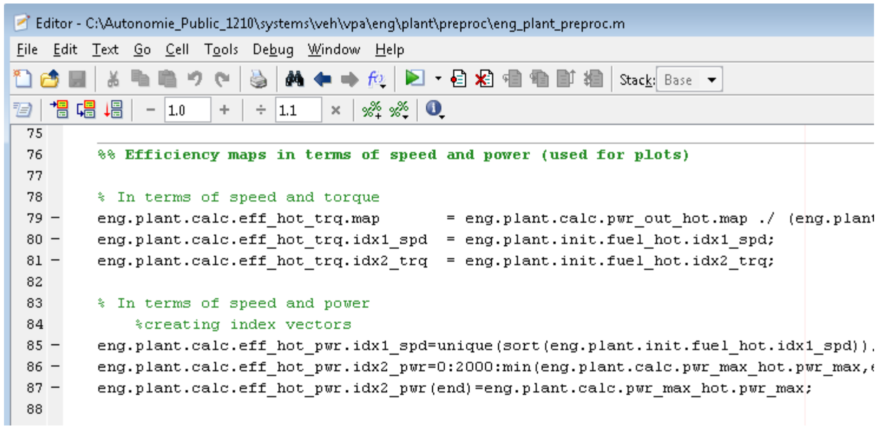


Initialization Files
in Matlab



```matlab
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% consumption table
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

eng.plant.init.fuel_hot.idx1_spd = [100 200 250 300 400 500 600];
eng.plant.init.fuel_hot.idx2_trq = [0    10    20    30    40    50    60    70    80

% Rows represent speed (rad/s).  Columns represent torque (N-m).  Table is fuel rate (k
eng.plant.init.fuel_hot.map = [...
1.2703   1.8823   2.4943   3.1063   3.7183   4.3303   4.9423   5.5543   6.1663   6.7783   7.3903
2.7548   3.8988   5.0428   6.1868   7.3308   8.4748   9.6188   10.7628  11.9068  13.0508  14.1948
3.2      4.6      6        7.4      8.8      10.2     11.6     13       14.4     15.8     17.2
4        5.755    7.51     9.265    11.02    12.775   14.53    16.285   18.04    19.795   21.55
5.8518   8.1188   10.3858  12.6528  14.9198  17.1868  19.4538  21.7208  23.9878  26.2548  28.5218
7.32     10.17    13.02    15.87    18.72    21.57    24.42    27.27    30.12    32.97    35.82
8.73     12.15    15.57    18.99    22.41    25.83    29.25    32.67    36.09    39.51    42.93

```

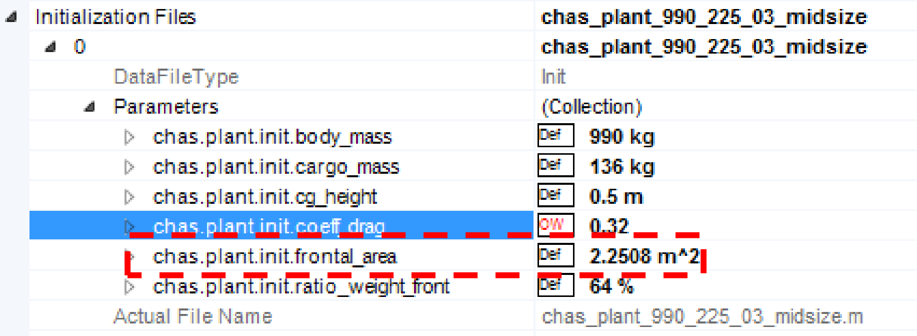
Pre & Post-processing Files
in Matlab



```matlab

%% Efficiency maps in terms of speed and power (used for plots)

% In terms of speed and torque
eng.plant.calc.eff_hot_trq.map       = eng.plant.calc.pwr_out_hot.map ./ (eng.plan
eng.plant.calc.eff_hot_trq.idx1_spd  = eng.plant.init.fuel_hot.idx1_spd;
eng.plant.calc.eff_hot_trq.idx2_trq  = eng.plant.init.fuel_hot.idx2_trq;

% In terms of speed and power
    %creating index vectors
eng.plant.calc.eff_hot_pwr.idx1_spd=unique(sort(eng.plant.init.fuel_hot.idx1_spd))
eng.plant.calc.eff_hot_pwr.idx2_pwr=0:2000:min(eng.plant.calc.pwr_max_hot.pwr_max,
eng.plant.calc.eff_hot_pwr.idx2_pwr(end)=eng.plant.calc.pwr_max_hot.pwr_max;

```

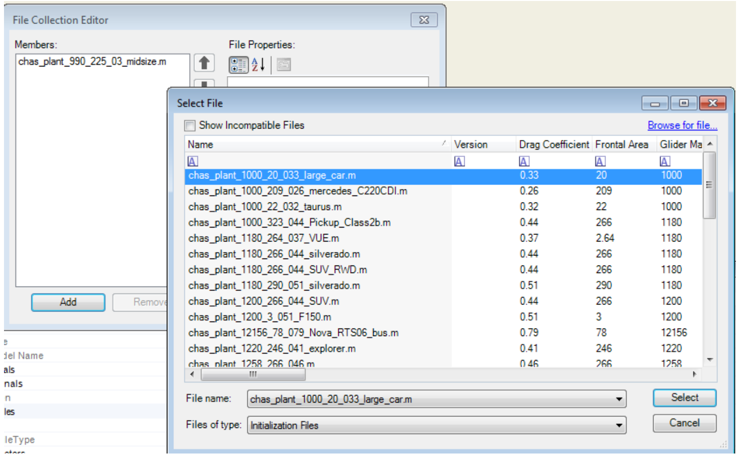
Users Can Customize Autonomie by Changing

Any Parameter



Initialization Files	chas_plant_990_225_03_midsize
0	chas_plant_990_225_03_midsize
DataFileType	Init
Parameters	(Collection)
chas.plant.init.body_mass	Def 990 kg
chas.plant.init.cargo_mass	Def 136 kg
chas.plant.init.cg_height	Def 0.5 m
chas.plant.init.coeff_drag	OW 0.32
chas.plant.init.frontal_area	Def 2.2508 m^2
chas.plant.init.ratio_weight_front	Def 64 %
Actual File Name	chas_plant_990_225_03_midsize.m

Any Initialization File



Members: chas_plant_990_225_03_midsize.m

File Properties:

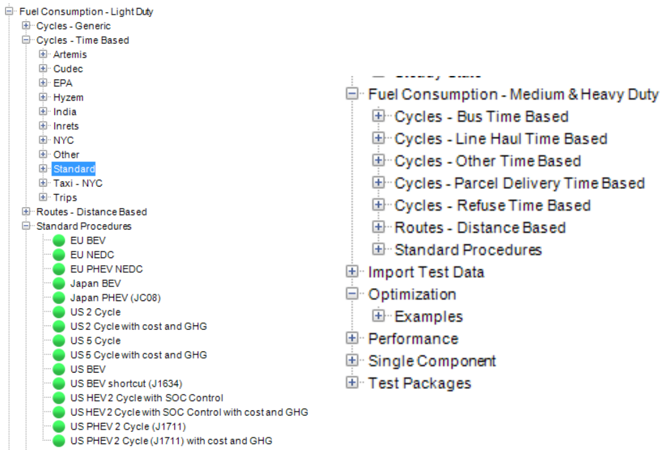
☐ Show Incompatible Files

Name	Version	Drag Coefficient	Frontal Area	Glider Ma
chas_plant_1000_20_033_large_car.m		0.33	20	1000
chas_plant_1000_209_026_mercedes_C220CDI.m		0.26	209	1000
chas_plant_1000_22_032_taurus.m		0.32	22	1000
chas_plant_1000_323_044_Pickup_Class2b.m		0.44	266	1180
chas_plant_1180_264_037_VUE.m		0.37	2.64	1180
chas_plant_1180_266_044_silverado.m		0.44	266	1180
chas_plant_1180_266_044_SUV_RWD.m		0.44	266	1180
chas_plant_1180_290_051_silverado.m		0.51	290	1180
chas_plant_1200_266_044_SUV.m		0.44	266	1200
chas_plant_1200_3_051_F150.m		0.51	3	1200
chas_plant_12156_78_079_Nova_RTS06_bus.m		0.79	78	12156
chas_plant_1220_246_041_explorer.m		0.41	246	1220
chas_plant_1258_266_046.m		0.46	266	1258

File name: chas_plant_1000_20_033_large_car.m

Files of type: Initialization Files

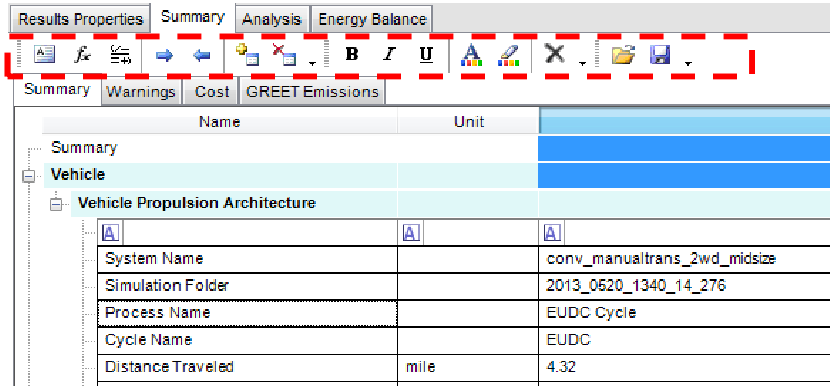
Any Use Case



- Fuel Consumption - Light Duty
  - Cycles - Generic
  - Cycles - Time Based
    - Artemis
    - Cudec
    - EPA
    - Hyzem
    - India
    - Inrets
    - NYC
    - Other
    - Standard
    - Taxi - NYC
    - Trips
  - Routes - Distance Based
  - Standard Procedures
    - EU BEV
    - EU NEDC
    - EU PHEV NEDC
    - Japan BEV
    - Japan PHEV (JC08)
    - US 2 Cycle
    - US 2 Cycle with cost and GHG
    - US 5 Cycle
    - US 5 Cycle with cost and GHG
    - US BEV
    - US BEV shortcut (J1634)
    - US HEV 2 Cycle with SOC Control
    - US HEV 2 Cycle with SOC Control with cost and GHG
    - US PHEV 2 Cycle (J1711)
    - US PHEV 2 Cycle (J1711) with cost and GHG

- Fuel Consumption - Medium & Heavy Duty
  - Cycles - Bus Time Based
  - Cycles - Line Haul Time Based
  - Cycles - Other Time Based
  - Cycles - Parcel Delivery Time Based
  - Cycles - Refuse Time Based
  - Routes - Distance Based
  - Standard Procedures
- Import Test Data
- Optimization
  - Examples
- Performance
- Single Component
- Test Packages

Any Post-processing

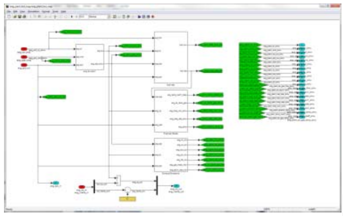


Name	Unit	
Summary		
Vehicle		
Vehicle Propulsion Architecture		
System Name		conv_manualtrans_2wd_midsize
Simulation Folder		2013_0520_1340_14_276
Process Name		EUDC Cycle
Cycle Name		EUDC
Distance Traveled	mile	4.32

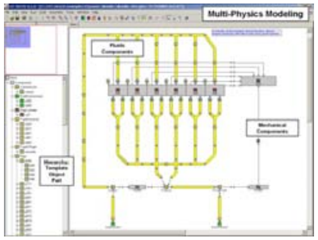
Developers Can Customize Autonomie by Adding / Modifying

Models & Control

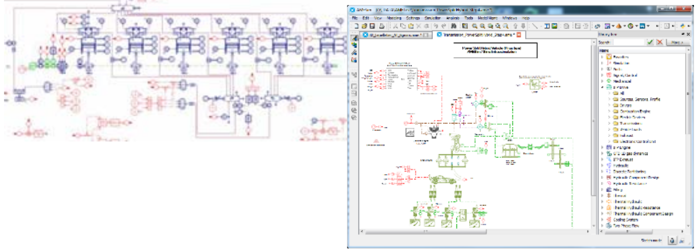
Simulink



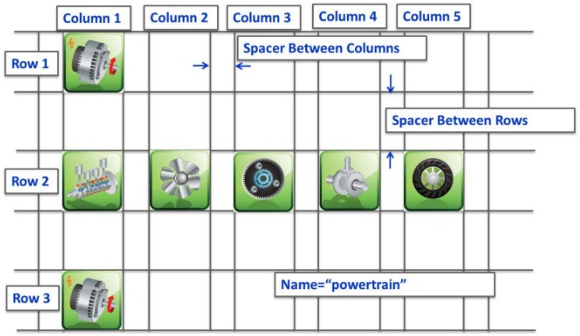
GTPower



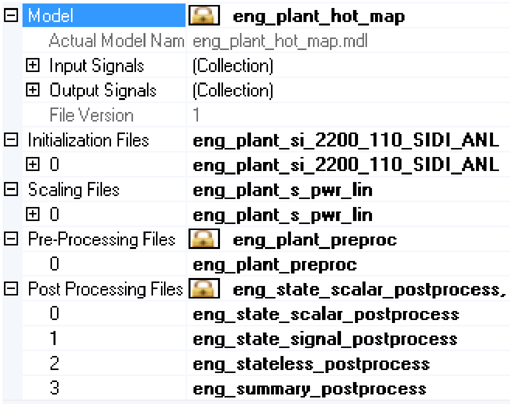
LMS AMESim…



Vehicle, Powertrain and Component Configurations

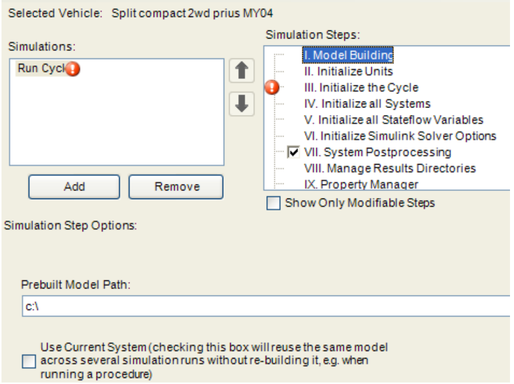


Pre & Post-processing



⊟ Model	eng_plant_hot_map
Actual Model Nam	eng_plant_hot_map.mdl
⊞ Input Signals	(Collection)
⊞ Output Signals	(Collection)
File Version	1
⊟ Initialization Files	eng_plant_si_2200_110_SIDI_ANL
⊞ 0	eng_plant_si_2200_110_SIDI_ANL
⊟ Scaling Files	eng_plant_s_pwr_lin
⊞ 0	eng_plant_s_pwr_lin
⊟ Pre-Processing Files	eng_plant_preproc
0	eng_plant_preproc
⊟ Post Processing Files	eng_state_scalar_postprocess,
0	eng_state_scalar_postprocess
1	eng_state_signal_postprocess
2	eng_stateless_postprocess
3	eng_summary_postprocess

Use Cases



Selected Vehicle: Split compact 2wd prius MY04

Simulations:

Run Cycl

Simulation Steps:

- I. Model Building
- II. Initialize Units
- III. Initialize the Cycle
- IV. Initialize all Systems
- V. Initialize all Stateflow Variables
- VI. Initialize Simulink Solver Options
- ☑ VII. System Postprocessing
- VIII. Manage Results Directories
- IX. Property Manager

☐ Show Only Modifiable Steps

Simulation Step Options:

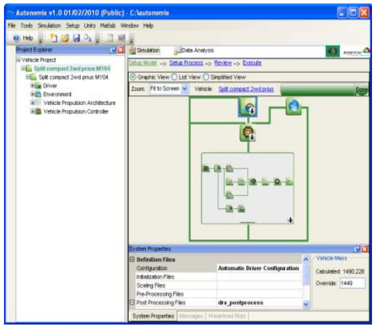
Prebuilt Model Path:

c:\

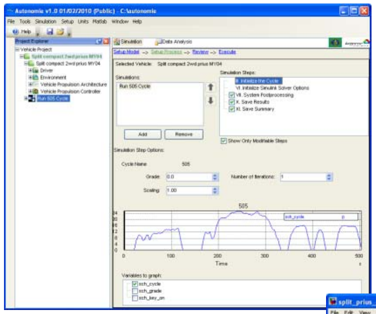
☐ Use Current System (checking this box will reuse the same model across several simulation runs without re-building it, e.g. when running a procedure)

Simulating a Vehicle Using Autonomie Is Quick!

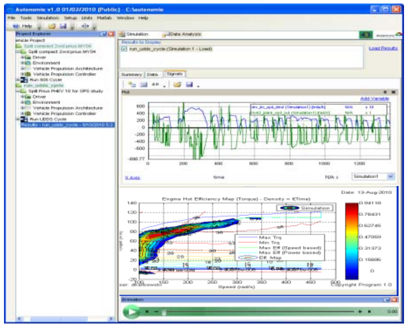
- **Vehicle definition**: selection of configuration, plant models, controllers.
- Existing vehicle/system **templates**, or user's own models



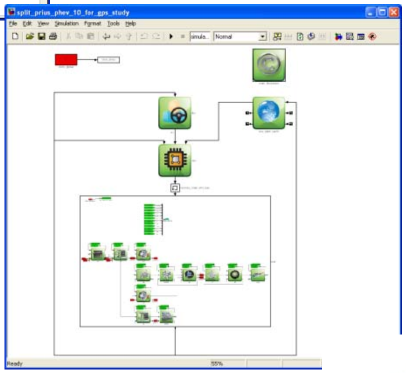
Simulation process definition: drive cycles, parametric study, etc.



Simulation results **analysis** in the GUI



- **Automated building** in **Simulink** using individual models
- Model **initialization**
- **Simulation**
- **Post-processing**, data saving
- Loading results in the GUI



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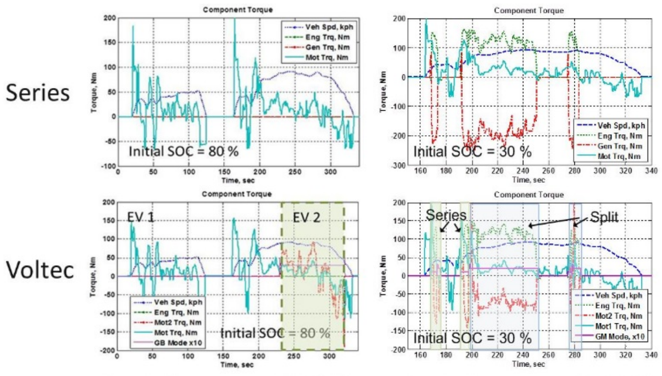
AUTONOMIE

PSAT & Autonomie Have Been Used to Evaluate Technologies' Energy Benefits for More Than 20 Years

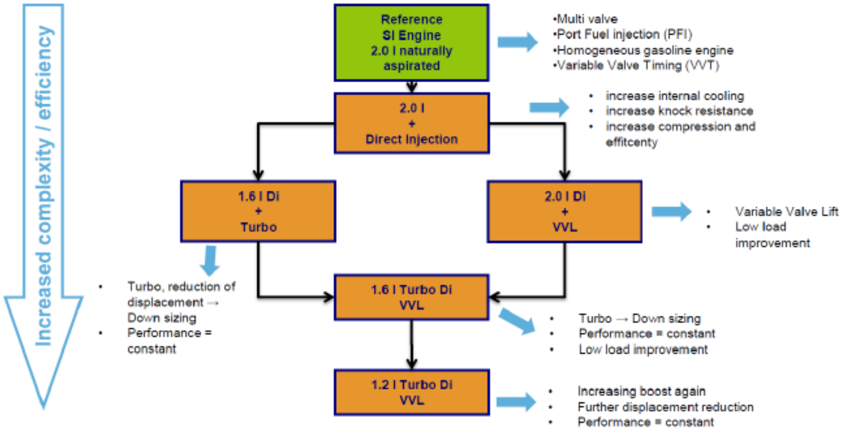
Impact of Powertrain Configurations



Comparison of component torque – Initial SOC = 80%, (top = series, bottom = GM Volt)

Comparison of component torque – Initial SOC = 30%, (top = series, bottom = GM Volt)

Impact of Component Technologies



Increased complexity / efficiency

Reference SI Engine 2.0 l naturally aspirated

- Multi valve
- Port Fuel injection (PFI)
- Homogeneous gasoline engine
- Variable Valve Timing (VVT)

2.0 l + Direct Injection

- increase internal cooling
- increase knock resistance
- increase compression and effitcenty

1.6 l Di + Turbo

- Turbo, reduction of displacement → Down sizing
- Performance = constant

2.0 l Di + VVL

- Variable Valve Lift
- Low load improvement

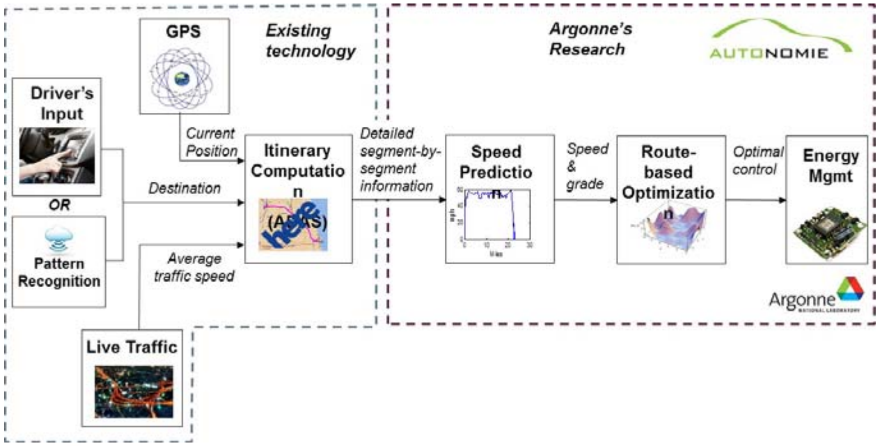
1.6 l Turbo Di VVL

- Turbo → Down sizing
- Performance = constant
- Low load improvement

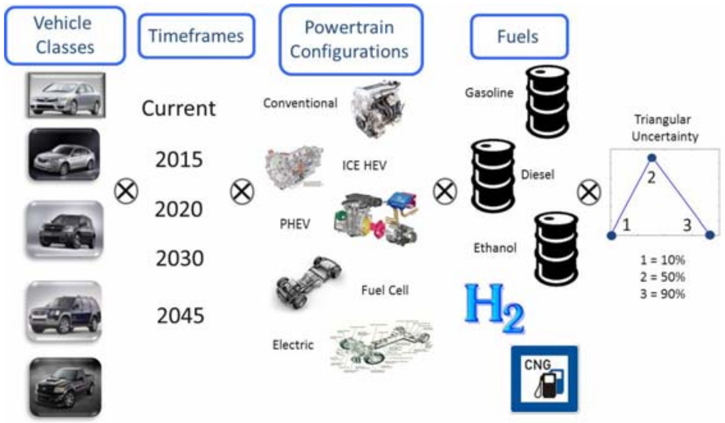
1.2 l Turbo Di VVL

- Increasing boost again
- Further displacement reduction
- Performance = constant

Impact of Advanced Control / Optimization



Large Scale Simulations



Autonomie Has Been Widely Used to Estimate the Energy Impact of Advanced Technologies

- Component technical targets (e.g., battery energy for a BEV100…)
- Powertrain technologies (e.g., E-REV vs power split…)
- Component technologies (e.g., 5 speed automatic transmission vs 6 speed automatic transmission…)
- Advanced vehicle level control (e.g., route based control…)
- Control calibration (e.g., shifting parameter selection…)

The studies have included

- Multiple vehicle classes (e.g., compact, midsize… up to HD)
- Multiple timeframes (current up to 2045)
- Uncertainty related to component technologies (e.g., low vs. high uncertainty)
- Driving cycles (standard, real world…)

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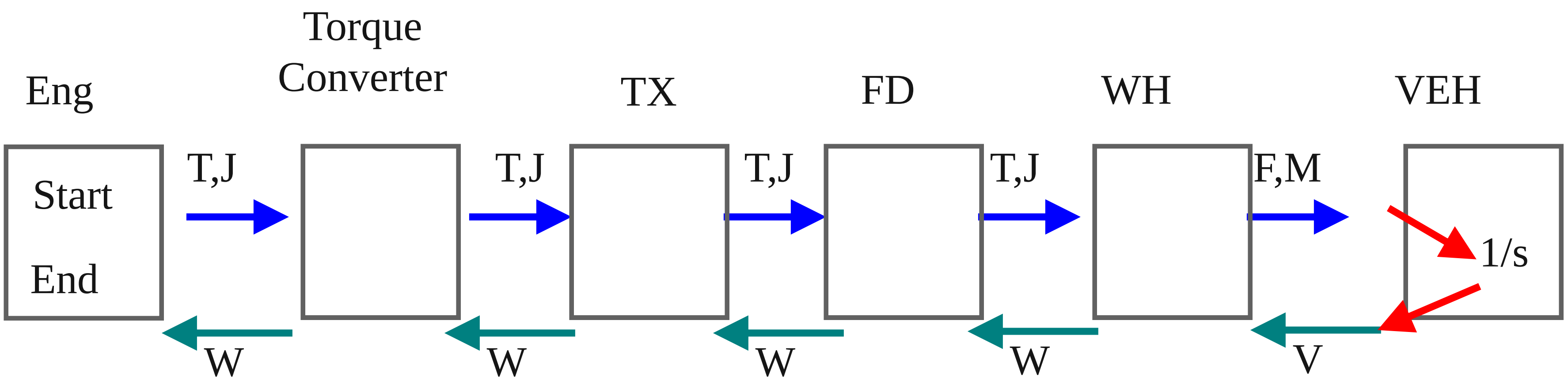
Outline

- Autonomie Overview
- Model Development and Validation
- Process to Estimate Technologies Effectiveness with Full Vehicle Simulation
- Vehicle Powertrain Sizing Algorithms and Validation
- Vehicle Simulation Results Quality Check Process

Autonomie Plant Model Fidelity

Vehicle energy consumption application developed with low frequency component models simulating longitudinal acceleration



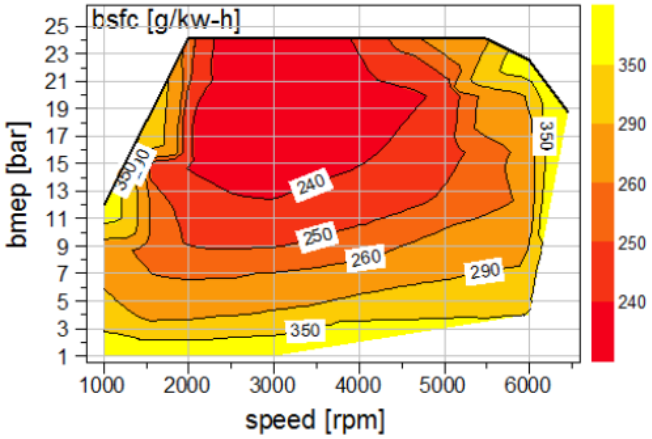
Conventional vehicle example

Carrying the inertia to the vehicle limits the number of required integrations (1/s) as well as avoid derivative equations

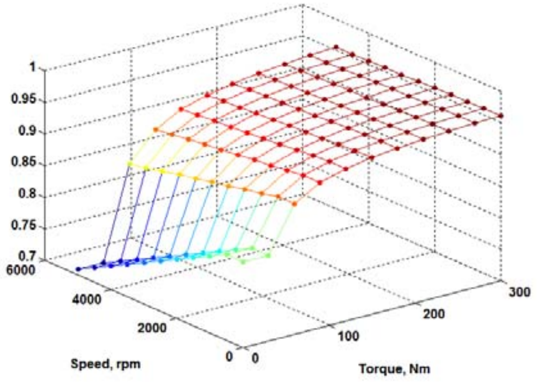
Autonomie Plant Model Fidelity (Cont'd)

Component performance are modeled using performance maps for components

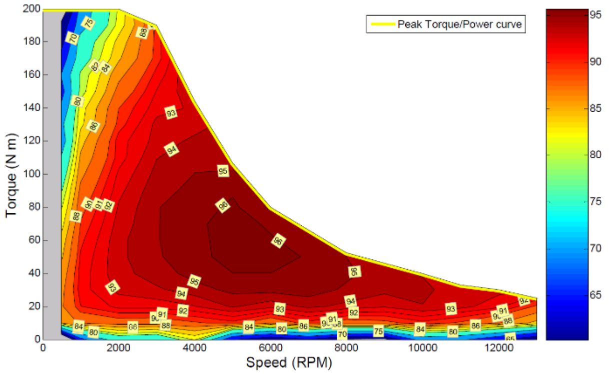
Engine



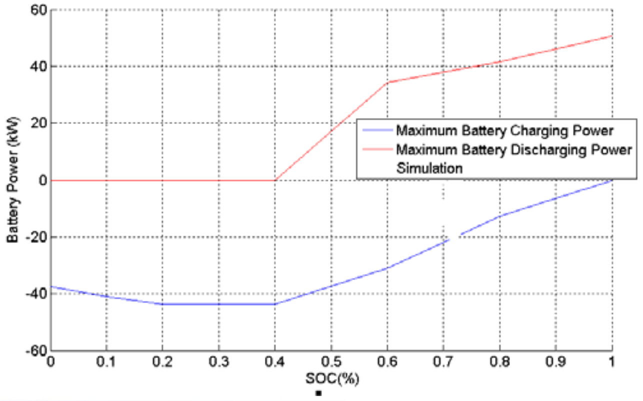
Transmission (per gear)



Electric Machine



Energy Storage

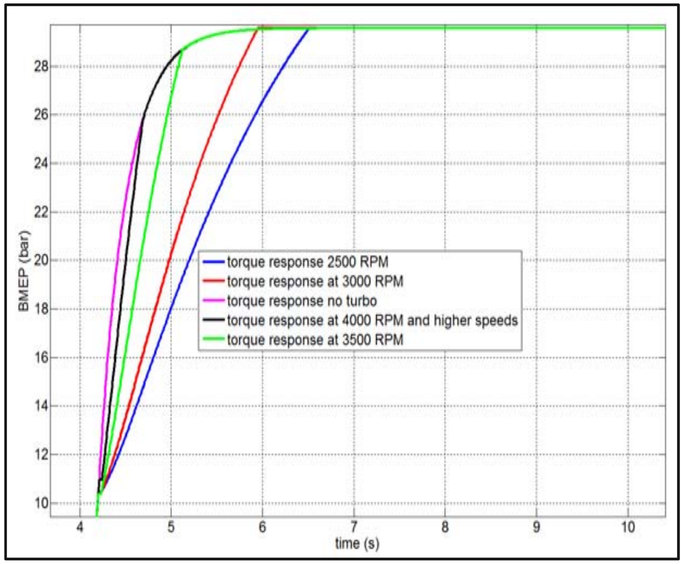


Data shown as an example

Autonomie Plant Model Fidelity (Cont’d)

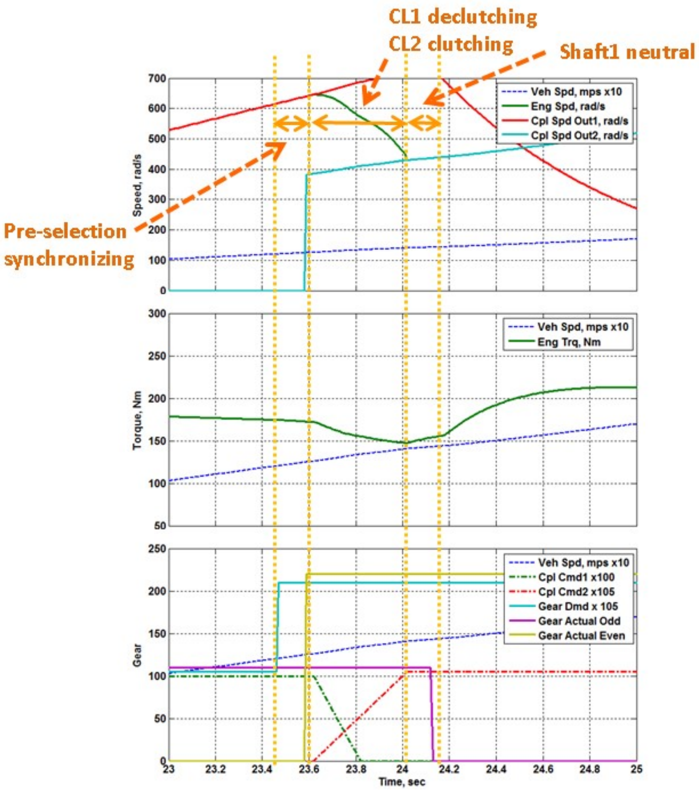
Transients are considered within each component (i.e., engine time response for turbochargers…) and for mode changes (i.e., engine ON/OFF, shifting events…)

Turbo Engine Time Response



=> Multiple engine models used depending on fuel, technology…

DCT Shifting Event

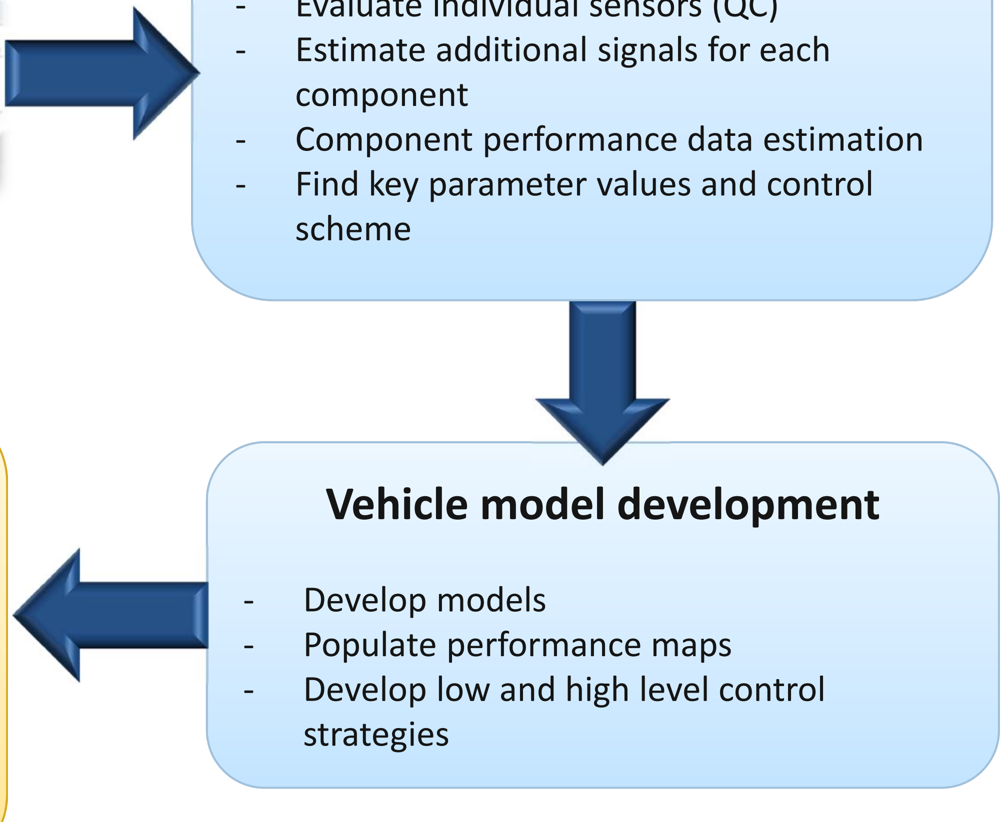

CL1 declutching
CL2 clutching

Shaft1 neutral

Pre-selection synchronizing

Extensive Model Validation Performed over the Past 15 Years Using ANL's APRF(1)

Vehicle Instrumentation, Test Selection



Test data analysis using 'Import Test Data' function in Autonomie

- Evaluate individual sensors (QC)
- Estimate additional signals for each component
- Component performance data estimation
- Find key parameter values and control scheme

Vehicle model development

- Develop models
- Populate performance maps
- Develop low and high level control strategies

Calibration and validation of the vehicle model with test data

- Dynamic performance validation
- Energy consumption validation

To quickly and accurately predict or evaluate the energy consumption and dynamic performance of the vehicle under various driving conditions.

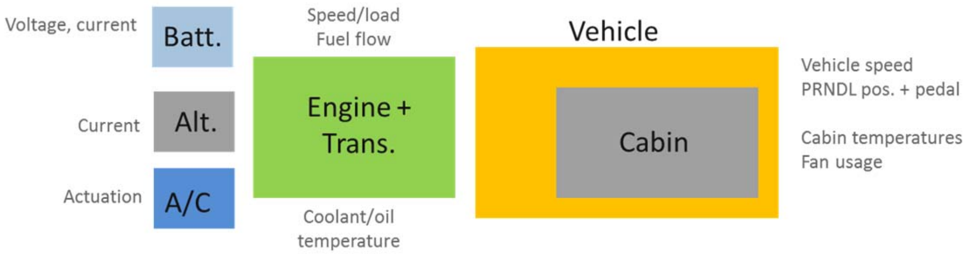
APRF = Advanced Powertrain Research Facility

List of Vehicles Recently Tested at Argonne's APRF

- 2015 Chevrolet Spark EV
- 2015 Kia Soul EV
- 2015 Honda Accord Hybrid
- 2015 BMW i3 BEV
- 2015 BMW i3 Rex
- 2014 Smart Electric
- 2014 BMW i3 Rex
- 2014 Mazda 3 iEloop
- 2014 Chevrolet Cruze Diesel
- 2013 Ford Focus BEV
- 2013 Dodge Ram 1500 HFE
- 2013 Ford Fusion Energi
- 2013 Nissan Leaf
- 2014 Honda Accord PHEV
- 2012 Mitsubishi iMiev
- 2013 Ford Cmax Energi
- 2013 Ford Cmax Hybrid
- 2013 VW Jetta Hybrid
- 2013 Toyota Prius PHV
- 2013 Honda Civic Hybrid
- 2013 VW Jetta TDI
- 2013 Chevrolet Volt
- 2013 Chevrolet Malibu Eco
- 2012 Honda Civic CNG
- 2012 Ford Focus Electric
- 2013 Nissan Altima
- 2013 Hyundai Sonata
- 2013 Chrysler 300
- 2012 Honda Civic
- 2012 Ford Fusion V6
- 2012 Ford Focus
- 2012 Ford F150 Ecoboost
- 2012 Fiat 500
- 2012 Peugeot 3008 Hybrid
- 2012 Nissan Leaf
- 2010 Ford Fusion Thermal
- 2011 Hyundai Sonata Hybrid
- 2011 VW Jetta TSI
- 2010 VW Golf TDI (start-stop)
- 2010 Smart (start-stop)
- 2010 Mazda 3 (start-stop)
- 2010 Honda CRZ
- 2010 Mercedes Benz S400h
- 2010 Toyota Prius
- 2010 Ford Fusion
- 2010 Honda Insight
- 2010 Mini E
- 2009 VW Jetta TDI
- 2008 Chevrolet Tahoe Hybrid
- 2007 Toyota Camry Hybrid
- 2006 Honda Civic Hybrid
- 2006 Opel Astra Diesel
- 2007 Toyota Camry Hybrid
- 2006 Honda Hybrid

Sample data available under http://www.anl.gov/energy-systems/group/downloadable-dynamometer-database

Many of these Vehicles Have Been Heavily Instrumented to Understand Vehicle Level Controls

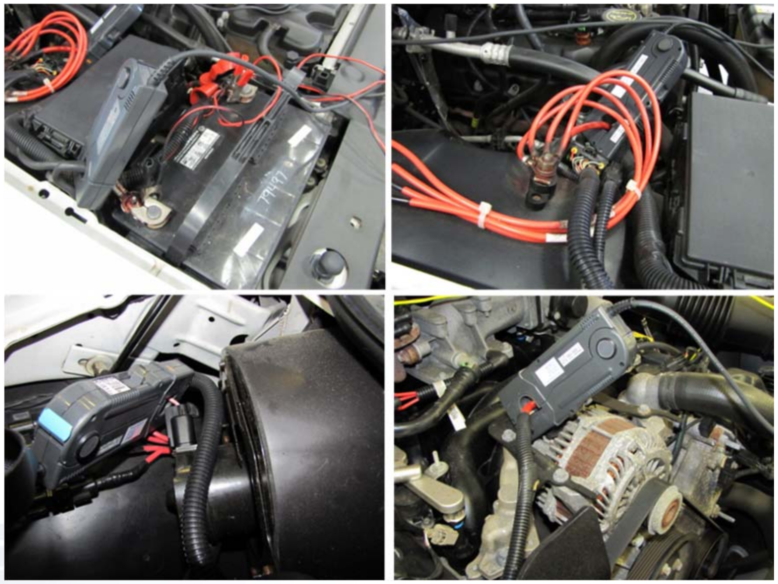


Argonne Instrumentation/Data Collection Capabilities Include:

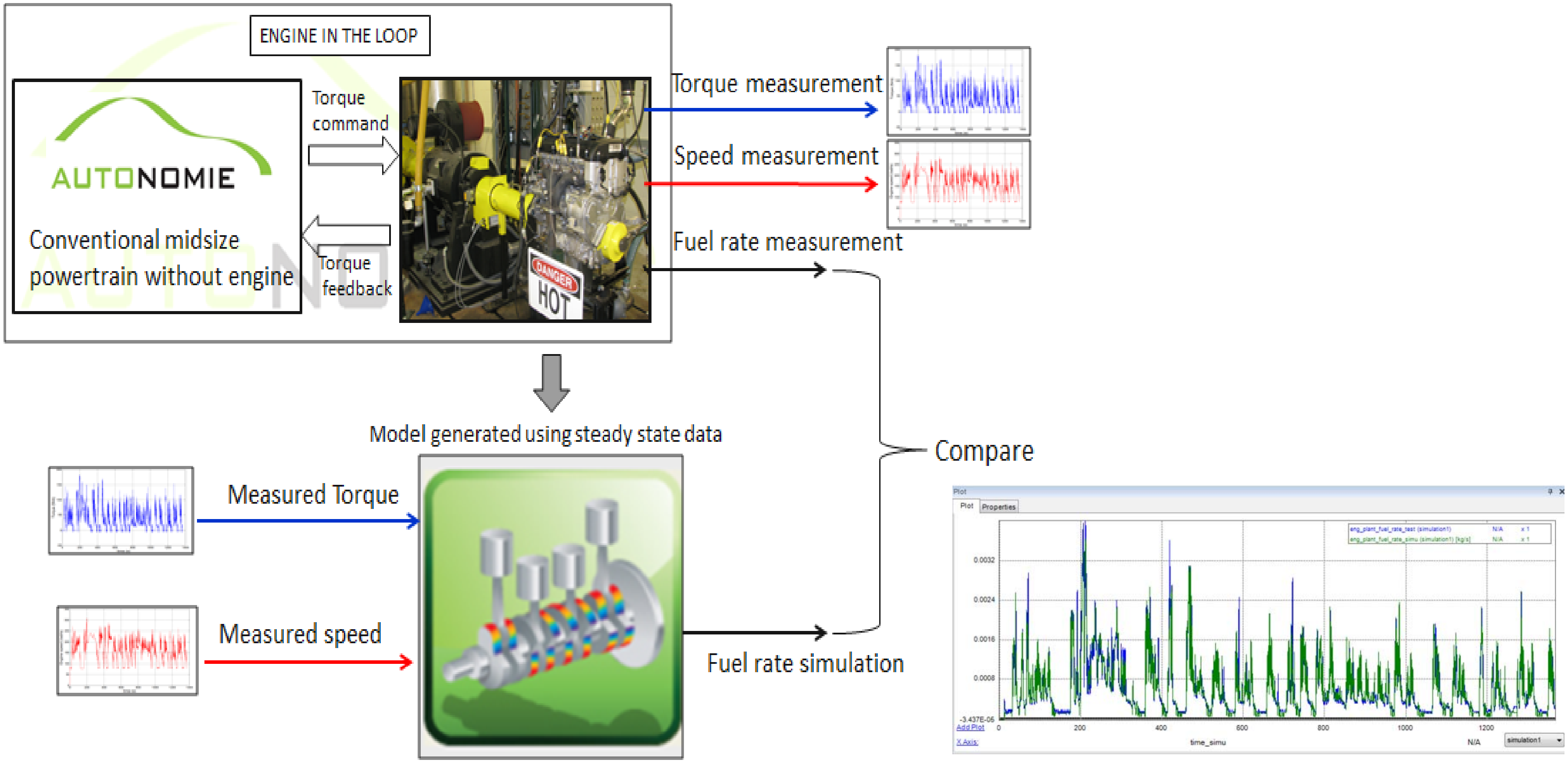
- Time synchronized data collection across a range of sensor types
  - Multiple CAN busses (on-vehicle or add-on components)
  - GPS
  - Temperatures
  - Isolated high voltage measurements
  - Current and voltage (i.e. accessories, other loads)
  - Component torques
  - Other in-vehicle communications links

Detailed evaluation of electrical nodes:

- 12V battery voltage and current
- In-vehicle accessory current
- Alternator current
- Cabin blower fan current



Individual Models Independently Validated



ENGINE IN THE LOOP

AUTONOMIE

Conventional midsize powertrain without engine

Torque command

Torque feedback

Torque measurement

Speed measurement

Fuel rate measurement

Model generated using steady state data

Measured Torque

Measured speed

Fuel rate simulation

Compare

Shifting Algorithm Validation Leveraging Multiple APRF Data Sets

Year	Model	Type	TM	Engine	EM
2006	Honda CIVIC	HEV	**CVT**	L4 1.6L 82kW	15 kW
2010	Honda Insight	HEV	**CVT**	L4 1.3L 73kW	10 kW
2013	Nissan Altima	Conv	**CVT**	L4 2.5L 136kW	-
2011	Hyundai Sonata	HEV	**AT 6spd**	I4 2.4L 154kW	30 kW
2012	Fiat 500	Conv	**AT 6spd**	L4 1.4L 83kW	-
2010	Mercedes S400	HEV (micro)	**AT 7spd**	L6 3.5L 205kW	15 kW
2012	Ford Fusion V6	Conv	**AT 6spd**	V6 3.0L 179kW	-
2013	Chrysler 300	Conv	**AT 8spd**	V6 3.6L 224kW	-
2013	Hyundai Sonata	Conv	**AT 6spd**	I4 2.4L 154kW	-
2012	Ford F-150	Conv	**AT 6spd**	V6 3.5L 272kW	-
2012	Ford Focus	Conv	**DCT 6spd**	L4 2.0L 119kW	-
2013	VW Jetta 2.0 TDI	Conv	**DCT 6spd**	Diesel 2.0L 104kW	-
2010	Mazda 3	Conv (istop)	**MT 5spd**	L4 2.0L 110kW	-
2010	Mercedes Smart	Conv (istop)	**AMT 5spd**	L3 1.0L 44kW	-
2012	Peugeot 3008 Hybrid 4	HEV	**AMT 6spd**	Diesel 2.0L 120kW	27 kW

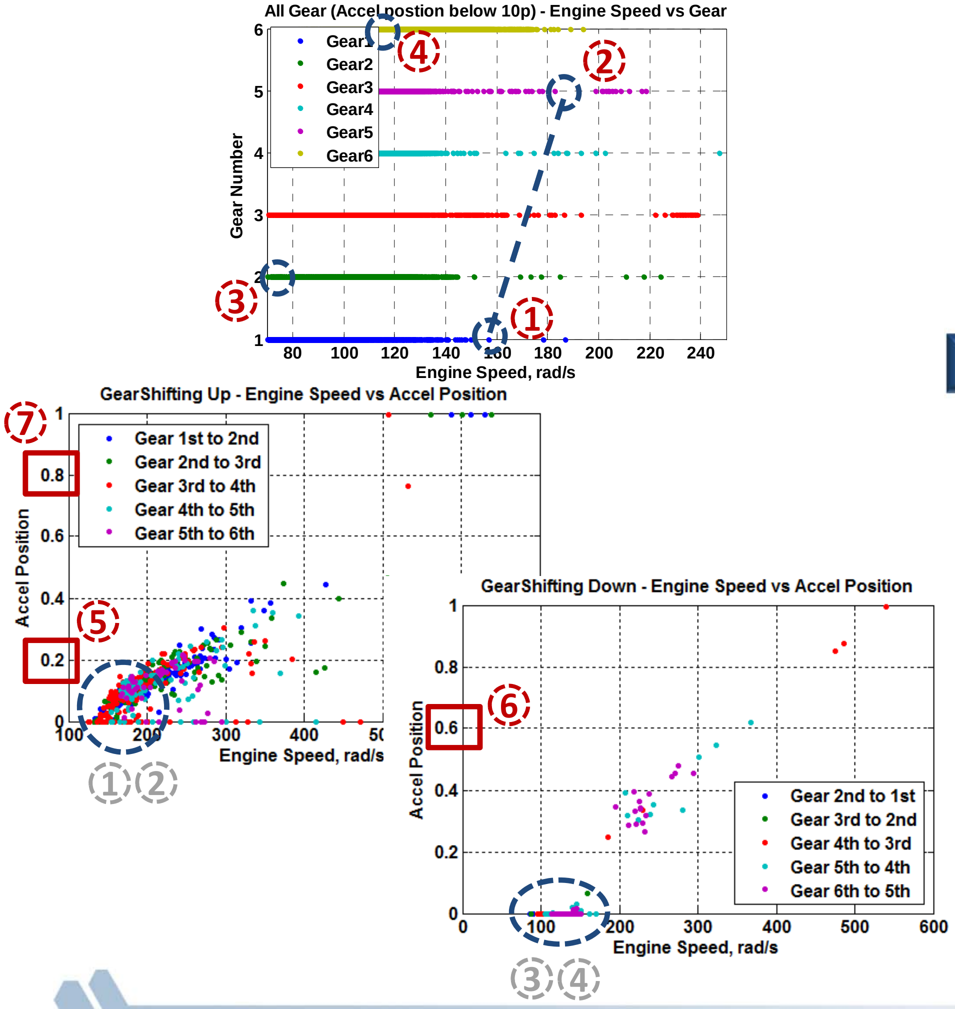
Integrated more than a dozen set of vehicle test data into Autonomie

🟨 analyzed for the shifting map 🟥 validated with test data

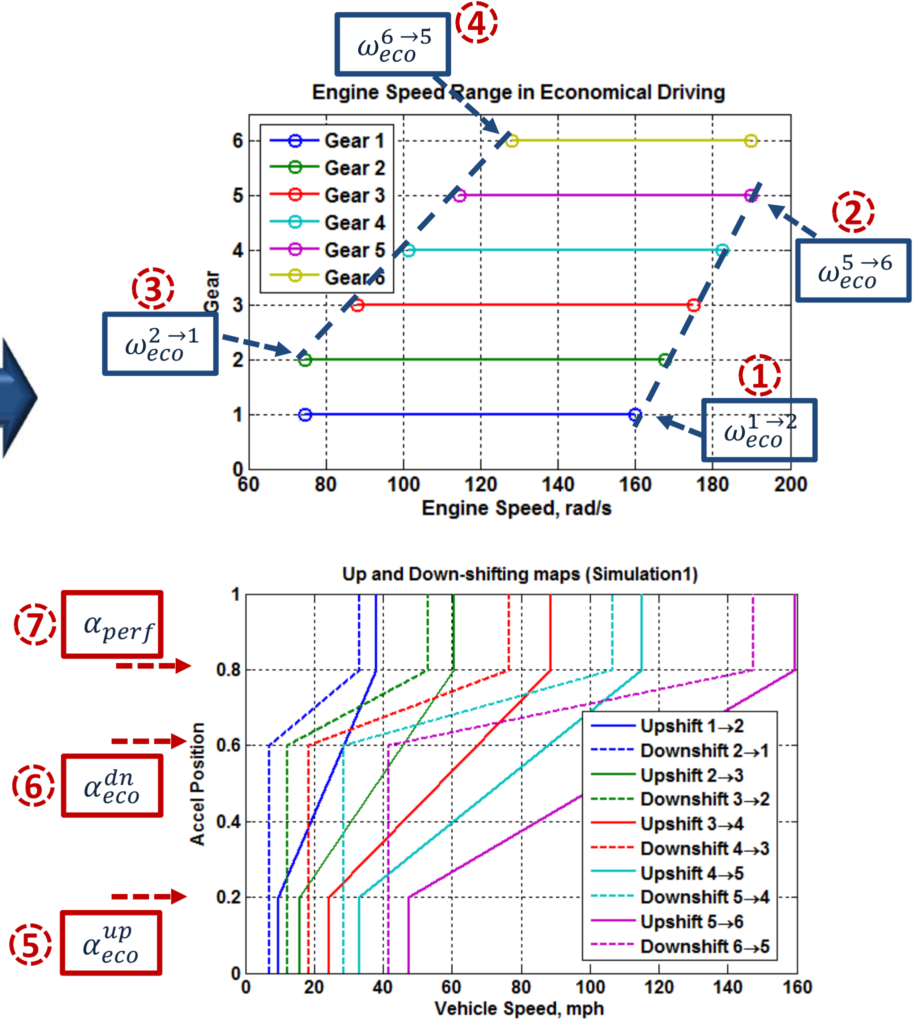
Shifting Algorithm Calibration Process

- Example : 2013 Hyundai Sonata Conv. I4 6ATX

APRF Test Data Analysis



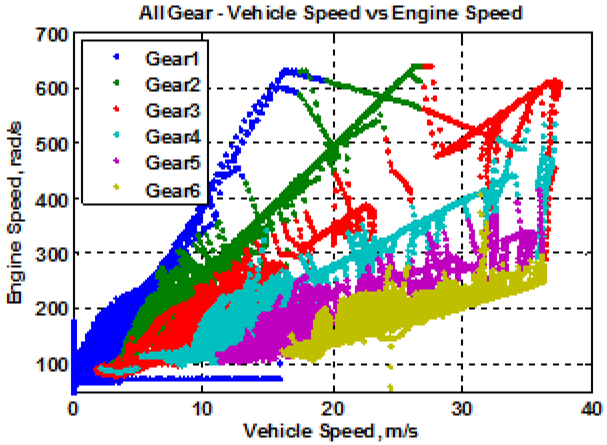
Shifting Algorithm



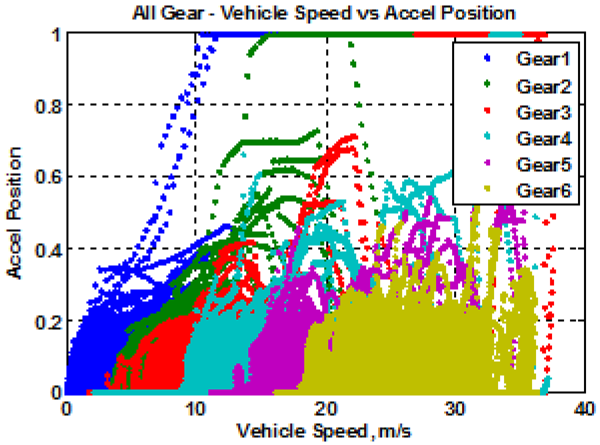
Automatic Transmission Shifting Logic

Automatic Transmission Example

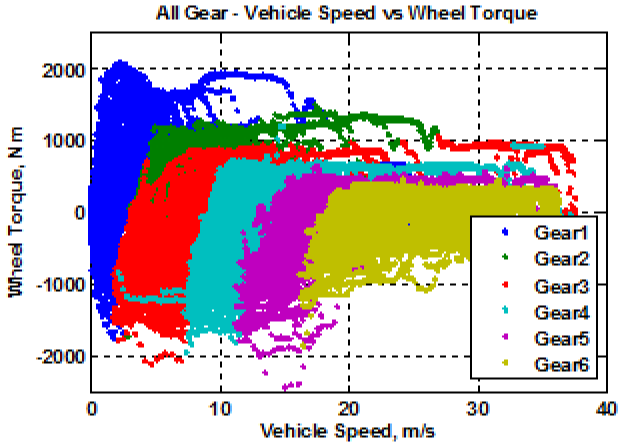
- 2013 Hyundai Sonata Conv. 6ATX Example



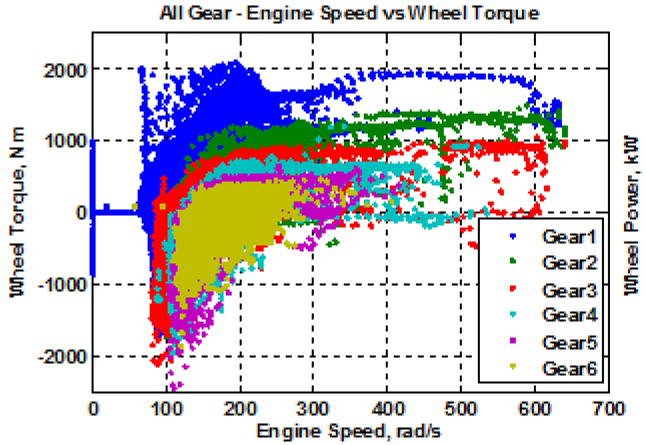
All Gear - Vehicle Speed vs Engine Speed



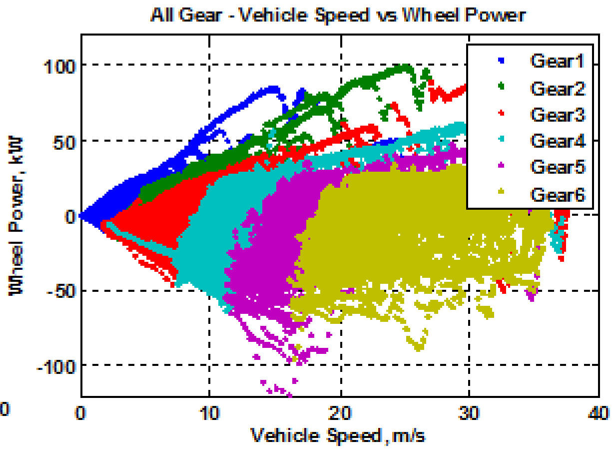
All Gear - Vehicle Speed vs Accel Position



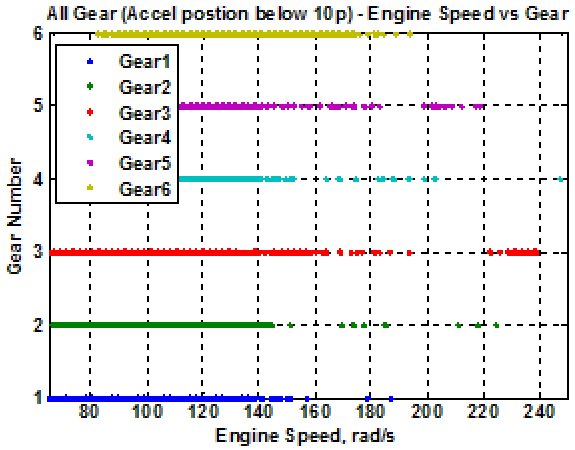
All Gear - Vehicle Speed vs Wheel Torque



All Gear - Engine Speed vs Wheel Torque



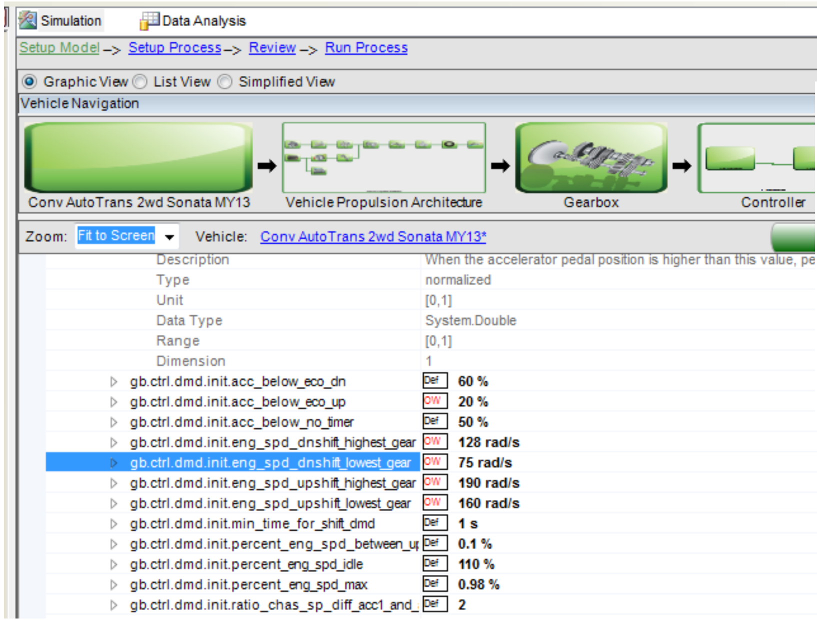
All Gear - Vehicle Speed vs Wheel Power



All Gear (Accel postion below 10p) - Engine Speed vs Gear

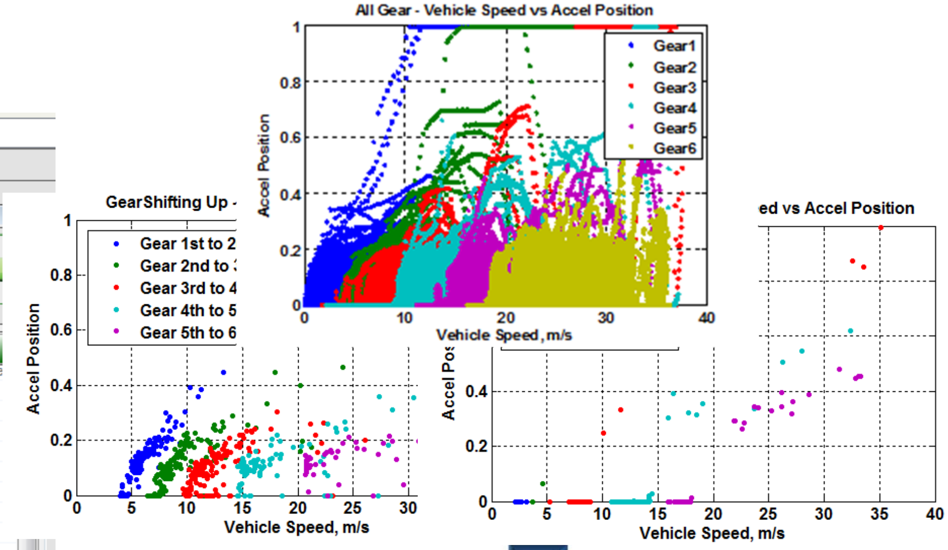
Shifting Algorithm Calibration Process

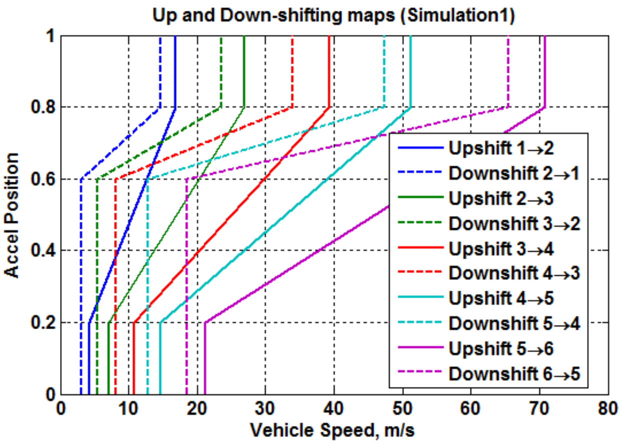
- Example : 2013 Hyundai Sonata Conv. I4 6ATX



Description	When the accelerator pedal position is higher than this value, pe
Type	normalized
Unit	[0,1]
Data Type	System.Double
Range	[0,1]
Dimension	1

gb.ctrl.dmd.init.acc_below_eco_dn	Def	60 %
gb.ctrl.dmd.init.acc_below_eco_up	OW	20 %
gb.ctrl.dmd.init.acc_below_no_timer	Def	50 %
gb.ctrl.dmd.init.eng_spd_dnshift_highest_gear	OW	128 rad/s
gb.ctrl.dmd.init.eng_spd_dnshift_lowest_gear	OW	75 rad/s
gb.ctrl.dmd.init.eng_spd_upshift_highest_gear	OW	190 rad/s
gb.ctrl.dmd.init.eng_spd_upshift_lowest_gear	OW	160 rad/s
gb.ctrl.dmd.init.min_time_for_shift_dmd	Def	1 s
gb.ctrl.dmd.init.percent_eng_spd_between_u	Def	0.1 %
gb.ctrl.dmd.init.percent_eng_spd_idle	Def	110 %
gb.ctrl.dmd.init.percent_eng_spd_max	Def	0.98 %
gb.ctrl.dmd.init.ratio_chas_sp_diff_acc1_and_	Def	2



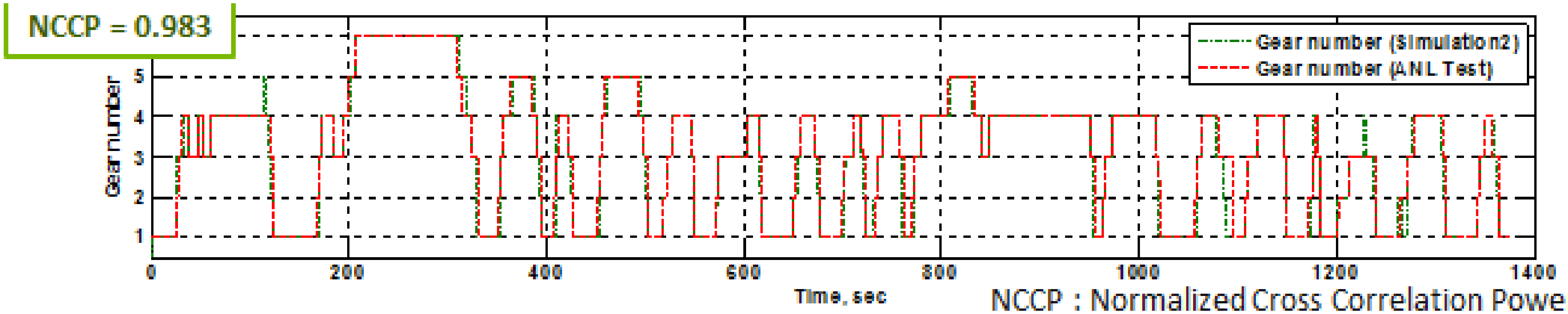


- gb.ctrl.dmd.init.eng_spd_upshift_highest_gear ②
- gb.ctrl.dmd.init.eng_spd_upshift_lowest_gear ①
- gb.ctrl.dmd.init.eng_spd_dnshift_highest_gear ④
- gb.ctrl.dmd.init.eng_spd_dnshift_lowest_gear ③

- gb.ctrl.dmd.init.acc_above_perfo ⑦
- gb.ctrl.dmd.init.acc_below_eco_dn ⑥
- gb.ctrl.dmd.init.acc_below_eco_up ⑤

Automatic Transmission Shifting Validation

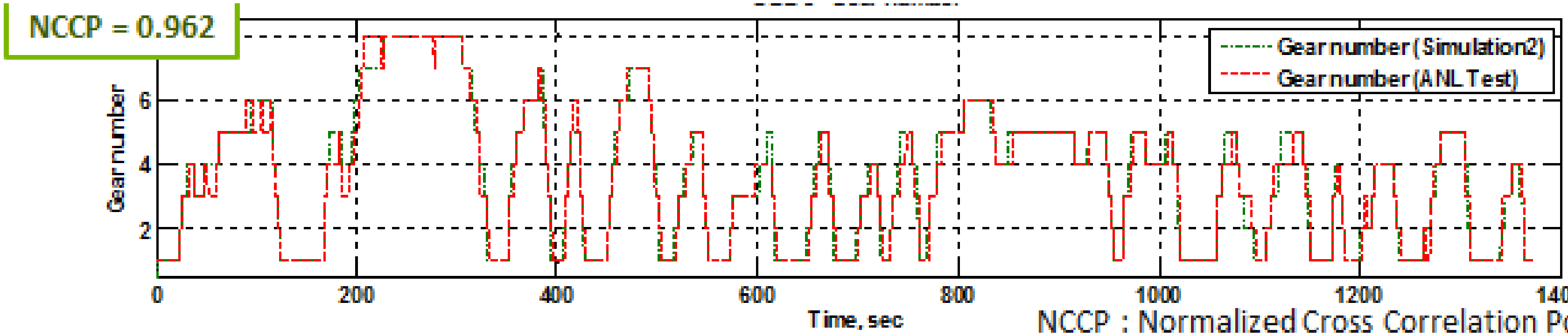
2013 Hyundai Sonata Conv. 6ATX – UDDS Driving Cycle



NCCP = 0.983

NCCP : Normalized Cross Correlation Power

2012 Chrysler 300 V6 8ATX – UDDS Driving Cycle



NCCP = 0.962

NCCP : Normalized Cross Correlation Power

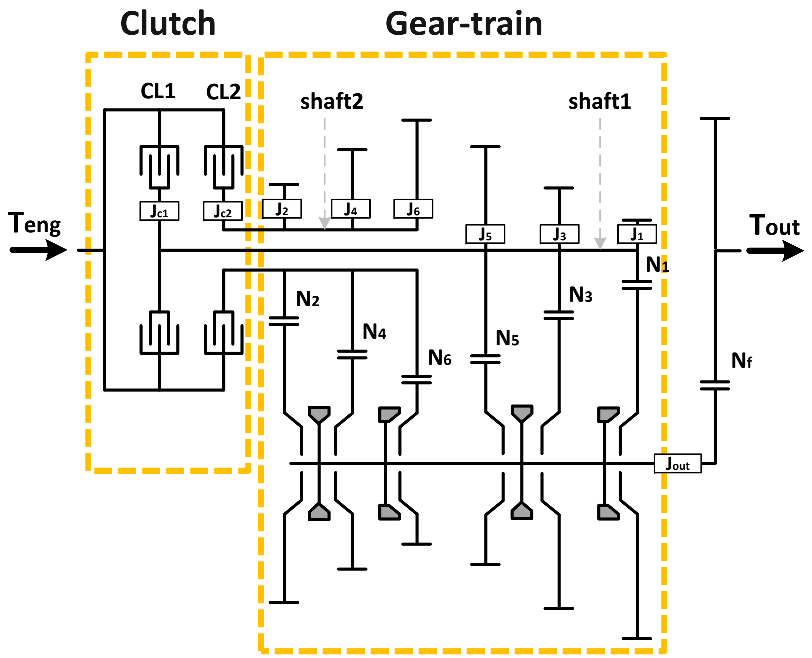
Normalized Cross Correlation Power (NCCP) – See SAE 2011-01-0881

Vehicle test data from ANL's APRF

Detailed Plant Models and Controls Developed for Advanced Transmissions

Example: DCT Plant Model Development

- System operating conditions



	N1	N2	S1	N2	N1	S2	S1	S2
CL1 – X	Standby		Not used		Not used		Shifting	
CL2 – X								
CL1 – O	Not used		Odd gear		Not used		Pre-selection	
CL2 – X								
CL1 – X	Not used		Not used		Even gear		Pre-selection	
CL2 – O								

O – clutch locked

X – clutch open

N – neutral

S – synchronized

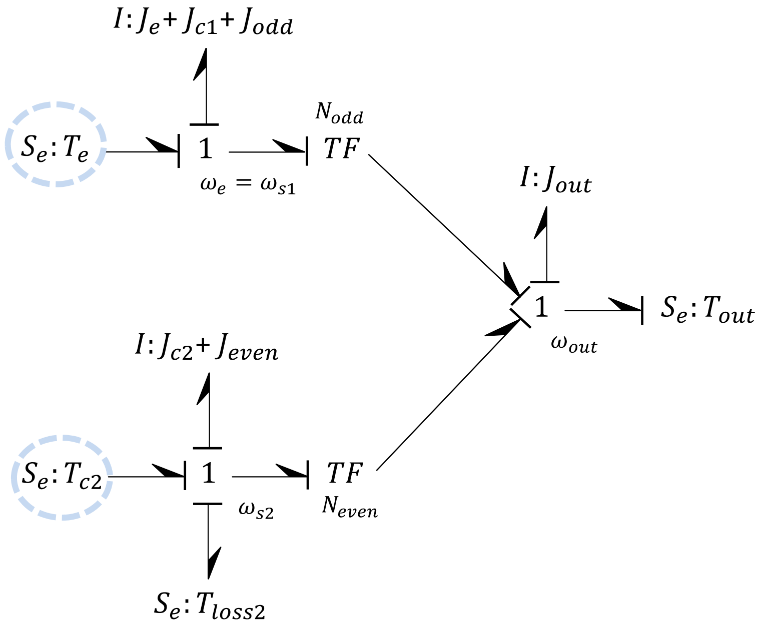
Example of gear shifting : 1st → 2nd

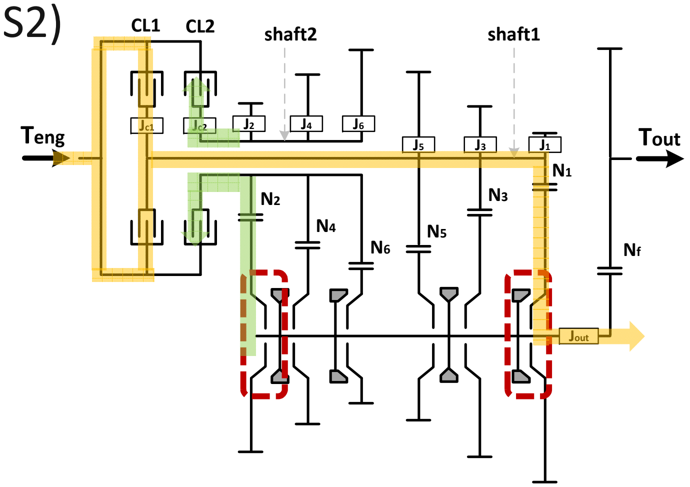
- Odd gear → Pre-selection → Shifting → Even gear…

Detailed Plant Models and Controls Developed for Advanced Transmissions

Example: DCT Plant Model Development

- For pre-selection mode (CL1-locked, CL2-open, S1, S2)





$$\omega_e = \omega_{s1} = N_{odd} \cdot \omega_{out}$$

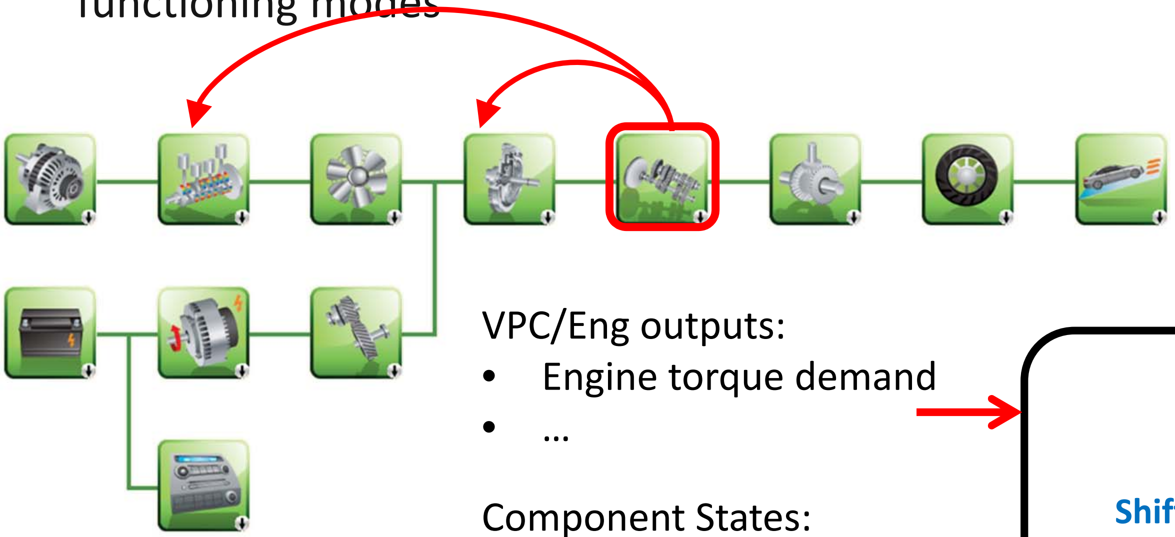
$$\omega_{s2} = N_{even} \cdot \omega_{out}$$

$$\begin{aligned} T_{out} = {} & N_{odd} \cdot \{T_e - (J_e + J_{c1} + J_{odd}) \cdot \dot{\omega}_e\} \\ & + N_{even} \cdot \{T_{c2} - T_{loss2} - (J_{c2} + J_{even}) \cdot \dot{\omega}_{s2}\} - J_{out} \cdot \dot{\omega}_{out} \end{aligned}$$

Detailed Plant Models and Controls Developed for Advanced Transmissions

Example: DCT Control Model Development

- An algorithm coordinates components during shifting events by defining functioning modes



VPC/Eng outputs:

- Engine torque demand
- …

Component States:

- i/o speeds
- i/o torques
- …

Gearbox control info:

- Gear demand
- …

Shifting Algorithm Transient Logic

Engine Mode

Clutch1 Mode

Clutch2 Mode

Gear1 demand

Gear2 demand

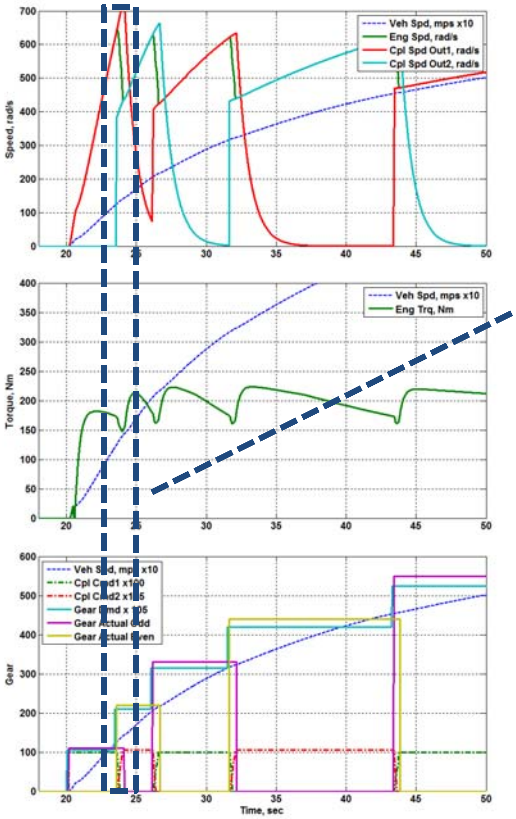
…

Low Level Controls Compared with Test Data

DCT Shifting Events Example

- Acceleration - U.S. performance process : 1st → 2nd

Par HEV Dual Clutch Trans

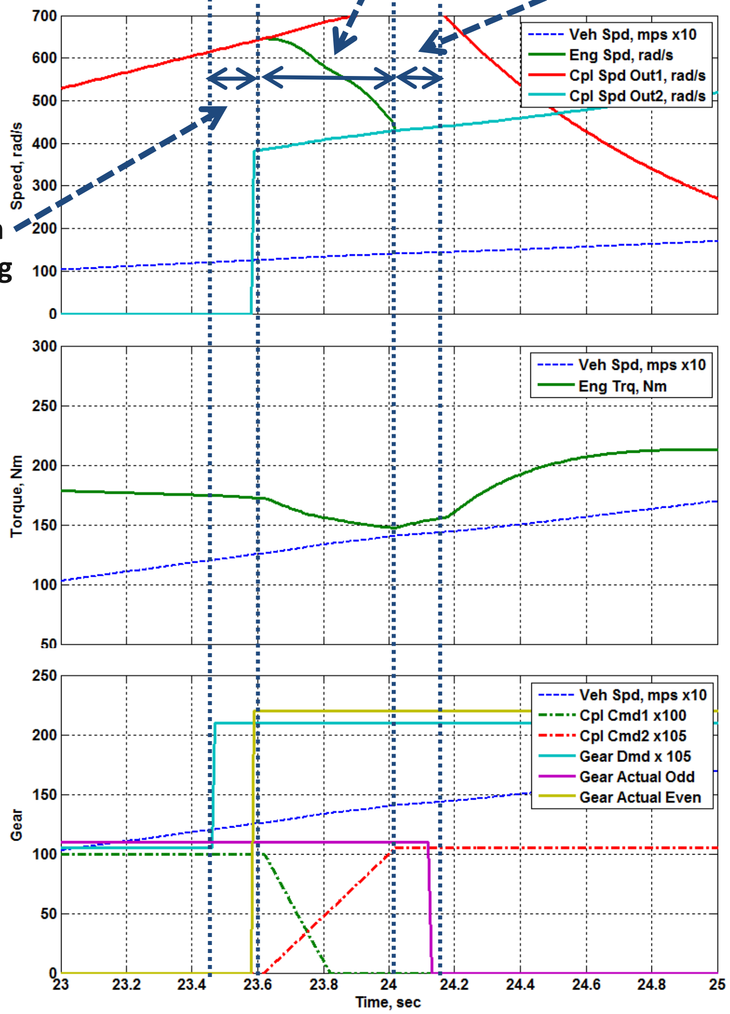


CL1 declutching

CL2 clutching

Shaft1 neutral

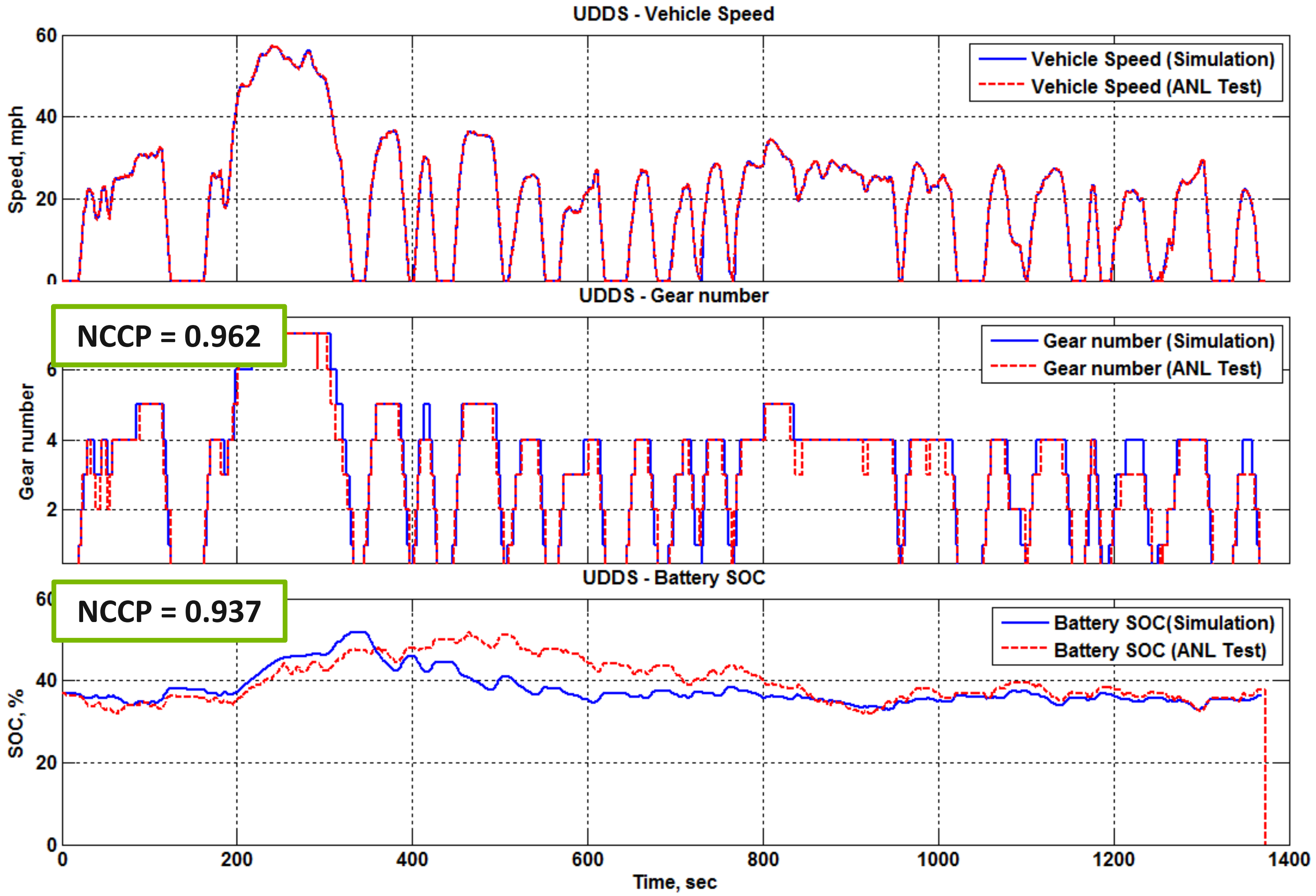
Pre-selection synchronizing



2013 VW Jetta HEV 7DCT Example

- UDDS – vehicle speed, SOC and gear number

Unresolved differences due to the fact that the vehicle level energy management was only correlated, not validated



NCCP = 0.962

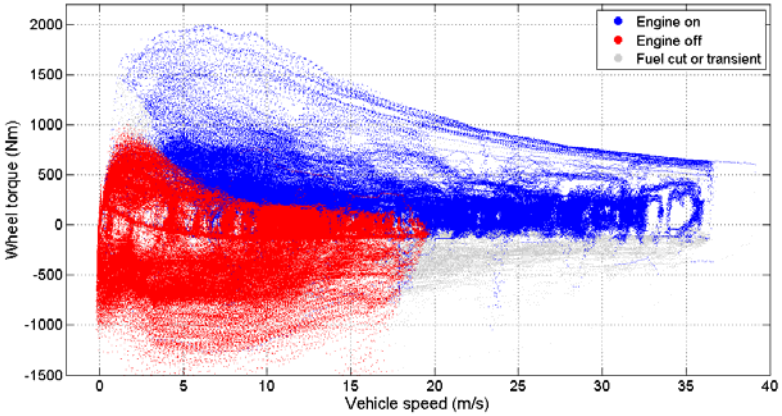
NCCP = 0.937

ANL APRF Test Data

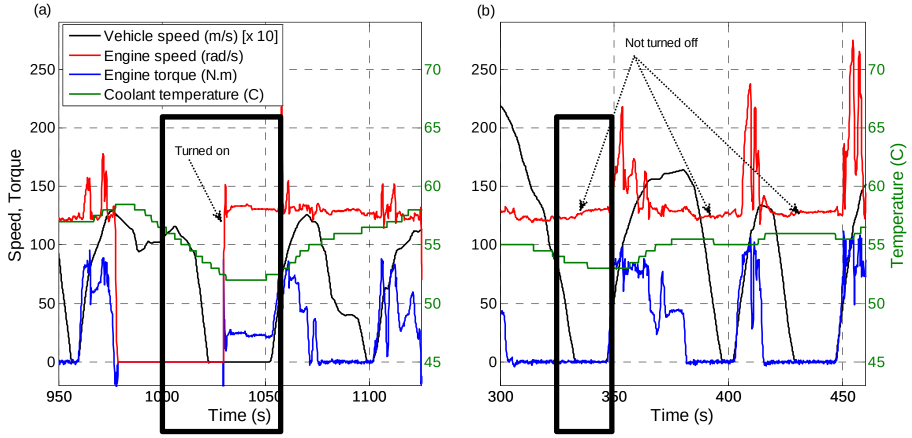
Vehicle Level Controls Logic Reverse Engineered

2010 Prius PHEV Example (APRF Test Data)

Mode Control (Engine On/Off)



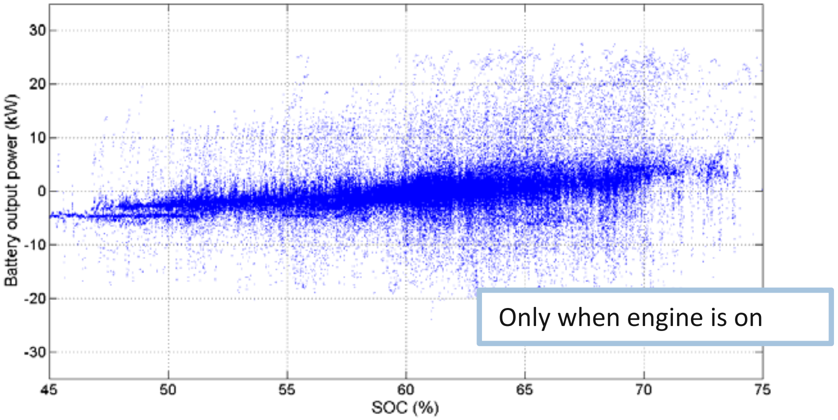
The engine is forced to be turned on if the coolant temperature is low.



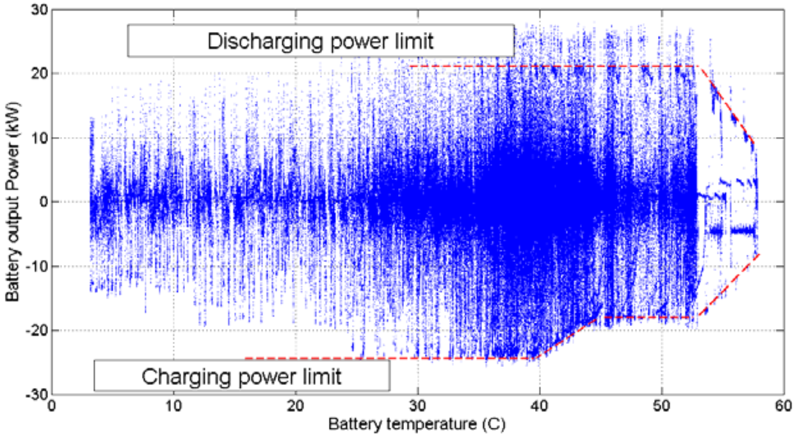
The engine is not turned off if the coolant temperature is low.

Desired battery power is proportional to SOC.

SOC Balancing



Only when engine is on



Discharging power limit

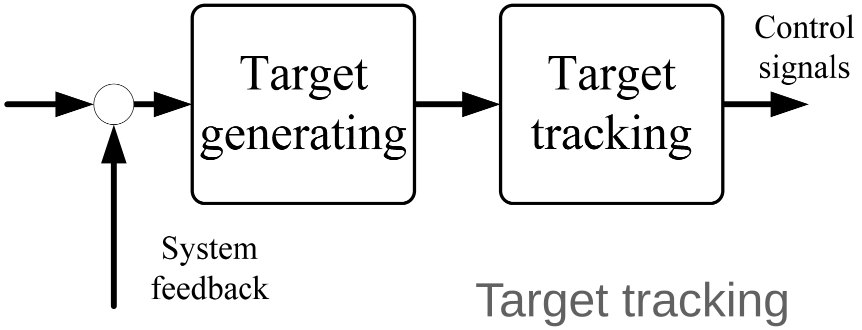
Charging power limit

Battery power is constrained by the battery temperature.

Vehicle Level Controls Logic Reverse Engineered

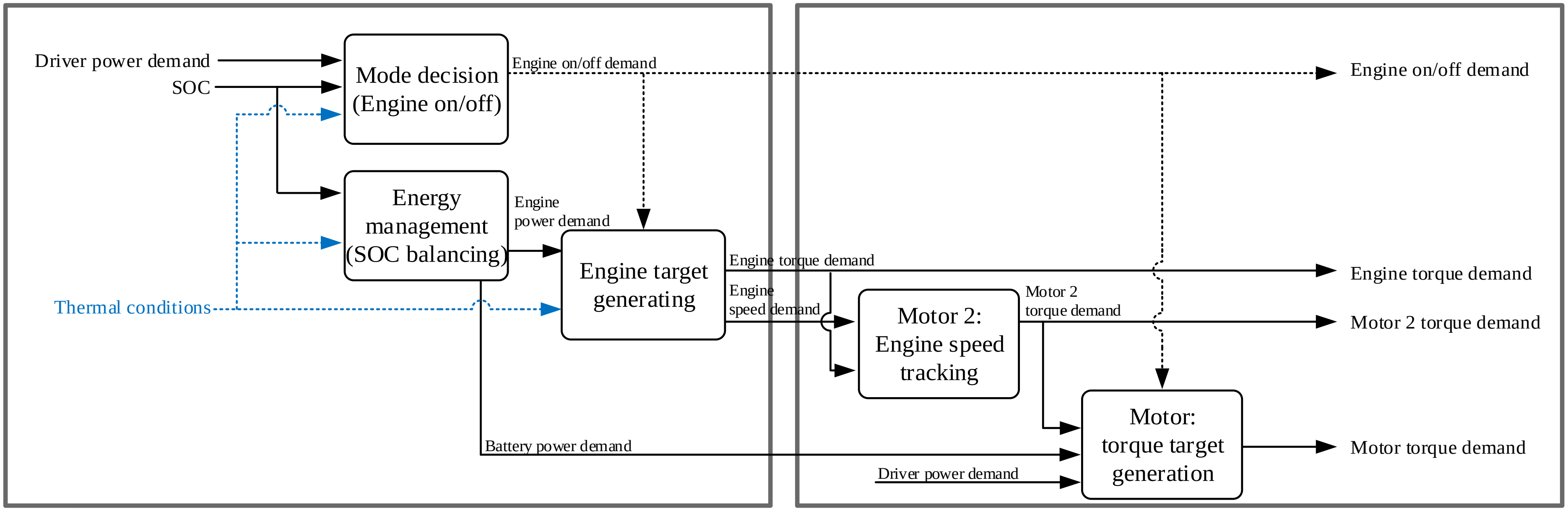
2010 Prius PHEV Example

Control concept based on the analyzed results



Target generating

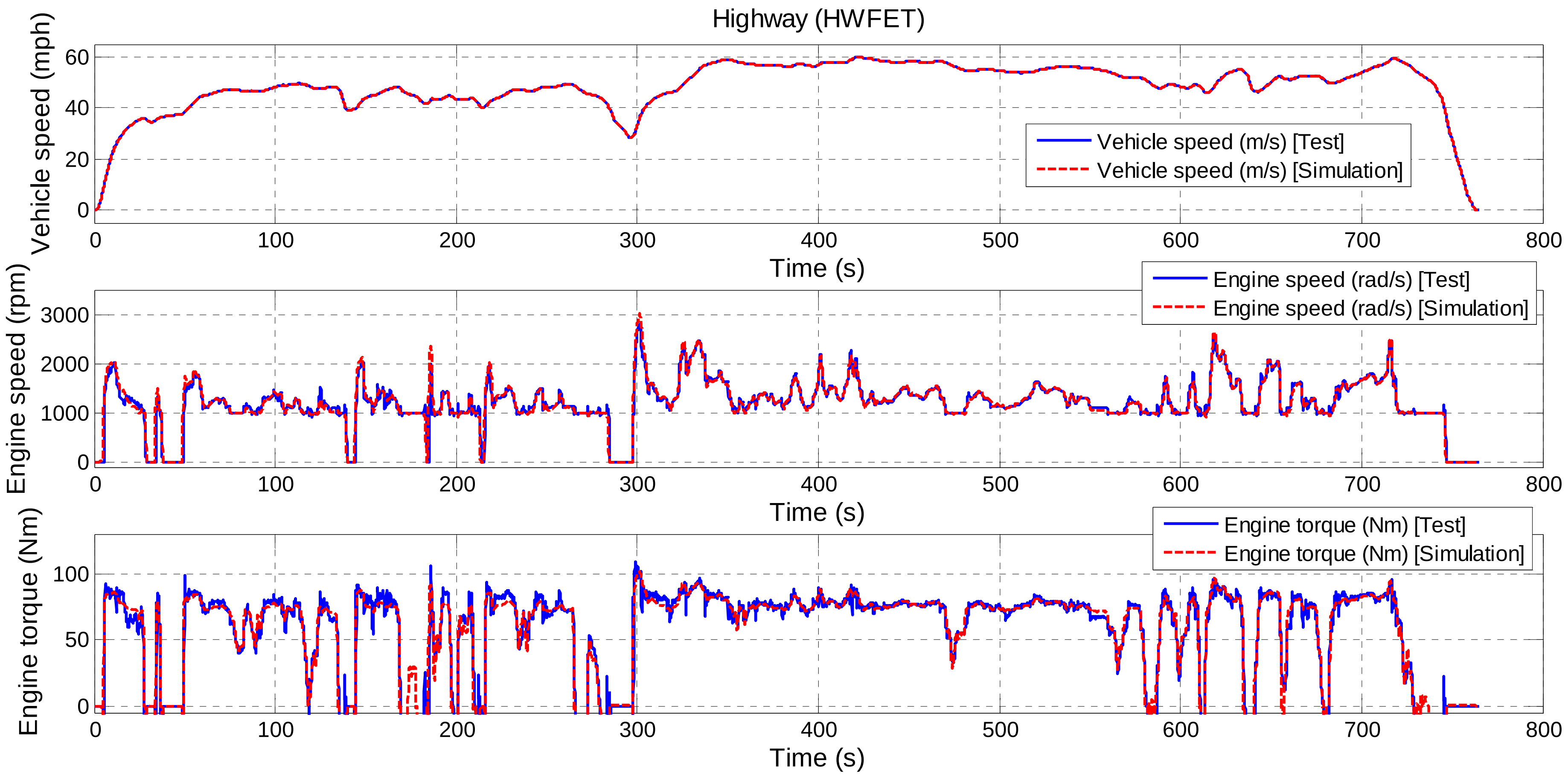
Target tracking



SAE 2014-01-1784

Component Operating Conditions Validated

Prius HEV Validation on HWFET

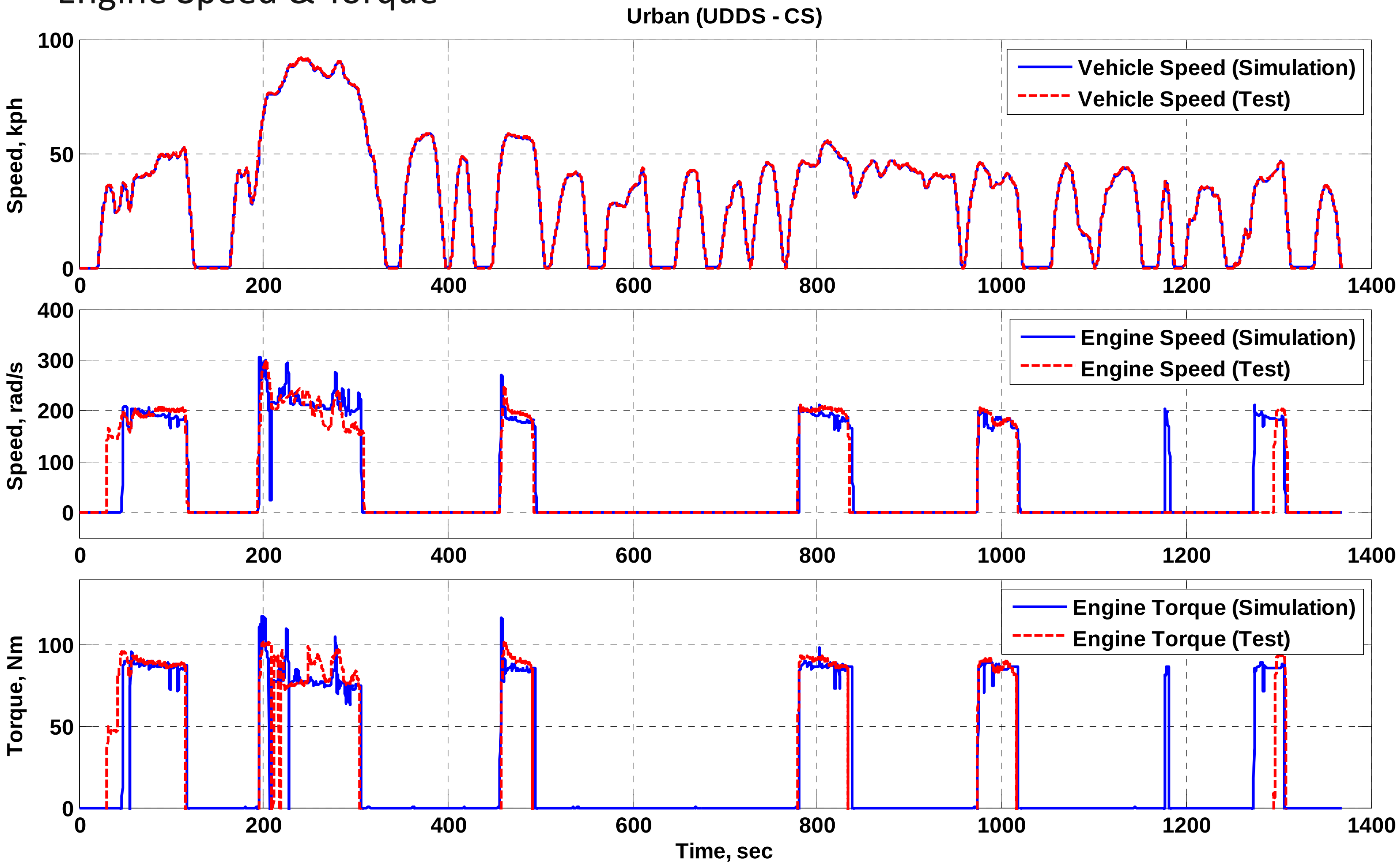


SAE 2012-01-1040

Component Operating Conditions Validated

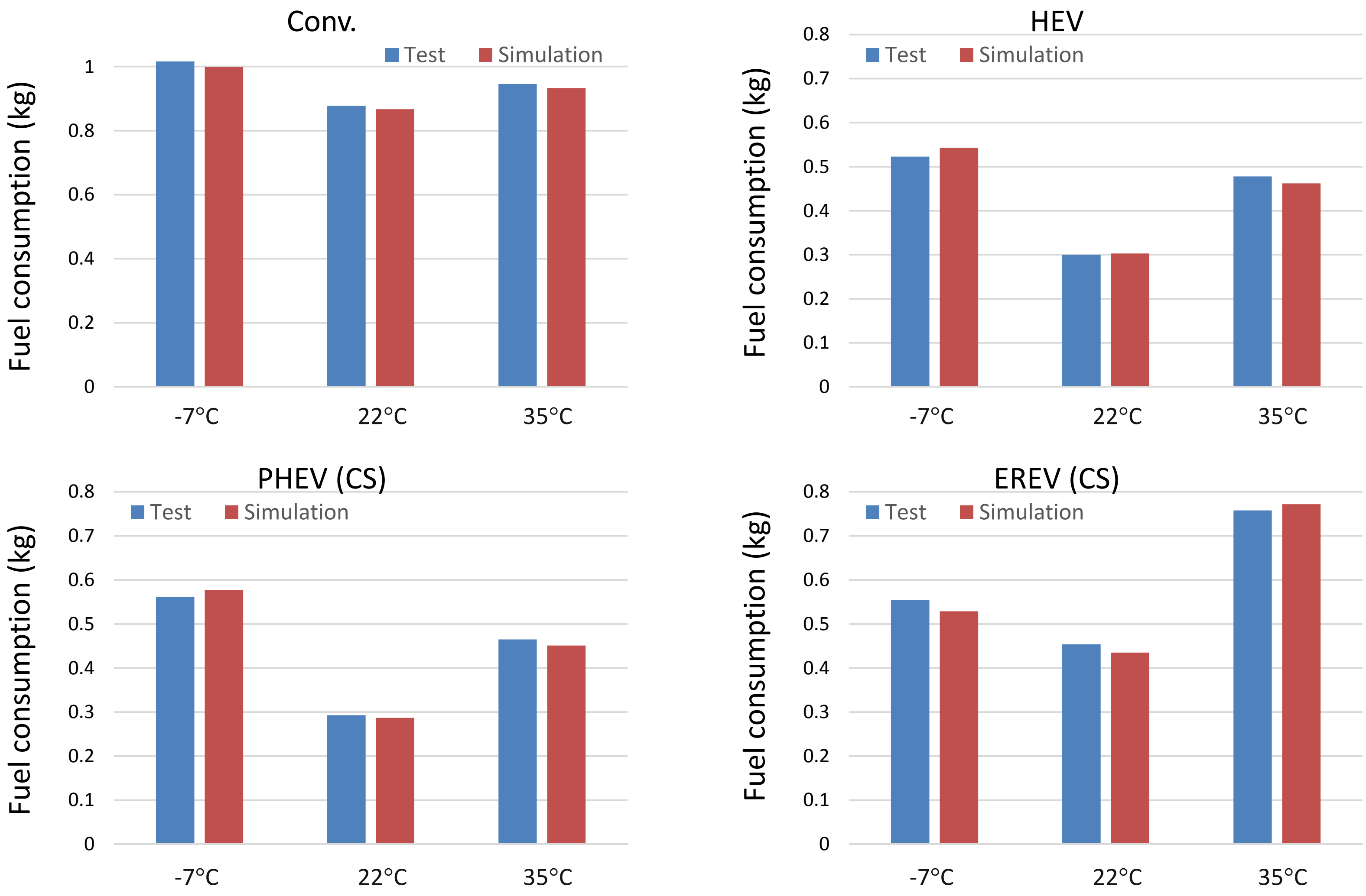
GM Volt Validation on UDDS (Extended Range)

- Engine Speed & Torque



Vehicle Model Validated within Test to Test Uncertainty

UDDS Driving Cycle for Multiple Powertrain and Temp.



List of References

Validation

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- N. Kim, A. Rousseau, and H. Lohse-Busch, “**Advanced Automatic Transmission Model Validation Using Dynamometer Test Data**”, SAE 2014-01-1778, SAE World Congress, Detroit, Apr14
- N. Kim, E. Rask and A. Rousseau, “**Control Analysis under Different Driving Conditions for Peugeot 3008 Hybrid 4**”, SAE 2014-01-1818, SAE World Congress, Detroit, Apr14
- D. Lee, A. Rousseau, E. Rask, “**Development and Validation of the Ford Focus BEV Vehicle Model**”, 2014-01-1809, SAE World Congress, Detroit, Apr14
- N. Kim, A. Rousseau, D. Lee, and H. Lohse-Busch, “**Thermal Model Development & Validation for the 2010 Toyota Prius**”, 2014-01-1784, SAE World Congress, Detroit, Apr14
- N. Kim, N. Kim, A. Rousseau, M. Duoba, “**Validating Volt PHEV Model with Dynamometer Test Data using Autonomie**”, SAE 2013-01-1458, SAE World Congress, Detroit, Apr13
- N. Kim, A. Rousseau, E. Rask, “**Autonomie Model Validation with Test Data for 2010 Toyota Prius**”, SAE 2012-01-1040, SAE World Congress, Detroit, Apr12
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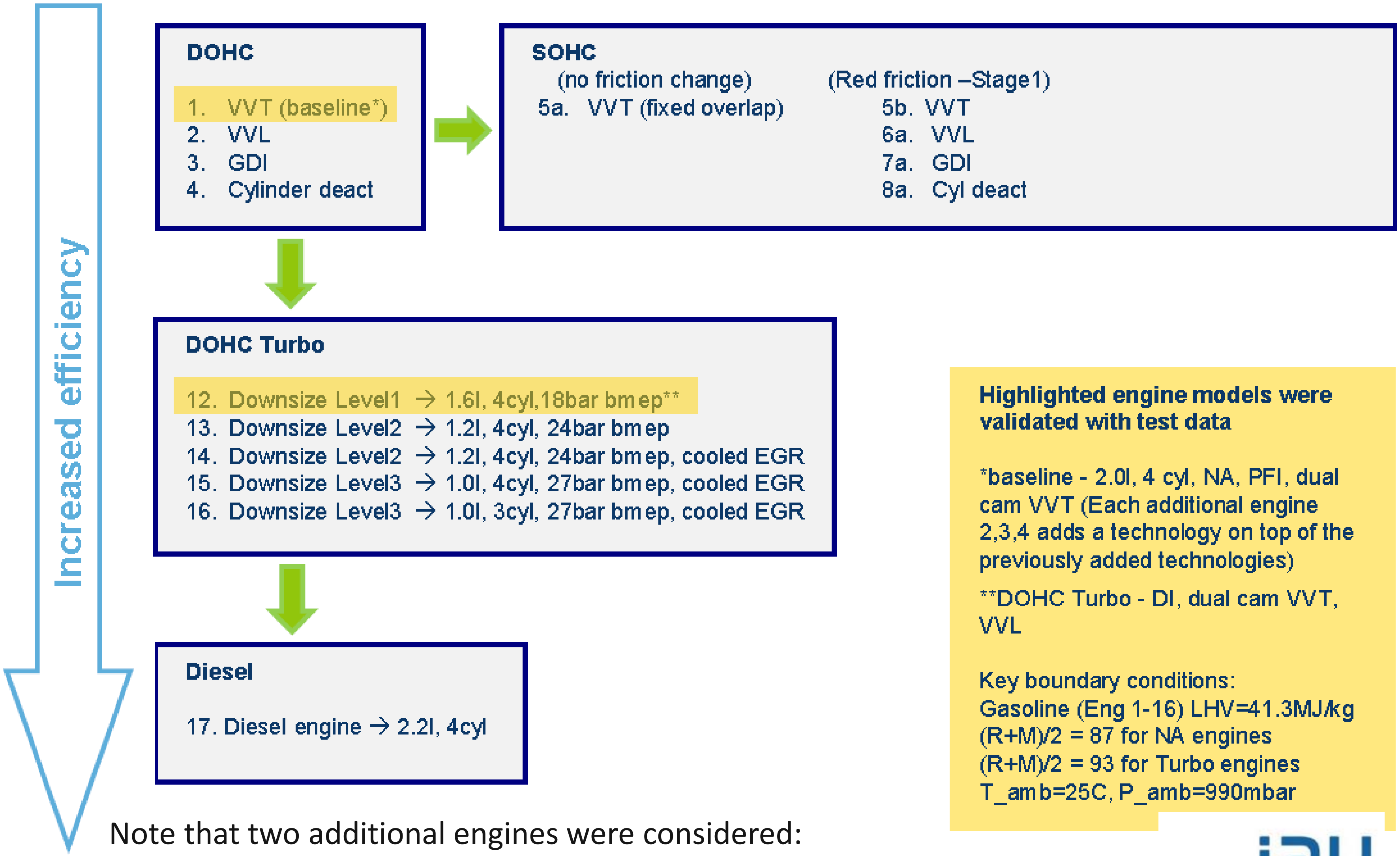
- Cao, Q., Pagerit, S., Carlson, R., Rousseau, A., "**PHEV Hymotion Prius model validation and control improvements**," 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, (Dec. 2007).
- Rousseau, A., Sharer, P., Pagerit, S., Duoba, M., "**Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT**," SAE paper 2006-01-0667, SAE World Congress, Detroit (April 2006).
- Pasquier, M., Rousseau, A., Duoba, M, "**Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedures**," 18th International Electric Vehicle Symposium (EVS18), Berlin, Germany, 12 pgs. (October 2001).
- Rousseau, A., Deville, B., Zini, G., Kern, J., Anderson, J., and Duoba, M., "**Honda Insight Validation Using PSAT**," Future Transportation Technology Conference, Costa-Mesa, 01–FTT49 (August 2001).
- Rousseau, A., and Pasquier, M., "**Validation of a Hybrid Modeling Software (PSAT) Using Its Extension for Prototyping (PSAT-PRO)**," Global Powertrain Congress, Detroit (June 2001).

Engine Performance Map Methodology

- Since comparing a technology (e.g., DOHC with VVL) from OEM A with another technology (e.g., DOHC with VVL + GDI) from OEM B risks introducing bias in the results (e.g., multiple technology differences due to OEM preferences or IP advantages/disadvantages, calibration differences between OEMs…), we have opted to use high fidelity engine models based on GTPower and add technologies incrementally.
- Set of engine maps developed by IAV under contract from U.S. DOE.
- Multiple technologies have been considered to properly quantify the effectiveness of each technologies.
- Different fuels considered through LHV (-> high octane fuels would have different engine performance data).

List of Engine Technologies Modeled by IAV



DOHC

1. VVT (baseline*)
2. VVL
3. GDI
4. Cylinder deact

SOHC

(no friction change)
5a. VVT (fixed overlap)

(Red friction –Stage1)
5b. VVT
6a. VVL
7a. GDI
8a. Cyl deact

DOHC Turbo

12. Downsize Level1 → 1.6l, 4cyl,18bar bmep**
13. Downsize Level2 → 1.2l, 4cyl, 24bar bmep
14. Downsize Level2 → 1.2l, 4cyl, 24bar bmep, cooled EGR
15. Downsize Level3 → 1.0l, 4cyl, 27bar bmep, cooled EGR
16. Downsize Level3 → 1.0l, 3cyl, 27bar bmep, cooled EGR

Diesel

17. Diesel engine → 2.2l, 4cyl

Highlighted engine models were validated with test data

*baseline - 2.0l, 4 cyl, NA, PFI, dual cam VVT (Each additional engine 2,3,4 adds a technology on top of the previously added technologies)

**DOHC Turbo - DI, dual cam VVT, VVL

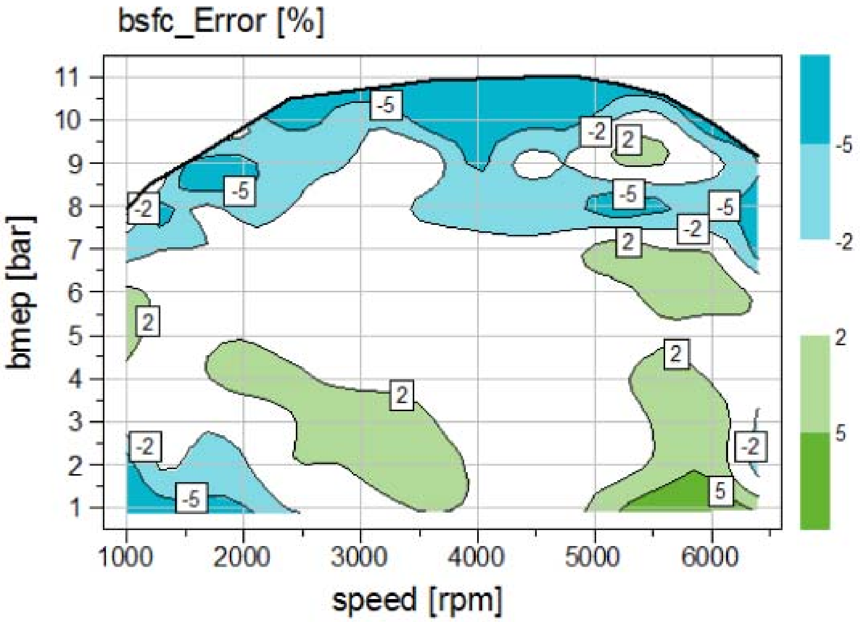
Key boundary conditions:
Gasoline (Eng 1-16) LHV=41.3MJ/kg
(R+M)/2 = 87 for NA engines
(R+M)/2 = 93 for Turbo engines
T_amb=25C, P_amb=990mbar

Note that two additional engines were considered:
- Mazda SkyActive from EPA dynamometer test data.
- Atkinson from APRF

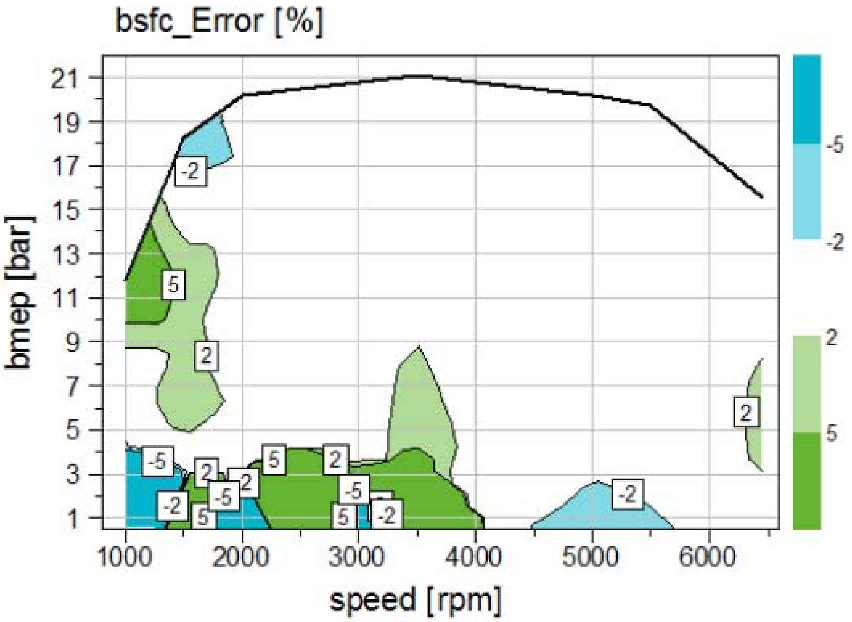
Baseline Engine Models Validated

Initial baseline reference models are calibrated with and validated against measurement data

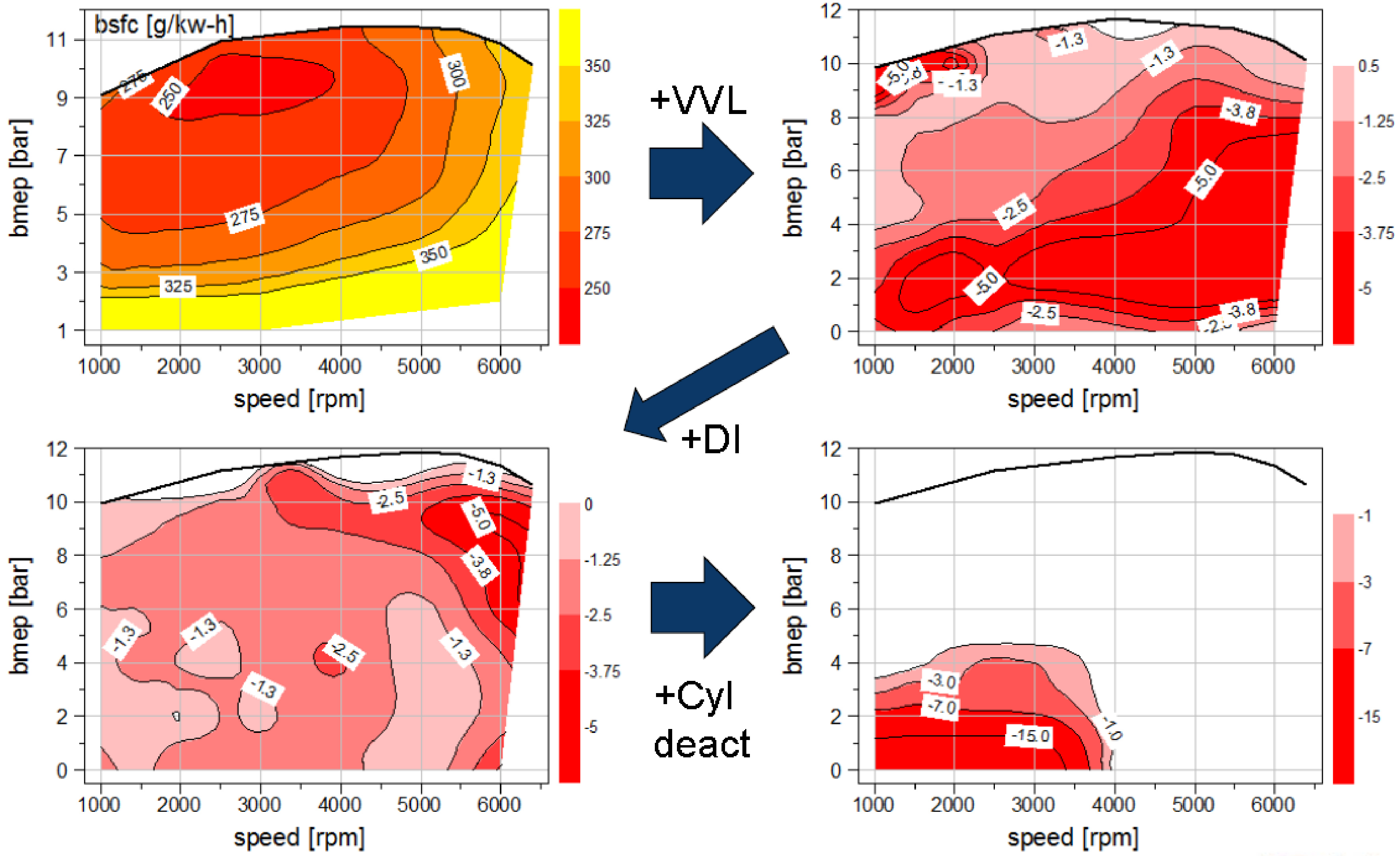
Engine 1
(2.0l, NA, PFI, dual VVT)



Engine 12
(1.6l, Turbo, DI, dual VVT, VVL)



Engine Technology Walkthrough Example



+VVL

+DI

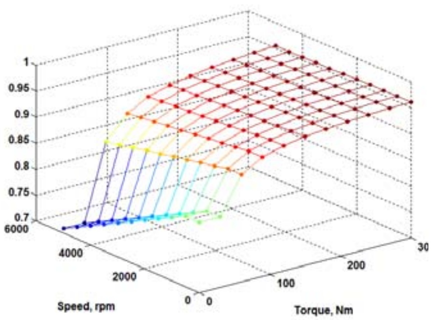
+Cyl deact

automotive engineering iav

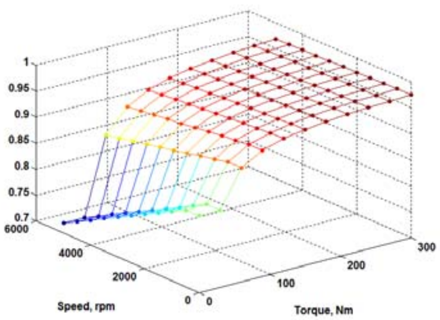
Transmission Methodology

- Applying technologies incrementally to a reference transmission avoids introducing bias in the results that could occur with an approach that compares specific OEM transmissions (i.e., gears might have been selected for different applications, efficiencies between OEMs might be inconsistent when comparing gear number impact…)
- A generic process was developed to "design" the transmission gear ratios based on a set of requirements and constraints.
- Similar efficiency curves were used across gearboxes

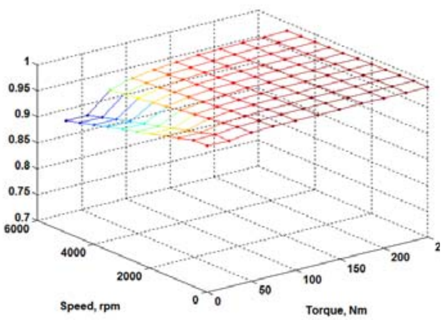
AT efficiency map – 1st Gear



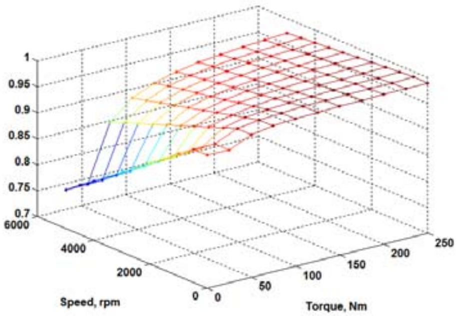
AT efficiency map – 6th Gear



DCT efficiency map – 1st Gear



DCT efficiency map – 6th Gear

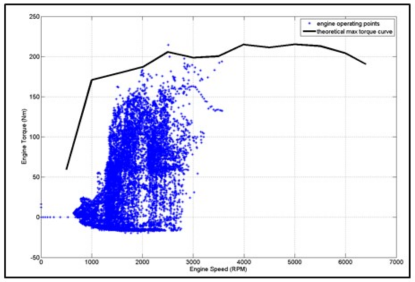


As a function of gear ratio, the efficiency of AT drops off slightly as we move farther away from a gear ratio of 1 (equal to the efficiency in direct drive)

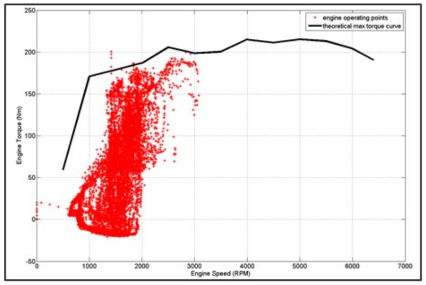
The efficiency of DCT could be broken down into a speed dependent term (spin loss) and a load dependent term (gear train mechanical efficiency)

Methodology (Example) for Gear Ratio Selection, Shift Parameter Selection, Control…

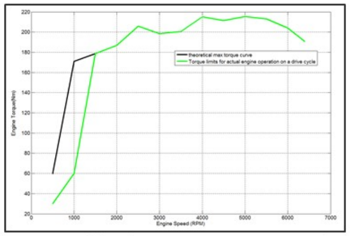
- Switch to top gear at 45 MPH
- Top gear operates above 1250 RPM to prevent lugging
- Max number of gear shifts per cycle (i.e., between 110 – 120 for 6 speed automatic on UDDS
- Top speed at about 4000 RPM in top gear
- Engine speed does not exceed 3000 RPM in first gear (UDDS Cycle, 6 speed automatic)
- Final drive close to observed industry trends for same vehicle class
- Engine torque reserve
- Gear span close to observed industry trends for same vehicle class
- …



Test data :Ford Focus I-4 6speed auto, LA92 cycle



Test data: Hyundai Sonata I-4 6speed auto, LA92 cycle



Engine operation will be restricted by the green curve in simulation.
The green curve is generated by visual inspection of engine operation at low speed.

Gear Ratios and Final Drive Methodology

Select Gear Span , top gear and final drive based on industry trends

Design progressive gear ratios based on algorithm

Ensure that selected gear ratios meet engine operation requirements and performance relationship between 6 AU*, 8 AU** and 8 speed DCT

Transmission & vehicle type	Span	Final drive
6 spd AU, conventional	>6	>2
8 speed AU, conventional	>7	>2
8 speed DCT, conventional	>7 & >8-speed AU	>2
6 speed AU, BISG	>6	Lower than 6 speed AU***
8 speed AU, BISG	>7	Lower than 8 speed AU***
8 speed DCT, BISG	>7 & >8-speed AU	Lower than 8 speed DCT***

Industry trends on span and final drive

*6 AU - 6 speed automatic, **8 AU – 8 speed automatic
*** to have similar performance as the conventional powertrain

Gear Span, Final Drive and Calculation of Gear Ratios for 6 speed AU

Gear ratios designed based on the formula:

$$i_n = i_z \left[\frac{Span}{\phi_2^{0.5(z-1)(n-1)}} \right]^{\frac{z-n}{z-1}} \quad z \neq 1$$

Where
Z = total number of gears.
n = gear number in consideration for design (varies from 1 to z).
φ_2 = progression factor (independent variable – normally between 1 and 1.2).

i_z = top gear ratio

i_n = nth gear ratio

- Variation of φ_2 between 1 and 1.2 is a trade-off between performance and FE.
- For this study, φ_2 which maximizes FE, has been chosen, for each transmission.
- Algorithm validated against transmissions for several compact cars.

1. H.Naunheimer, et al , 'Automotive Transmissions – Fundamentals, Selection, Design And applications', Springer publications.

Gear Selection Algorithm Validation

- Using Least Squares Error method, ϕ_2 was determined for a number of 6 speed transmissions in the market.

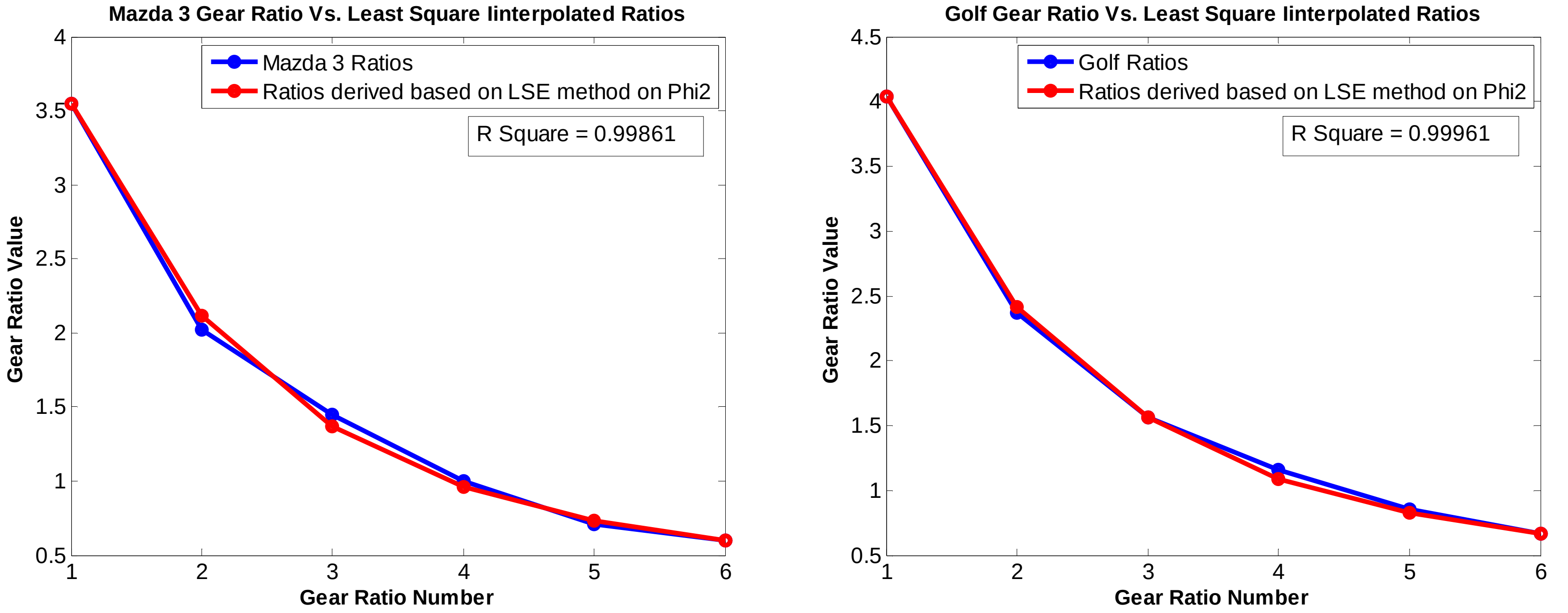


Figure 2: Algorithm applied to Mazda 3 and Volkswagen Golf Ratios

✓ Variation of ϕ_2 from 1.0 to 1.2 to get the best compromise between Fuel Eco, Performance and Number of Shifts
✓ New Ratios: Interpolated Ratios calculated with Theoretical Equations in order to fit existing vehicle ratios best

	Focus	Cruze	Mazda 3	Golf	Average	Study
Phi 2	1.09	1.04	1.08	1.08	1.07	**1.07**

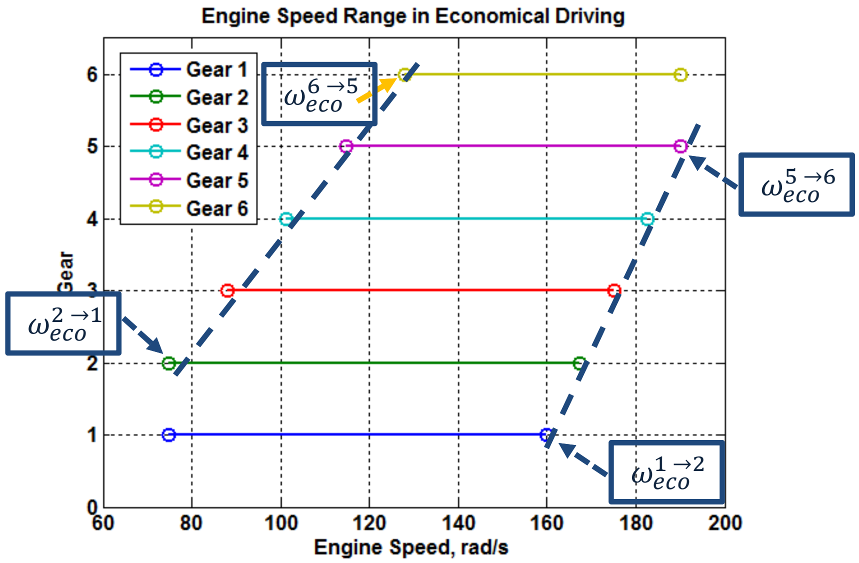
Table 2: Market Vehicle ϕ_2 interpolation the compare the simulation Phi2 Value

Shifting Control Algorithm

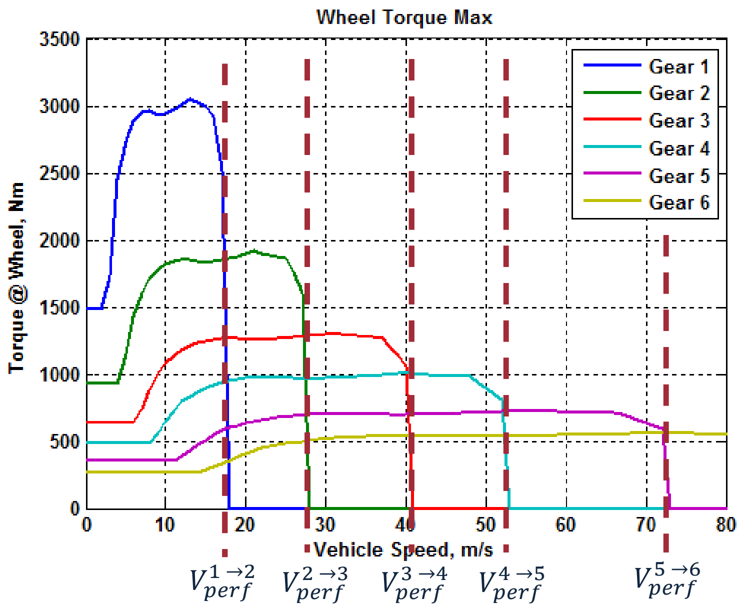
- The shifting initializer defines the shifting maps (i.e., values of the parameters of the shifting controller) specific to a selected set of component assumptions.

Economical Shifting Speeds At very low pedal position

Performance Shifting Speeds At high pedal position



Example of engine speed range in economical driving, and economical shift



Maximum engine torque at wheels and performance upshift speeds

Shifting Control Algorithm

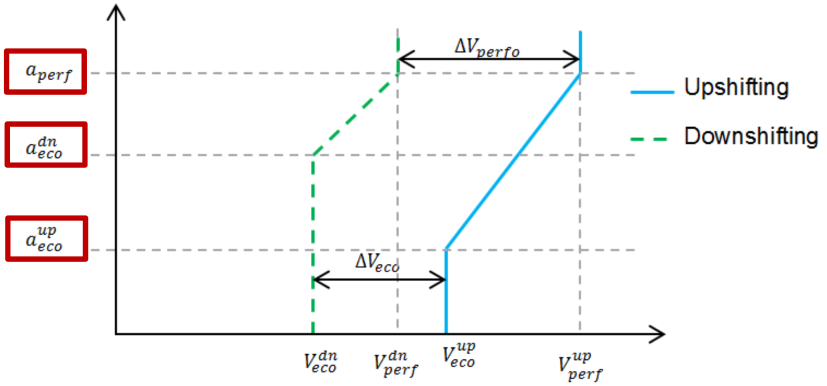
- Final shifting curves

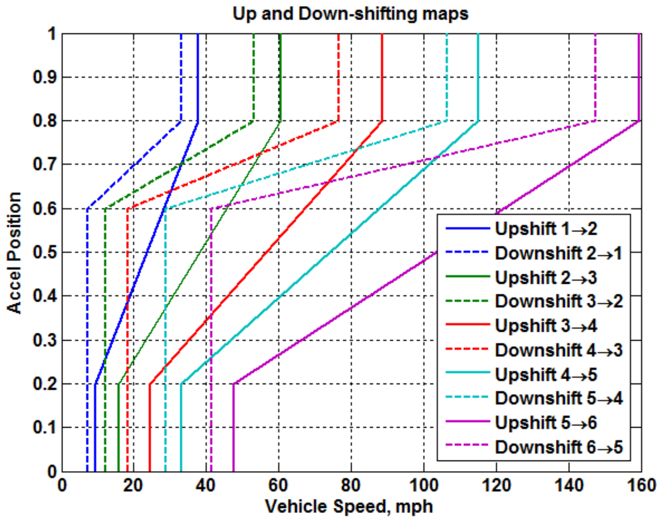
Economical Shifting Speeds

V^{dn}_{perf} V^{up}_{perf}

Performance Shifting Speeds

V^{dn}_{eco} V^{up}_{eco}

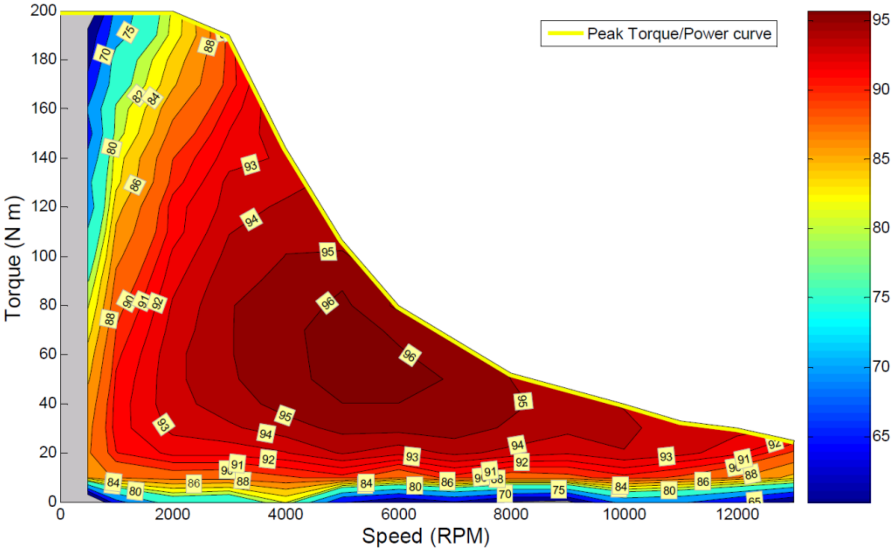




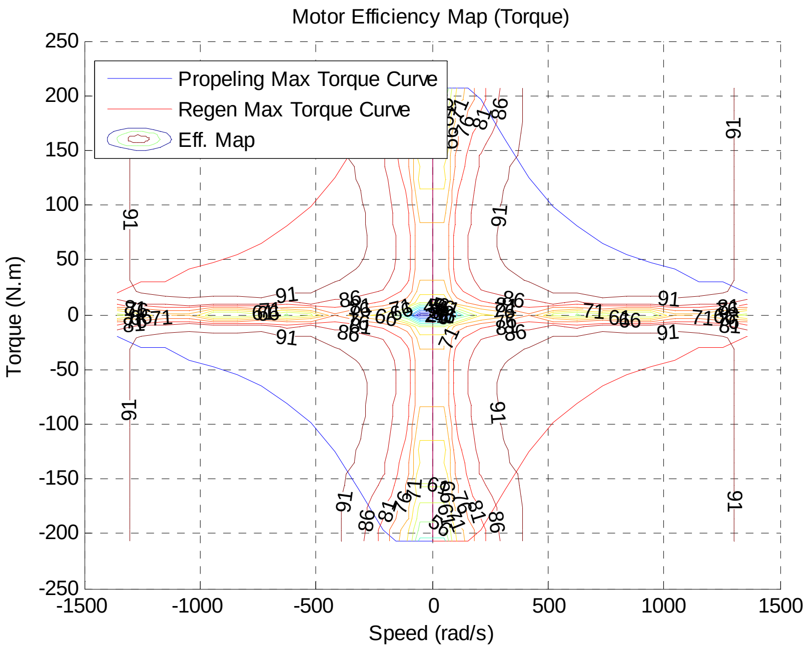
Shifting speed curves for a default light-duty vehicle in Autonomie

Electric Machine Performance Maps from DOE Funded Research

- Electric machine map (2010 Prius example)
  - Motor maps were obtained from Oak Ridge National Laboratory (ORNL).



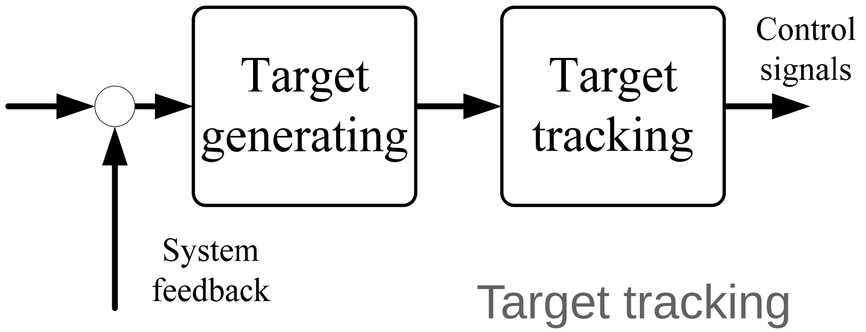
Mitch Olszewski, EVALUATION OF THE 2010 TOYOTA PRIUS HYBRID SYNERGY DRIVE SYSTEM



Vehicle Control Logic

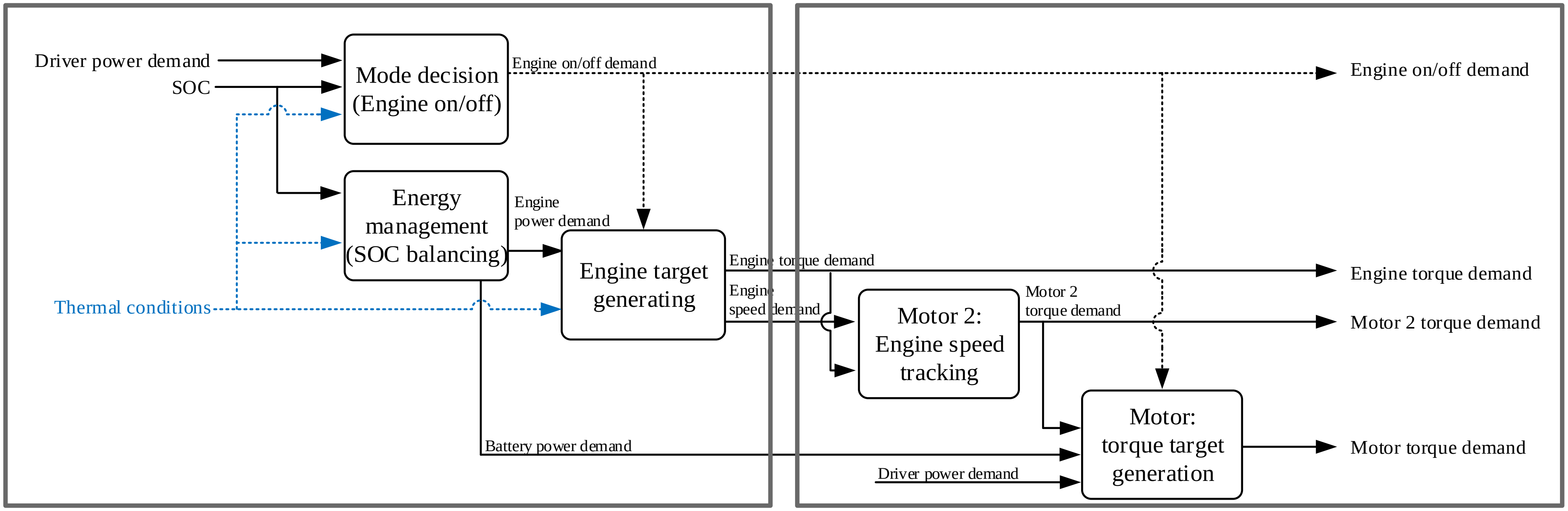
Example of Power Split HEV

Control concept based on the analyzed results



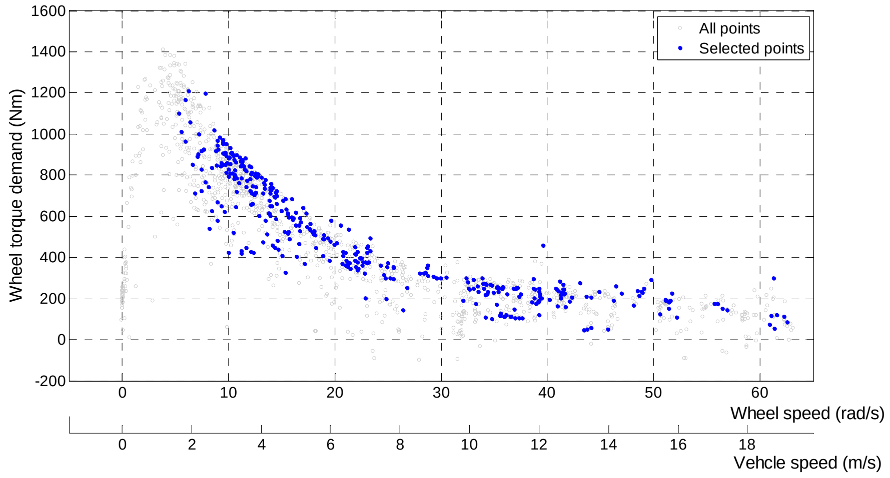
Target generating

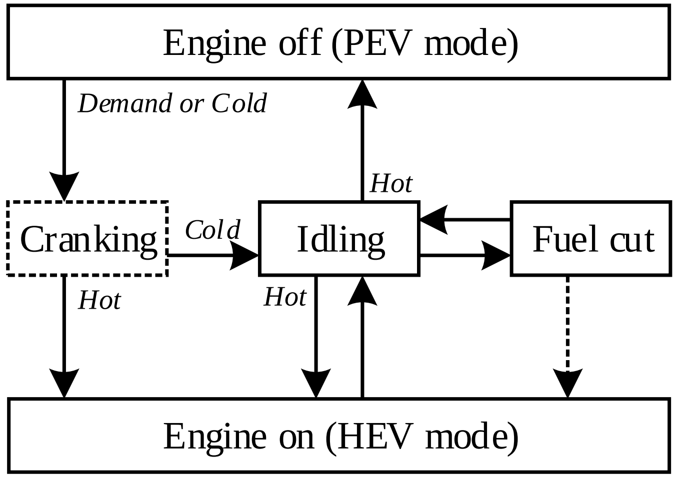
Target tracking



Vehicle Control Development

Example of Power Split HEV





Engine off (PEV mode)

Demand or Cold

Hot

Cranking

Cold

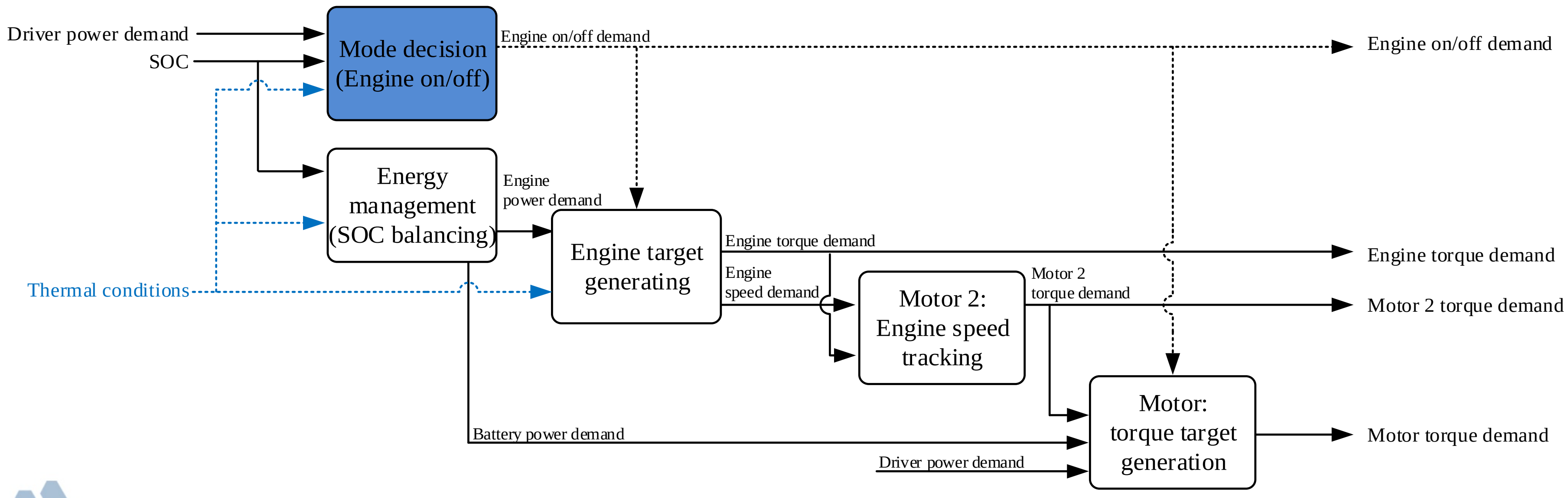
Idling

Fuel cut

Hot

Hot

Engine on (HEV mode)



Driver power demand

SOC

Thermal conditions

Mode decision (Engine on/off)

Engine on/off demand

Engine on/off demand

Energy management (SOC balancing)

Engine power demand

Engine target generating

Engine torque demand

Engine torque demand

Engine speed demand

Motor 2: Engine speed tracking

Motor 2 torque demand

Motor 2 torque demand

Battery power demand

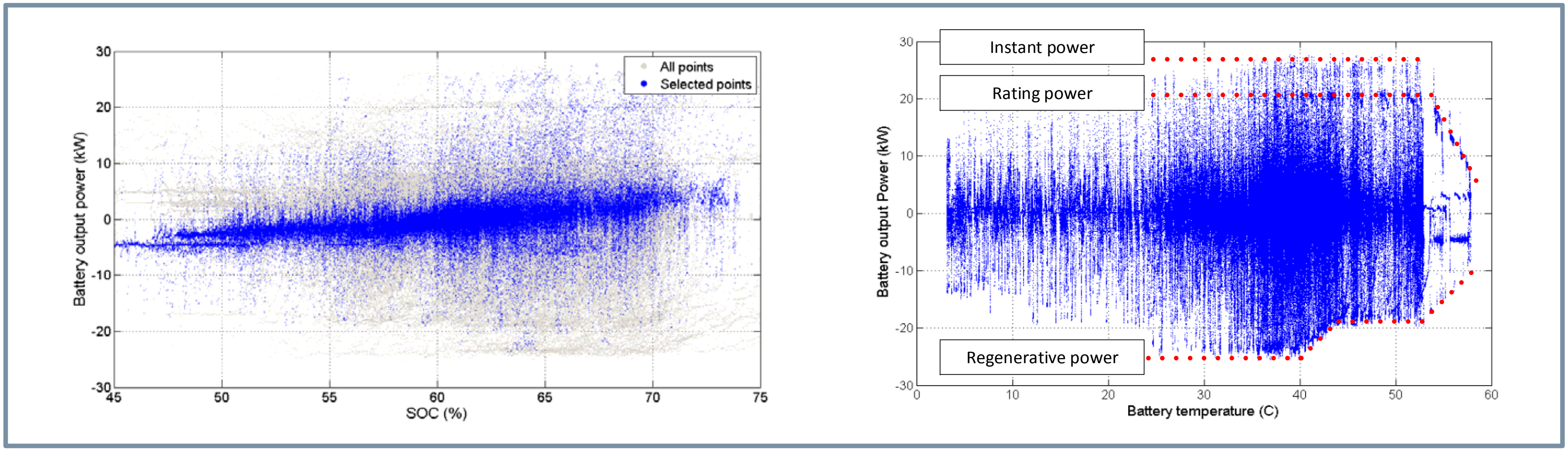
Driver power demand

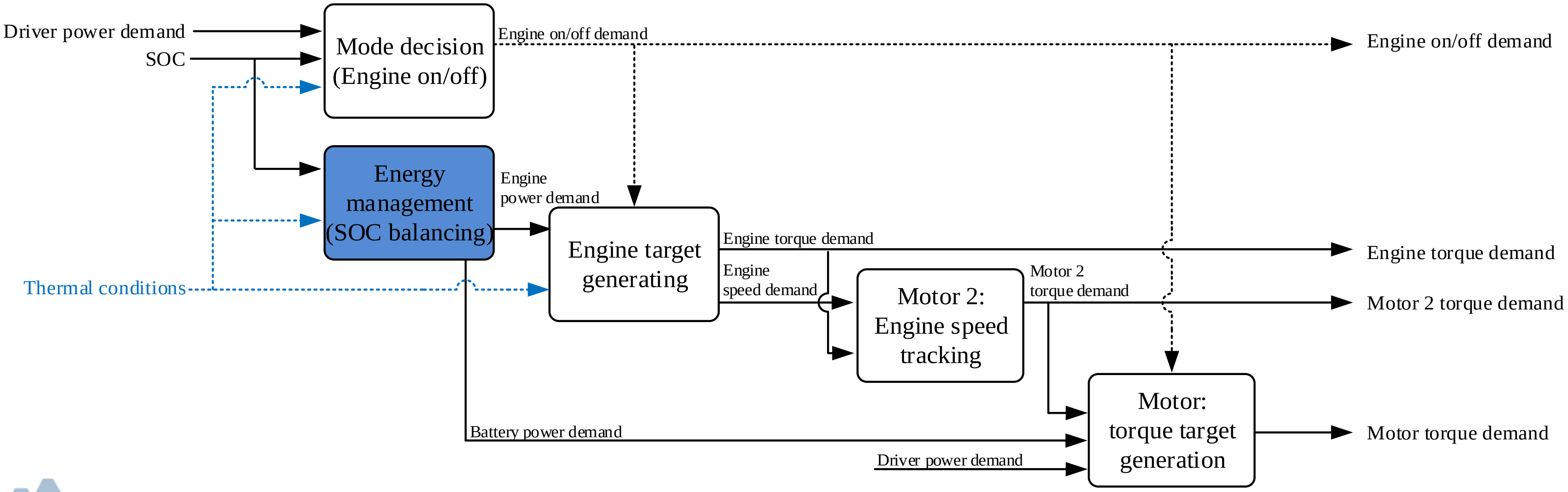
Motor: torque target generation

Motor torque demand

Vehicle Control Development

Example of Power Split HEV





Driver power demand

SOC

Thermal conditions

Mode decision (Engine on/off)

Energy management (SOC balancing)

Engine target generating

Motor 2: Engine speed tracking

Motor: torque target generation

Engine on/off demand

Engine power demand

Engine torque demand

Engine speed demand

Motor 2 torque demand

Battery power demand

Driver power demand

Engine on/off demand

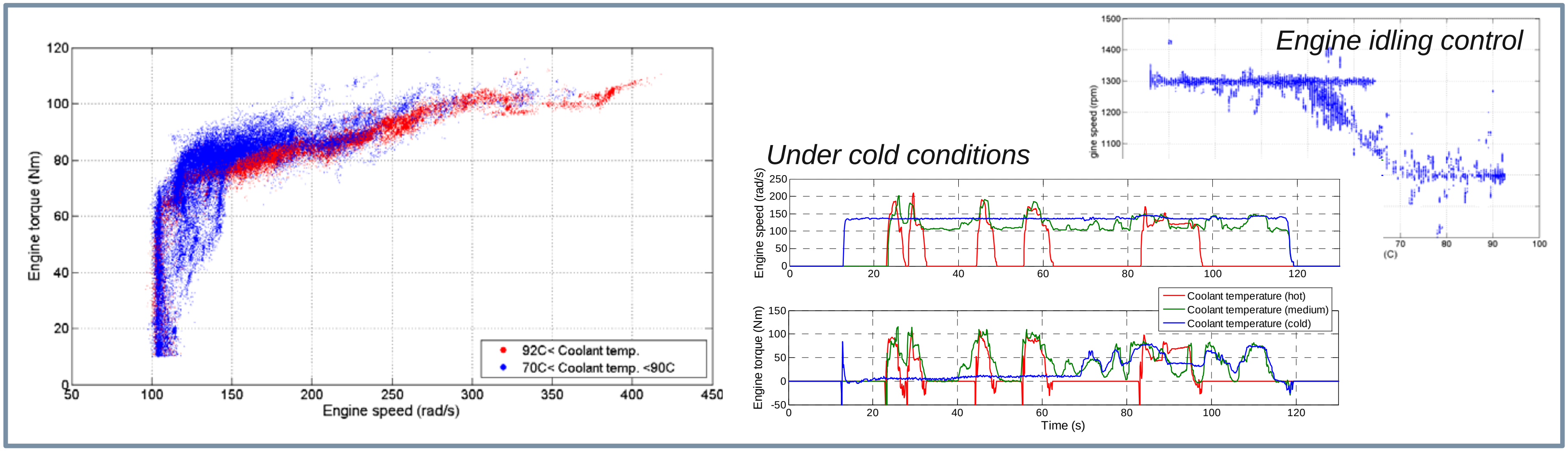
Engine torque demand

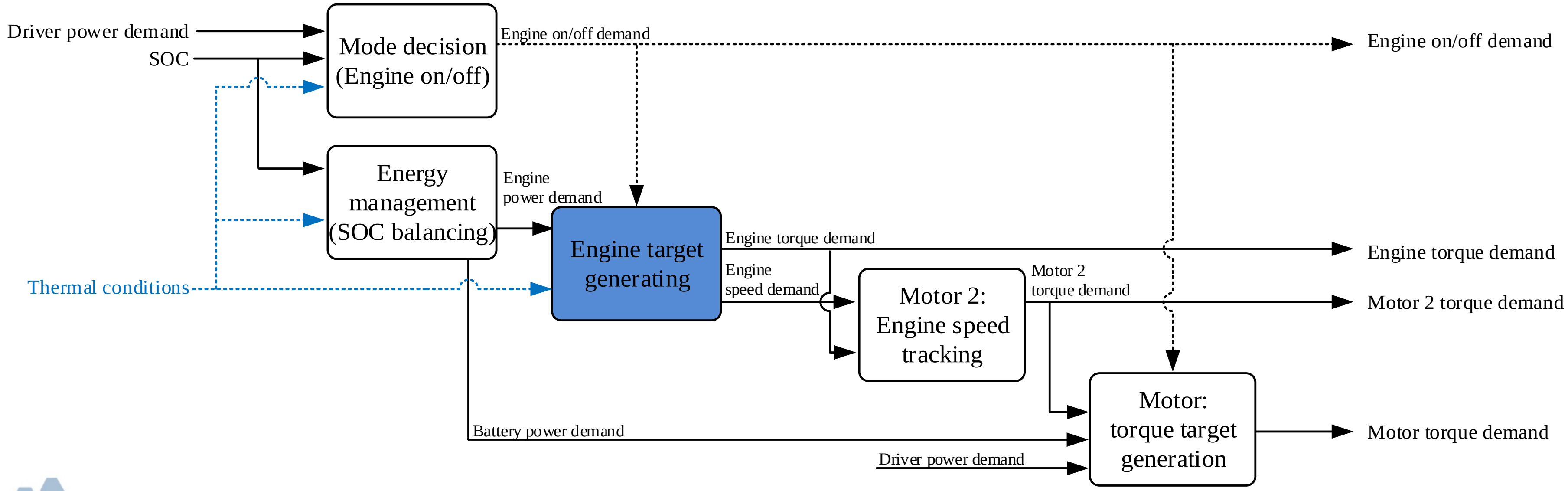
Motor 2 torque demand

Motor torque demand

Vehicle Control Development

Example of Power Split HEV




Driver power demand

SOC

Thermal conditions

Mode decision (Engine on/off)

Engine on/off demand

Energy management (SOC balancing)

Engine power demand

Engine target generating

Engine torque demand

Engine speed demand

Motor 2: Engine speed tracking

Motor 2 torque demand

Battery power demand

Driver power demand

Motor: torque target generation

Engine on/off demand

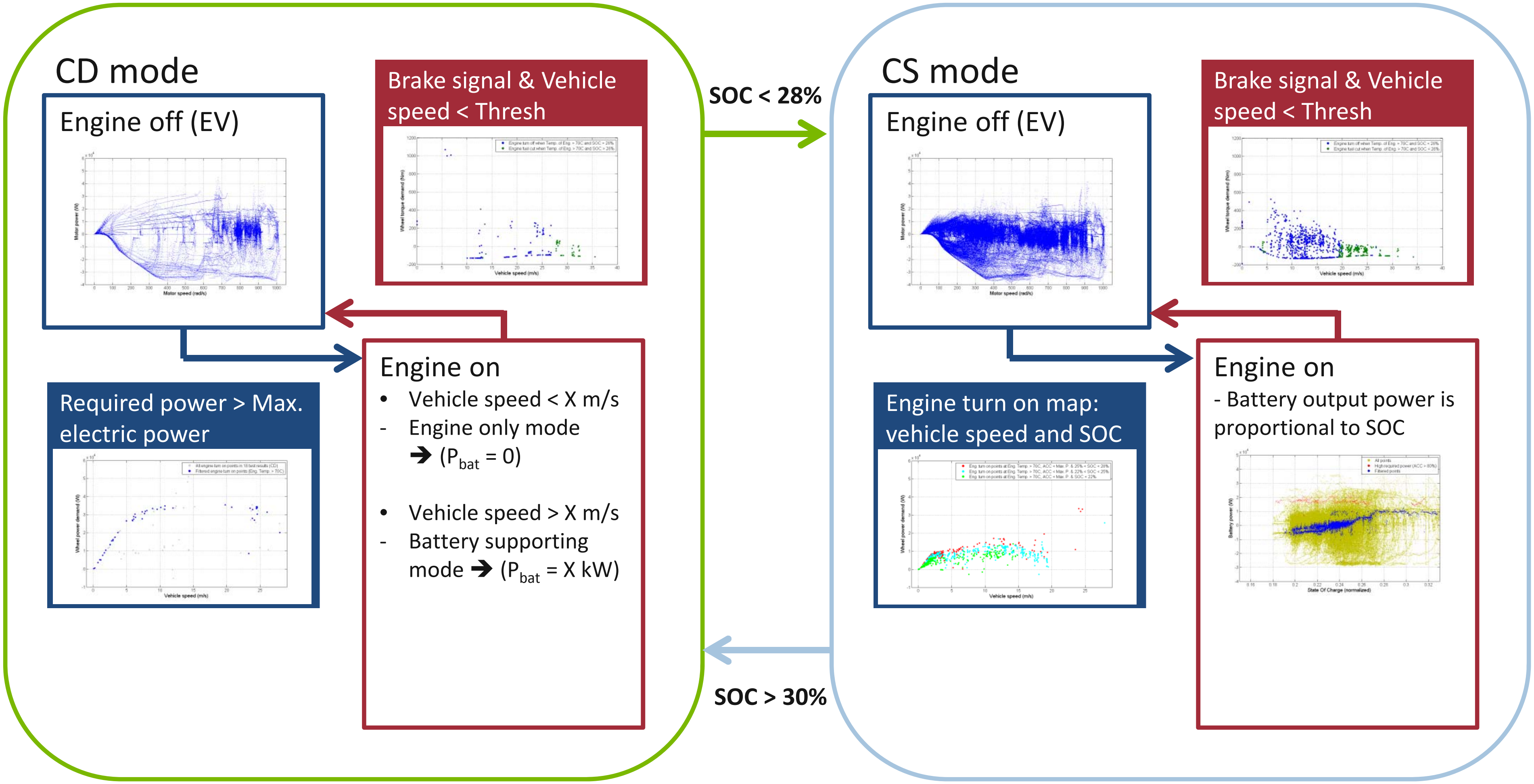
Engine torque demand

Motor 2 torque demand

Motor torque demand

Vehicle Control Development

Example of Power Split PHEV



CD mode

Engine off (EV)

Brake signal & Vehicle speed < Thresh

Required power > Max. electric power

Engine on
- Vehicle speed < X m/s
- Engine only mode ➔ (P_{bat} = 0)

- Vehicle speed > X m/s
- Battery supporting mode ➔ (P_{bat} = X kW)

SOC < 28%

SOC > 30%

CS mode

Engine off (EV)

Brake signal & Vehicle speed < Thresh

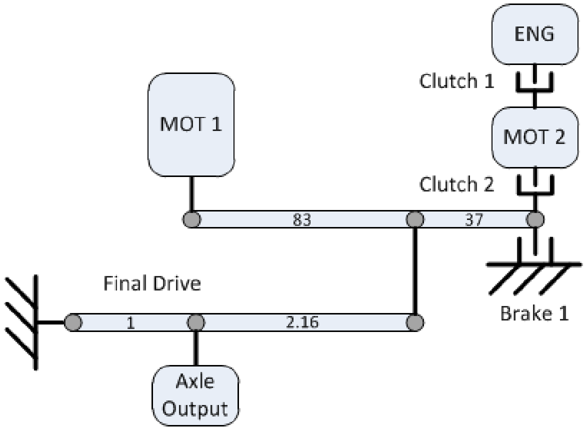
Engine turn on map: vehicle speed and SOC

Engine on

\- Battery output power is proportional to SOC

E-REV PHEV Control Algorithm

VOLTEC Gen 1



Operation Modes

One-Motor EV

Two-Motor EV

Series One-Motor ER

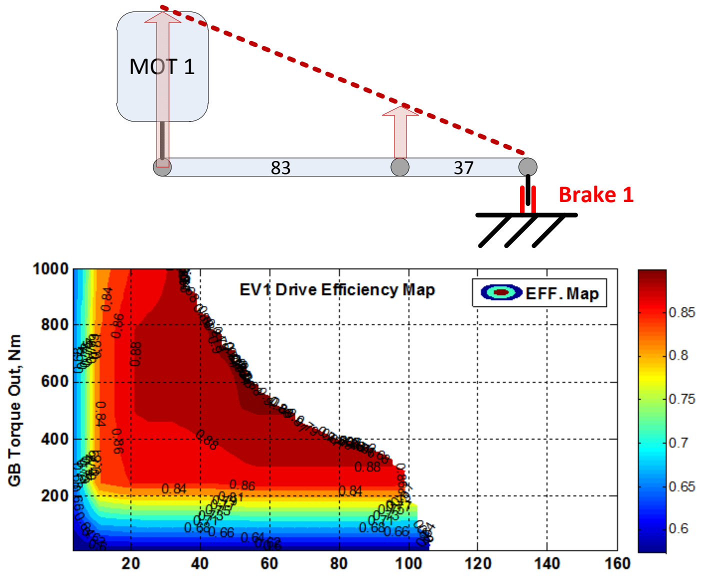
Combined Two-Motor ER

- In EV operation
  - One-Motor EV (EV1) : The single-speed EV drive power-flow, which provides more tractive effort at lower driving speeds.
  - Two-Motor EV (EV2) : The output power-split EV drive power-flow, which has greater efficiency than one-motor EV at higher speeds and lower loads.
- In extended-range
  - Series One-Motor ER (Series) : The series extended-range power-flow that provides more tractive effort at lower driving speeds.
  - Combined Two-Motor ER (Split) : The output power-split extended-range power-flow that has greater efficiency than series at higher speeds and lighter loads.

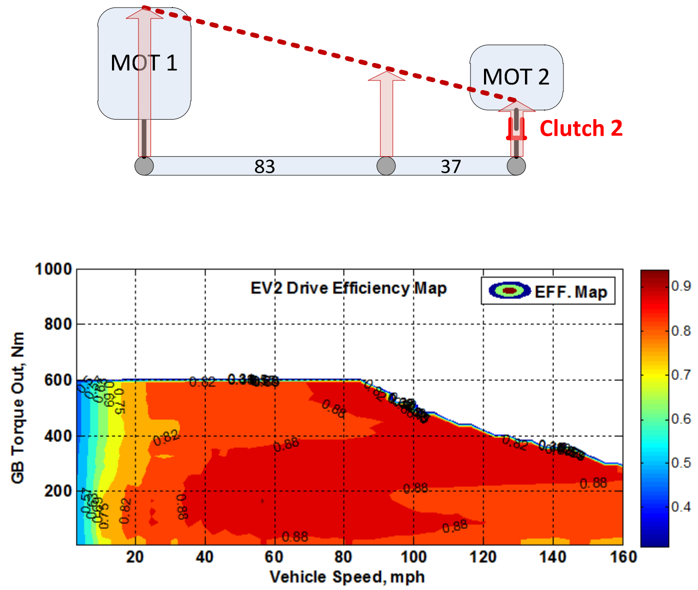
E-REV PHEV Control Algorithm

VOLTEC Gen 1: Electric driving mode (EV1 or EV2)

- Electric drive modes



EV1 : The speed of MC1 is always determined by output speed.

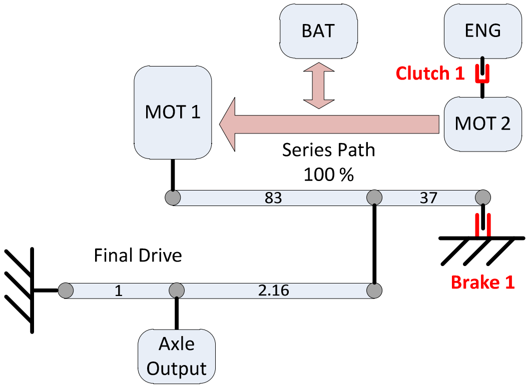


EV2 : The system has a degree of freedom for operation speed.

E-REV PHEV Control Algorithm

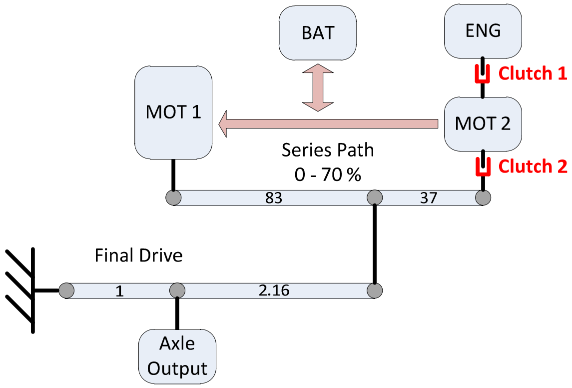
VOLTEC Gen 1: extended range mode (Series or Power Split)

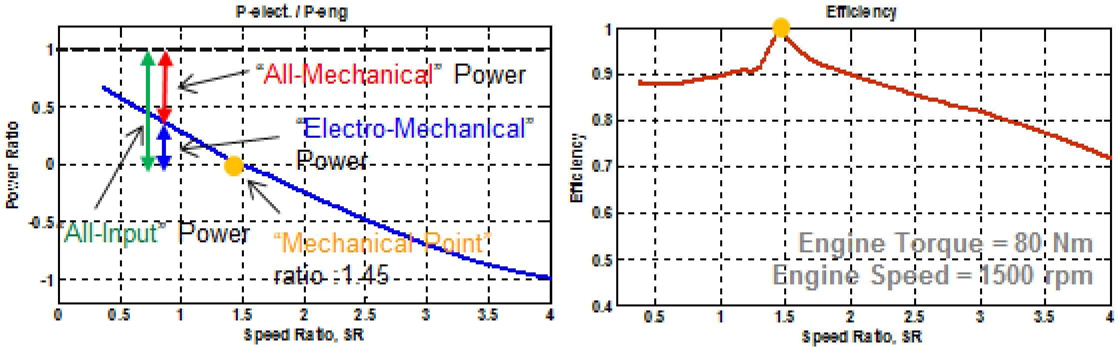
- Series one-motor extended-range



Because of the single-speed One-Motor EV drive, efficiency declines at higher driving speeds. 100% of the driving power must go through the series path and suffer the associated conversion losses.

- Electro-mechanical power with power split



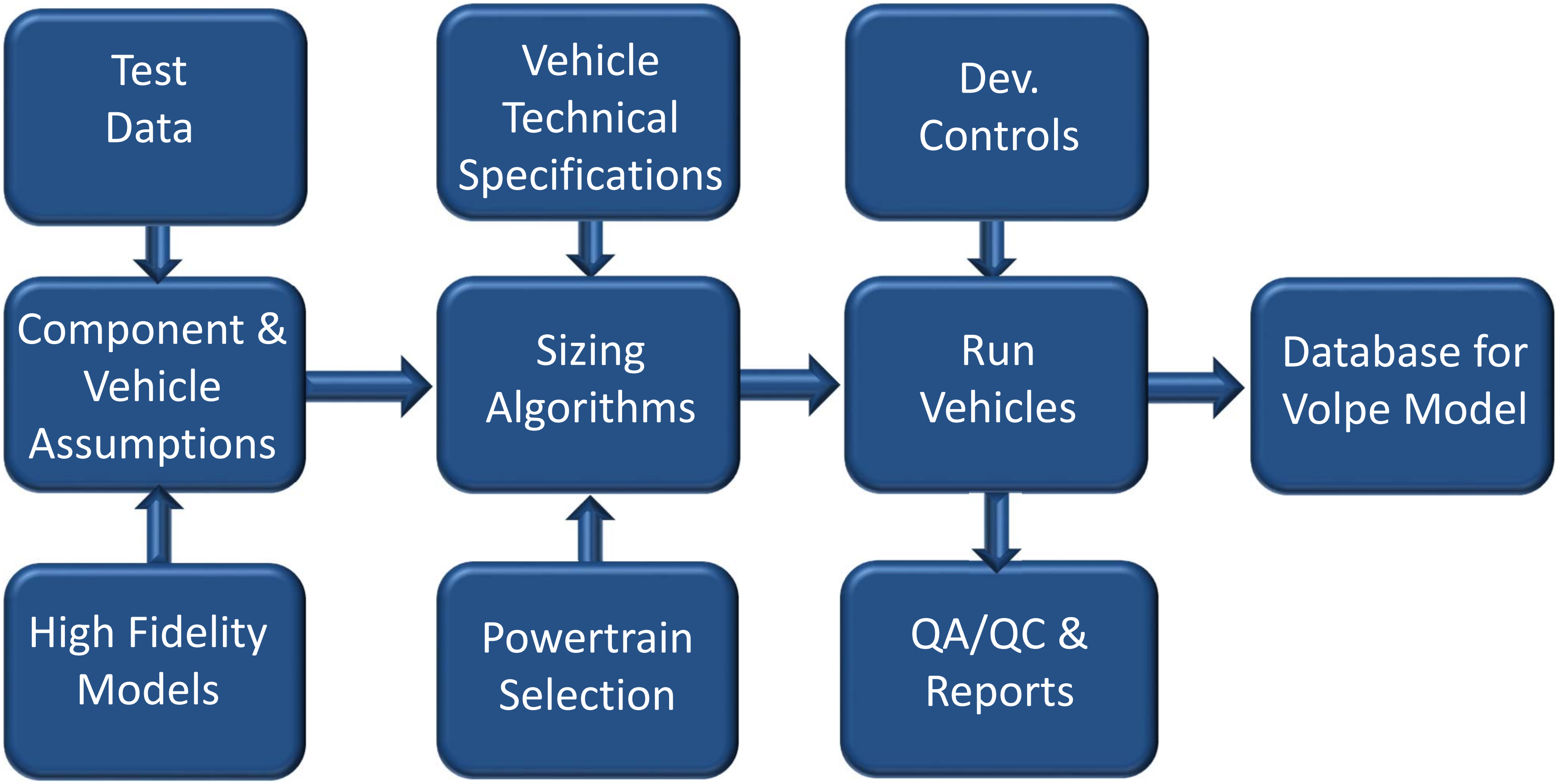


The primary benefit of the output split power-flow is improved efficiency due to the reduction in series path losses.

Outline

- Autonomie Overview
- Model Development and Validation
- Process to Estimate Technologies Effectiveness with Full Vehicle Simulation
- Vehicle Powertrain Sizing Algorithms and Validation
- Vehicle Simulation Results Quality Check Process

Methodology


Test Data

Vehicle Technical Specifications

Dev. Controls

Component & Vehicle Assumptions

Sizing Algorithms

Run Vehicles

Database for Volpe Model

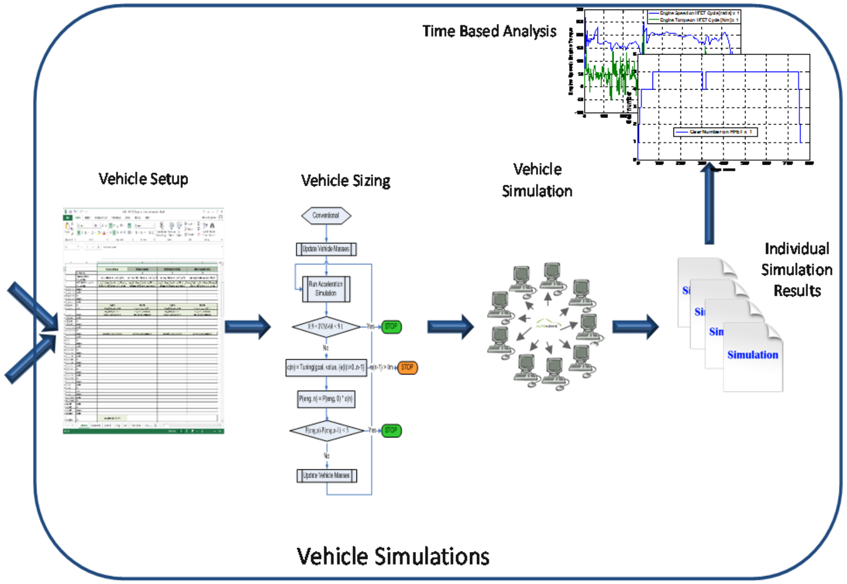
High Fidelity Models

Powertrain Selection

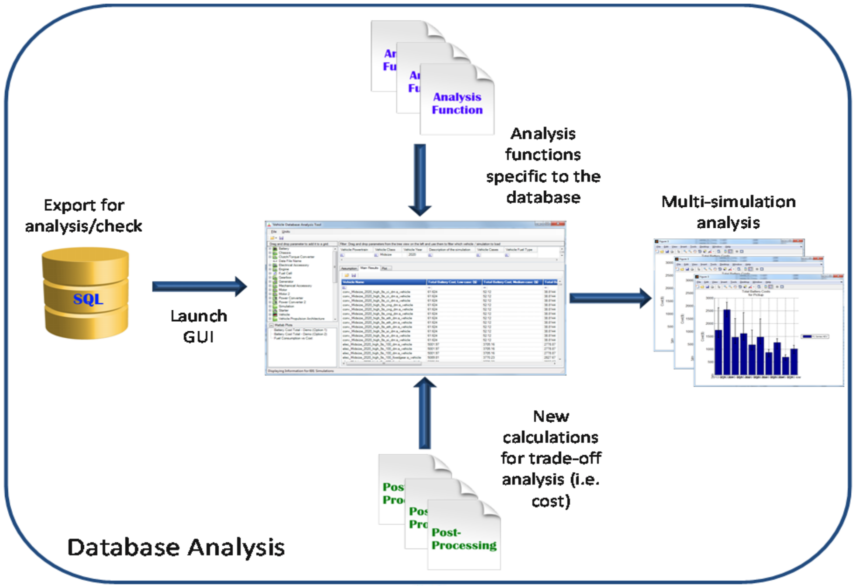
QA/QC & Reports

A. Moawad, A. Rousseau, P. Balaprakash, S. Wild, “**Novel Large Scale Simulation Process to Support DOT’s CAFE Modeling System**”, International Journal of Automotive Technology (IJAT), Paper No. 220150349, Nov 2015

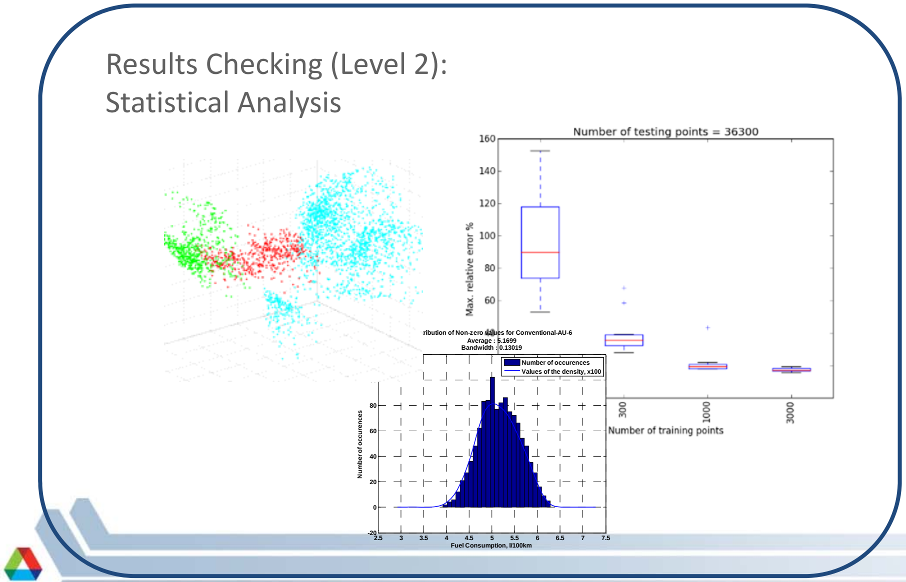
Process Overview



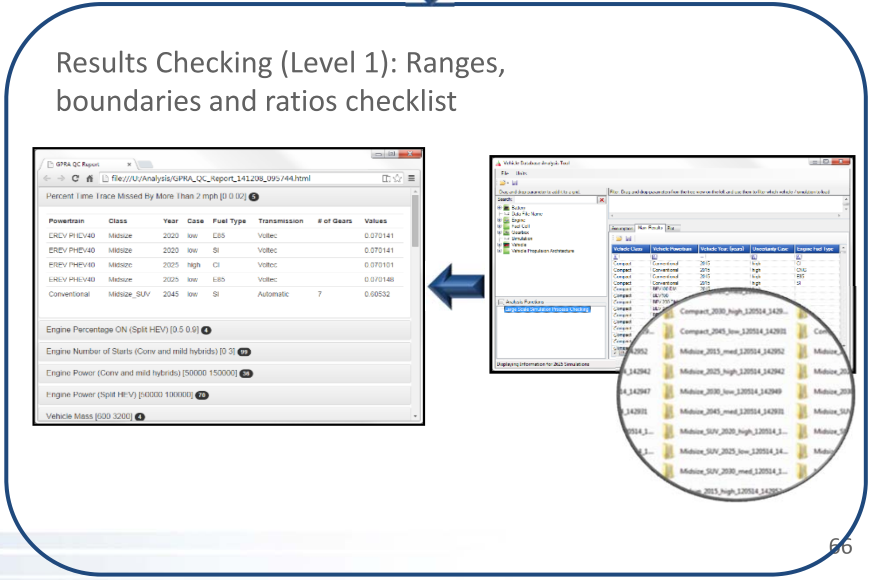
Vehicle Simulations



Database Analysis



Results Checking (Level 2): Statistical Analysis



Results Checking (Level 1): Ranges, boundaries and ratios checklist

GPRA QC Report

file:///U:/Analysis/GPRA_QC_Report_141208_095744.html

Percent Time Trace Missed By More Than 2 mph [0 0.02] 5

Powertrain	Class	Year	Case	Fuel Type	Transmission	# of Gears	Values
EREV PHEV40	Midsize	2020	low	E85	Voltec		0.070141
EREV PHEV40	Midsize	2020	low	SI	Voltec		0.070141
EREV PHEV40	Midsize	2025	high	CI	Voltec		0.070101
EREV PHEV40	Midsize	2025	low	E85	Voltec		0.070148
Conventional	Midsize_SUV	2045	low	SI	Automatic	7	0.60532

Engine Percentage ON (Split HEV) [0.5 0.9] 4

Engine Number of Starts (Conv and mild hybrids) [0 3] 99

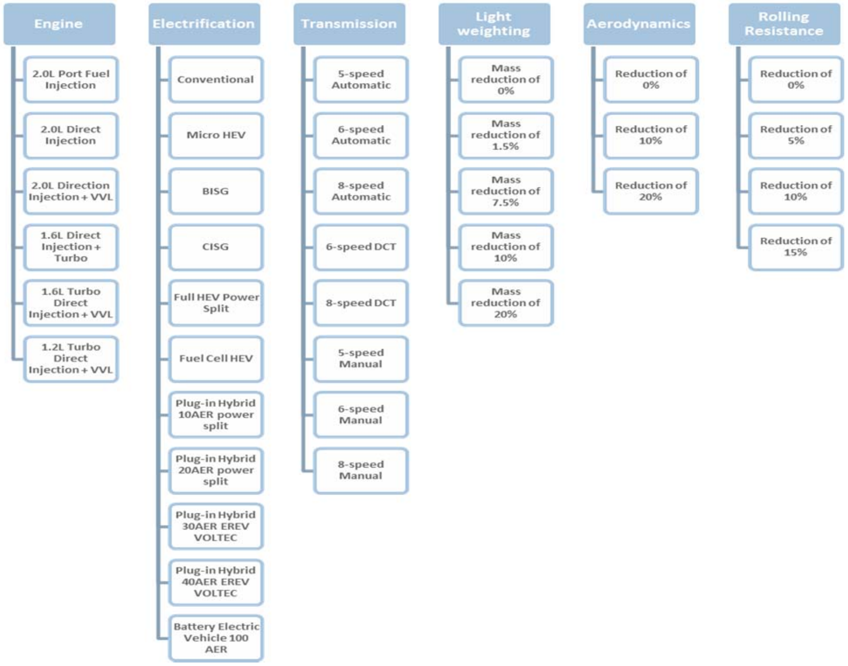
Engine Power (Conv and mild hybrids) [50000 150000] 38

Engine Power (Split HEV) [50000 100000] 70

Vehicle Mass [600 3200] 4

Large Number of Technology Combinations

- The Volpe/CAFE model currently relies on multiple decision trees to represent component technology options, including:
  - Engine
  - Powertrain electrification
  - Transmission
  - Light-weighting
  - Aerodynamics
  - Rolling resistance



Engine	Electrification	Transmission	Light weighting	Aerodynamics	Rolling Resistance
2.0L Port Fuel Injection	Conventional	5-speed Automatic	Mass reduction of 0%	Reduction of 0%	Reduction of 0%
2.0L Direct Injection	Micro HEV	6-speed Automatic	Mass reduction of 1.5%	Reduction of 10%	Reduction of 5%
2.0L Direction Injection + VVL	BISG	8-speed Automatic	Mass reduction of 7.5%	Reduction of 20%	Reduction of 10%
1.6L Direct Injection + Turbo	CISG	6-speed DCT	Mass reduction of 10%		Reduction of 15%
1.6L Turbo Direct Injection + VVL	Full HEV Power Split	8-speed DCT	Mass reduction of 20%		
1.2L Turbo Direct Injection + VVL	Fuel Cell HEV	5-speed Manual			
	Plug-in Hybrid 10AER power split	6-speed Manual			
	Plug-in Hybrid 20AER power split	8-speed Manual			
	Plug-in Hybrid 30AER EREV VOLTEC				
	Plug-in Hybrid 40AER EREV VOLTEC				
	Battery Electric Vehicle 100 AER				

- The objective is to provide an efficient process to perform individual vehicle simulations representing every combination of vehicle class, powertrain, and component technologies.

How Many Technology Combinations?

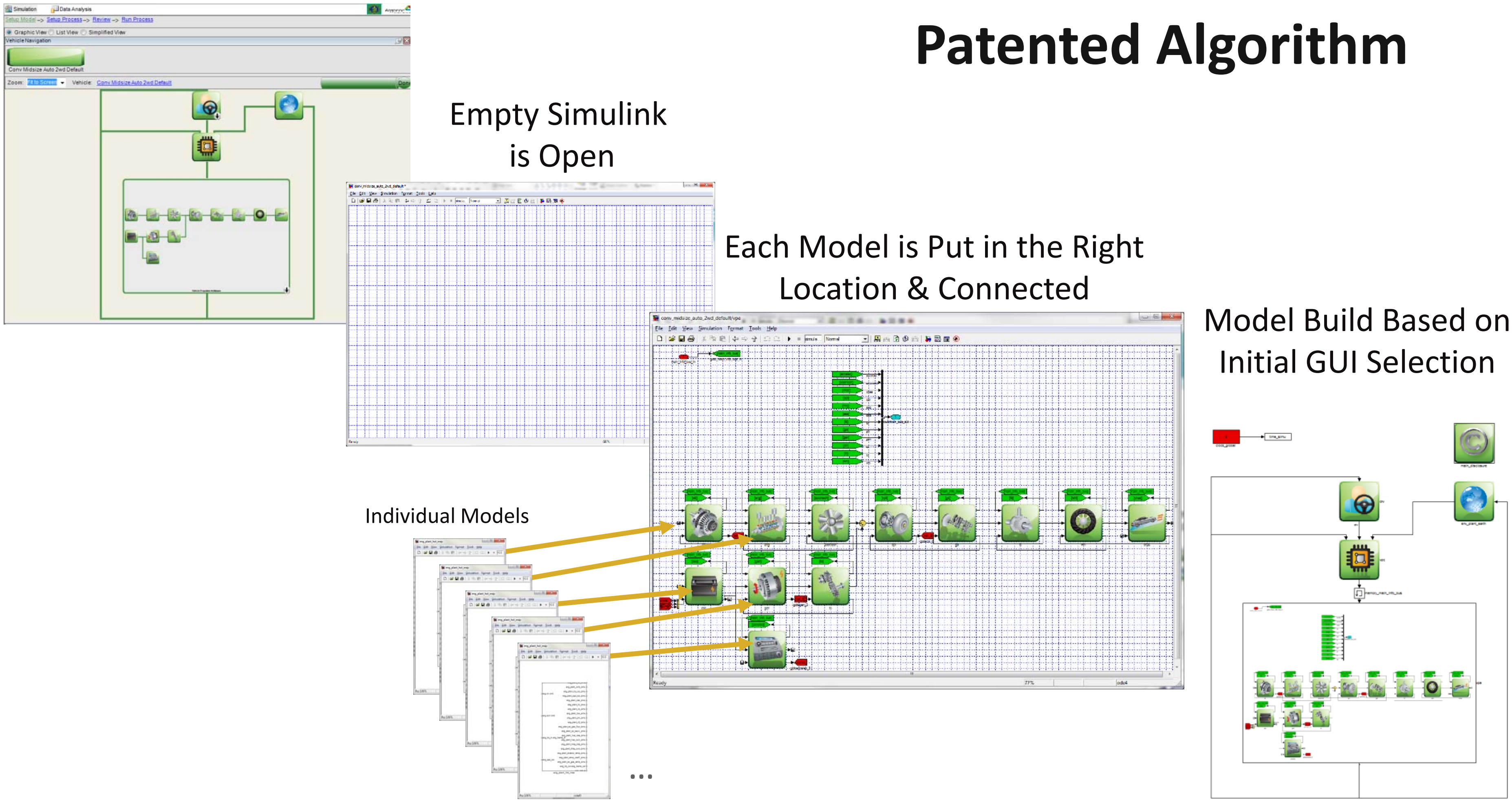
The current list includes:

- 5 vehicle classes (Compact, Midsize, Small SUV, Midsize SUV, Pickup);
- 17 engine technologies;
- 11 electrification levels, comprising 4 levels no- or low-electrification (conventional vehicle is equivalent to no-electrification level) and 7 levels of hybridization;
- 8 transmission technologies (applied to no/low-electrification-level vehicles only);
- 5 light-weighting levels;
- 4 rolling-resistance levels; and
- 3 aerodynamic levels.

> 150,000 vehicle combinations

Complete Models are Built Automatically

Patented Algorithm



User Select Options in GUI

Empty Simulink is Open

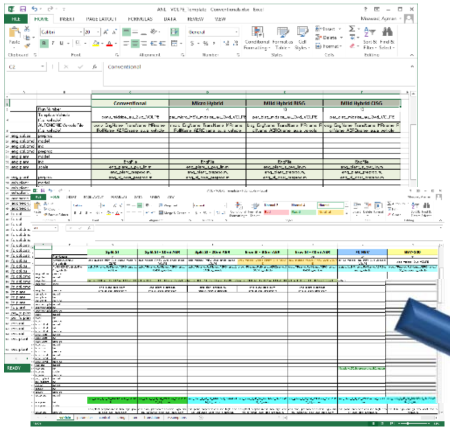
Each Model is Put in the Right Location & Connected

Model Build Based on Initial GUI Selection

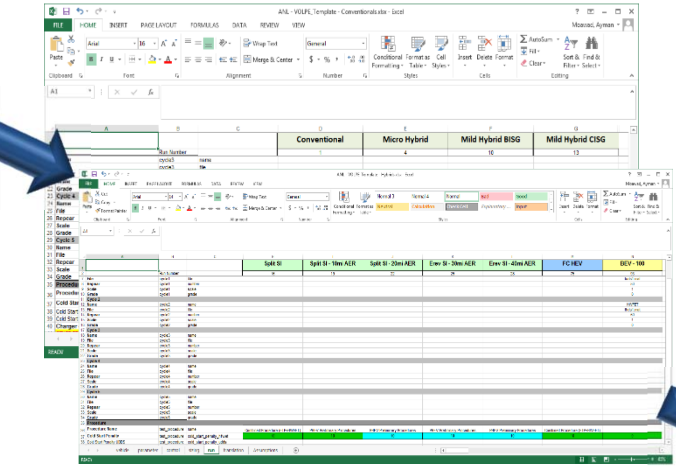
Individual Models

Vehicle Simulation Process (1/2)

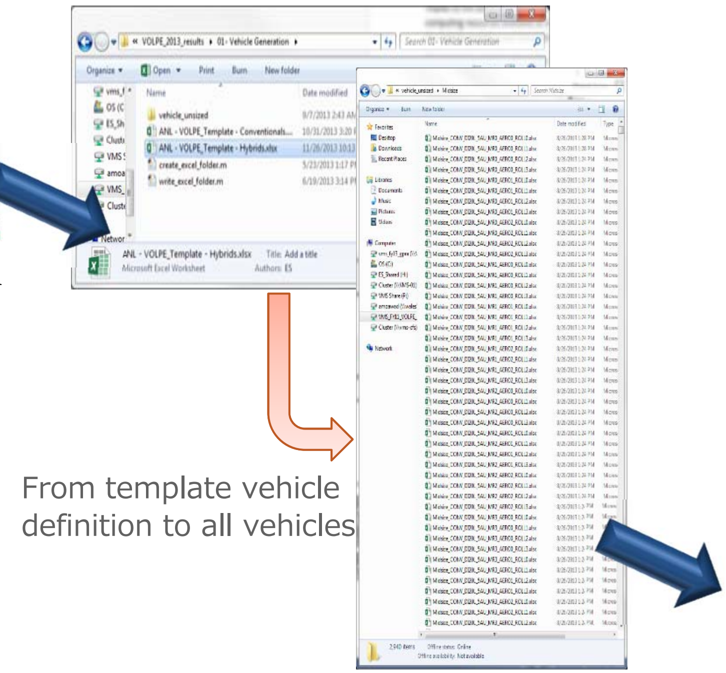
Define Individual Vehicle



Select Driving Cycles



Build Each Vehicle

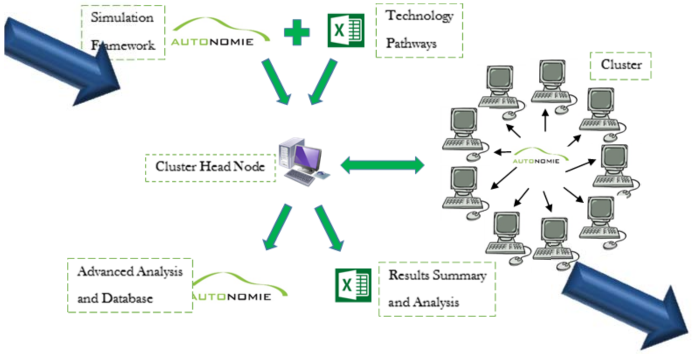


From template vehicle definition to all vehicles

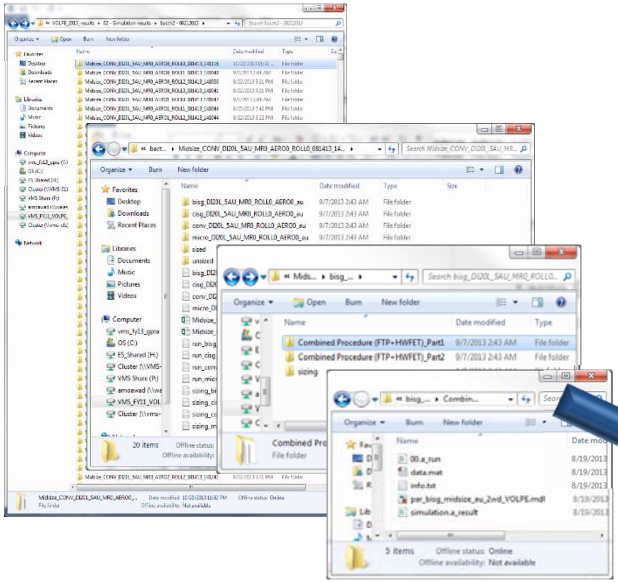
- Define vehicle configurations, component models, initialization files, preprocessing files….
- Define component performance data (e.g., power, mass, final drive ratio, aero, etc…).
- Define control (Force EV mode, engine turn on thresholds, shifting parameters, etc…).
- Select sizing rule to run the vehicle performance test.
- Select drive cycles and standard procedures to be run.

Vehicle Simulation Process (2/2)

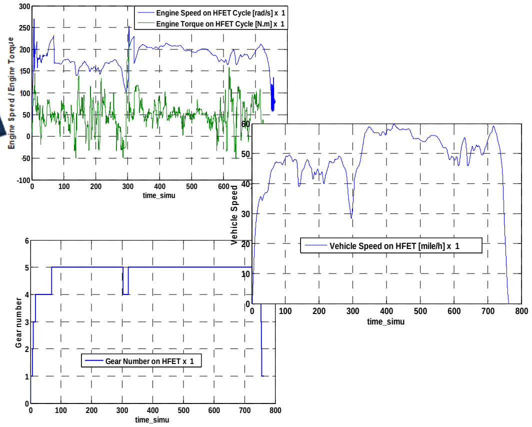
Run Simulations
w/ Distributed Computing



Save All The Results



Perform Individual
Results Analysis



Large Scale Data Set Analysis Challenges

=> Manually analyzing very large number of data sets has proven cumbersome, error prone and time consuming

- Autonomie has numerous post-processing tools, but they focus on individual vehicles analysis
- For large datasets, the requirements are different:
  - Managing lots and lots of data (number of files, disk size, access time, etc.)
  - Looking at high level indicators and spotting overall trends
  - Performing post-processing calculations without rerunning all of the vehicles
- Autonomie’s normal output files are unnecessarily cumbersome for this sort of large scale data manipulation

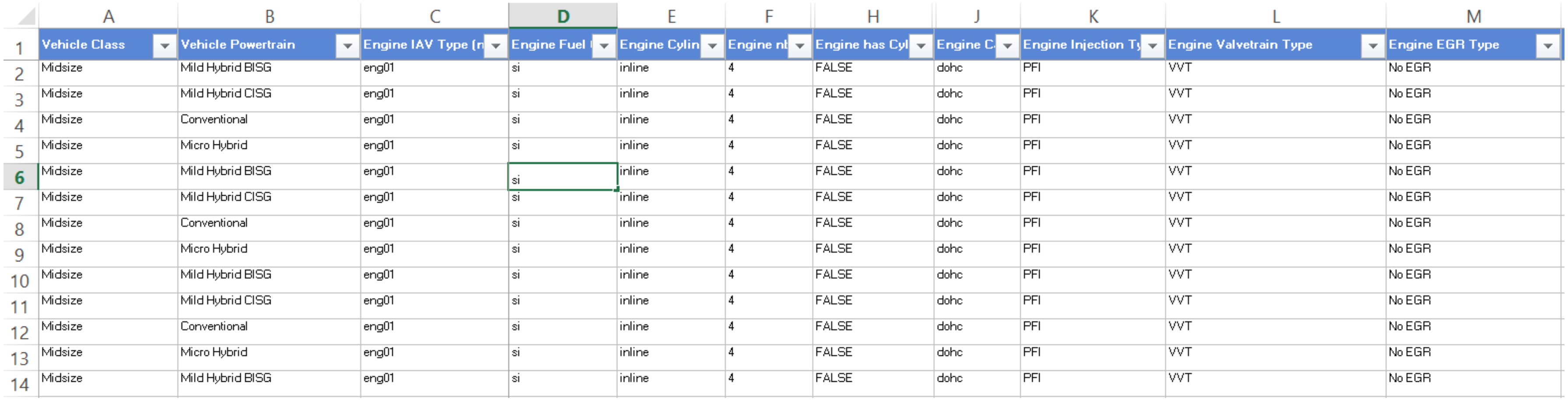
Solution: Leverage Autonomie structure to develop a new post-processing procedure centered around large data set analysis

Database Generation

- A new process was developed to generate a targeted database containing information from a very large number of Autonomie results.
- The inputs are:
  - A folder containing all of the Autonomie result files. Example study (296 GB of data, 7,503 .a_result files).
  - An XML file that lists the parameters to include into the database.
- The output is an optimized database containing only the requested information. Example study (30.4 MB of data, 27 min. to generate database).
- New, targeted databases can be created with any subset of any study.

Database Example

- The database (SQL or XLS) includes a large number of parameters including:
  - Vehicle class, powertrain type…
  - Component information (technology, power, energy, weight..)
  - Main results (fuel and electrical consumption…)



	A	B	C	D	E	F	H	J	K	L	M
1	Vehicle Class	Vehicle Powertrain	Engine IAV Type (n	Engine Fuel	Engine Cylin	Engine nb	Engine has Cyl	Engine C	Engine Injection Ty	Engine Valvetrain Type	Engine EGR Type
2	Midsize	Mild Hybrid BISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
3	Midsize	Mild Hybrid CISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
4	Midsize	Conventional	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
5	Midsize	Micro Hybrid	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
6	Midsize	Mild Hybrid BISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
7	Midsize	Mild Hybrid CISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
8	Midsize	Conventional	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
9	Midsize	Micro Hybrid	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
10	Midsize	Mild Hybrid BISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
11	Midsize	Mild Hybrid CISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
12	Midsize	Conventional	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
13	Midsize	Micro Hybrid	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR
14	Midsize	Mild Hybrid BISG	eng01	si	inline	4	FALSE	dohc	PFI	VVT	No EGR

- A data dictionary will also be provided

Database Analysis (1/2)

SQL Database Created Based on Selected List of Parameters

INPUT

- Vehicle Name
- Vehicle Class
- Mass Reduction
- Electric Range
- Rolling Resistance
- Aerodynamics
- Powertrain Type
- Engine Type
- Transmission Type
- Fuel Type
- Battery Type

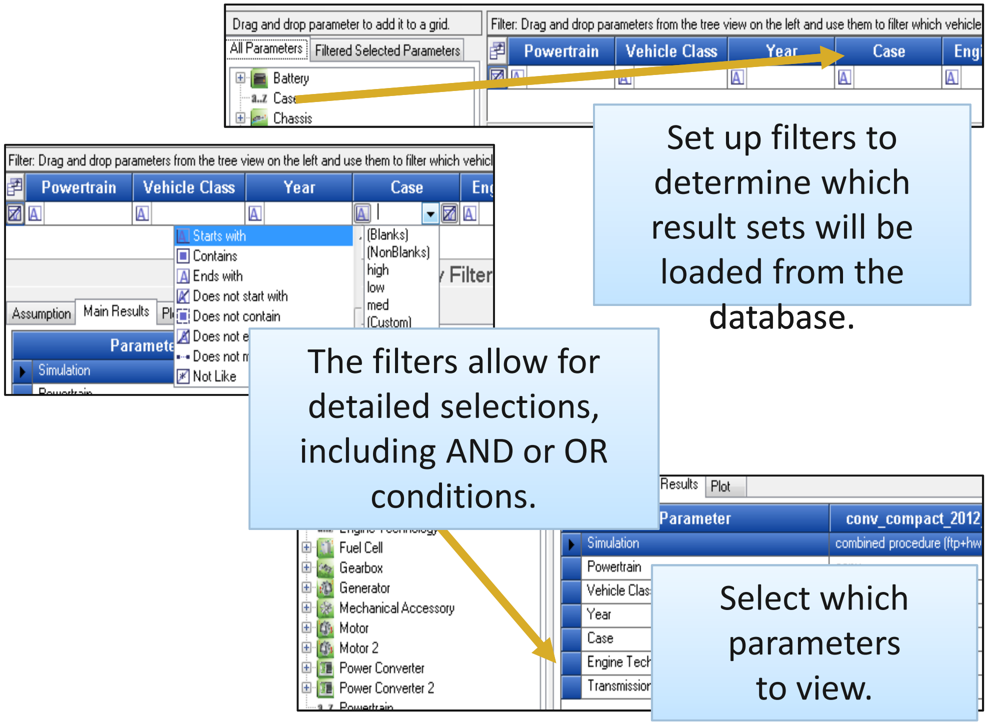
OUTPUT

- Engine Power
- Fuel Cell Power
- Motor 1 Power
- Motor 2 Power
- Battery Usable Energy
- Vehicle Mass
- FTP Fuel Consumption
- FTP Electrical Consumption
- HFET Fuel Consumption
- HFET Electrical Consumtpion
- Combined Fuel Consumption
- Combined Electrical Consumption

AUTONOMIE PROCESS

Database Analysis (2/2)

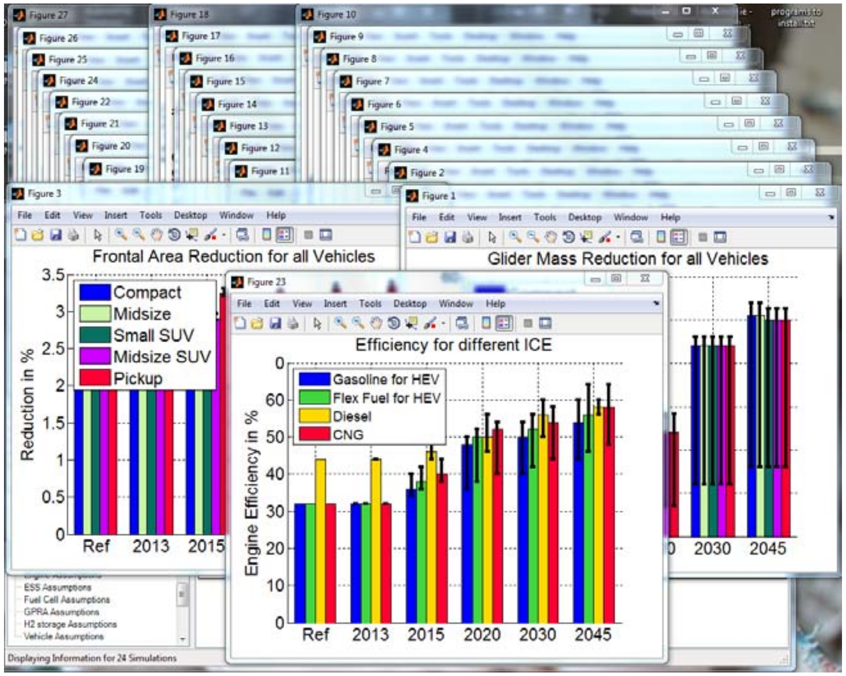
Graphical User Interface Created to Check Simulation Results



Set up filters to determine which result sets will be loaded from the database.

The filters allow for detailed selections, including AND or OR conditions.

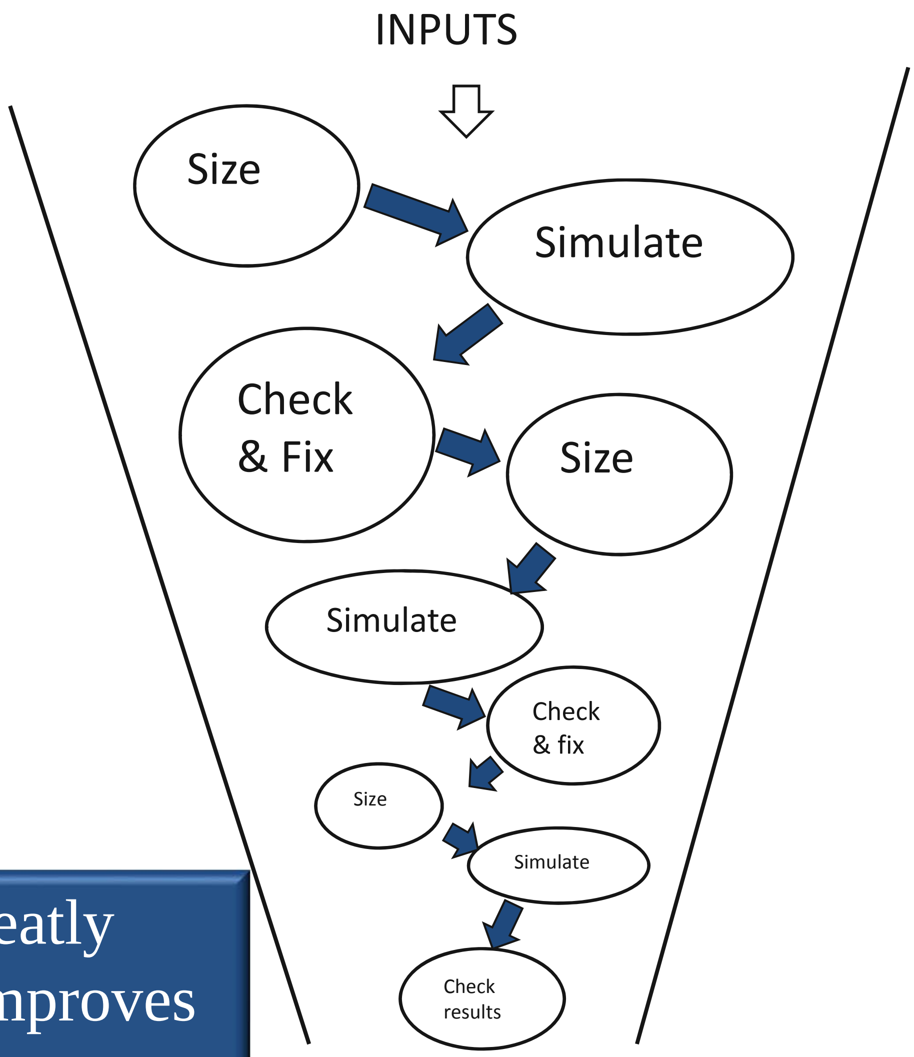
Select which parameters to view.



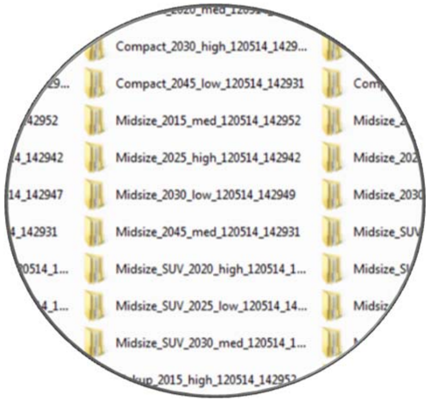
Automated Checking Process

- Hundreds of thousands of vehicles are simulated
- Due to the large number of results, this could lead to
  - Increased number of iterations.
  - Erroneous results propagating to further steps of the study.
  - Delays in generating results.

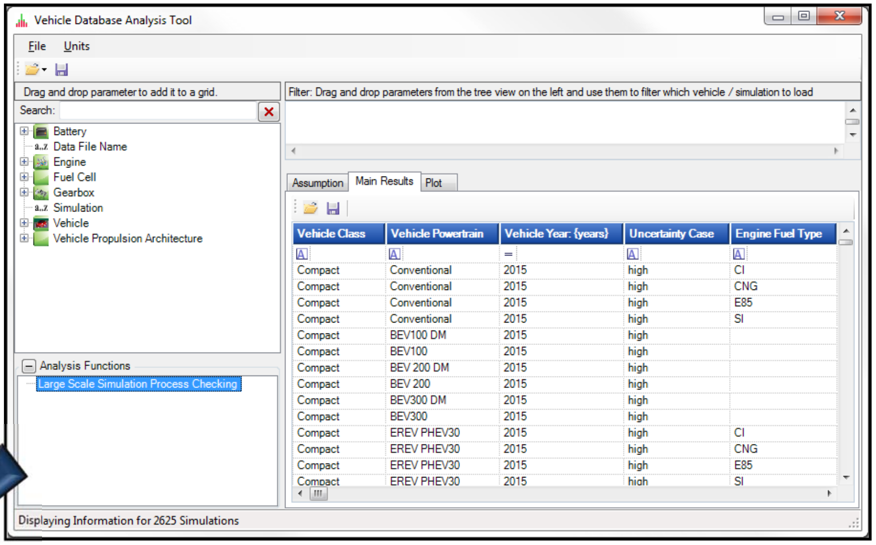
Automated checking process greatly reduces simulation iterations and improves quality of results.



Automated Checking Leverages Database Generation Process Used for Large Scale Simulation

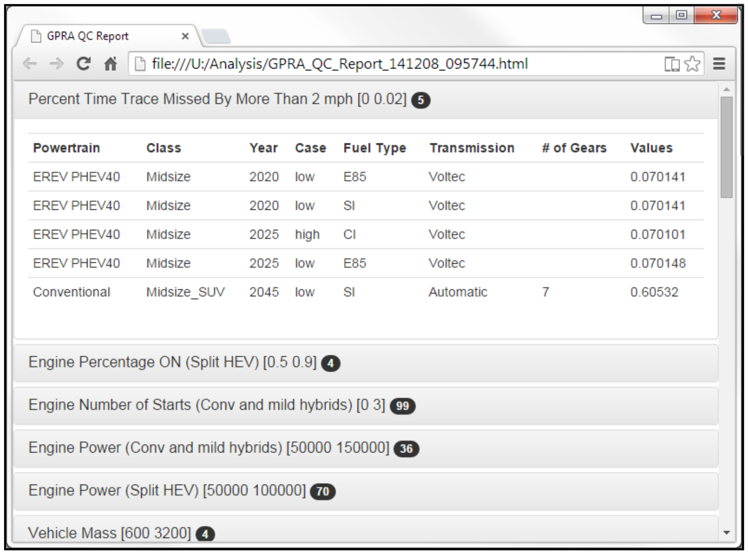


Compact_2030_high_120514_1429...
Compact_2045_low_120514_142931
Midsize_2015_med_120514_142952
Midsize_2025_high_120514_142942
Midsize_2030_low_120514_142949
Midsize_2045_med_120514_142931
Midsize_SUV_2020_high_120514_1...
Midsize_SUV_2025_low_120514_14...
Midsize_SUV_2030_med_120514_1...



Vehicle Class	Vehicle Powertrain	Vehicle Year: {years}	Uncertainty Case	Engine Fuel Type
Compact	Conventional	2015	high	CI
Compact	Conventional	2015	high	CNG
Compact	Conventional	2015	high	E85
Compact	Conventional	2015	high	SI
Compact	BEV100 DM	2015	high	
Compact	BEV100	2015	high	
Compact	BEV 200 DM	2015	high	
Compact	BEV 200	2015	high	
Compact	BEV300 DM	2015	high	
Compact	BEV300	2015	high	
Compact	EREV PHEV30	2015	high	CI
Compact	EREV PHEV30	2015	high	CNG
Compact	EREV PHEV30	2015	high	E85
Compact	EREV PHEV30	2015	high	SI

Displaying Information for 2625 Simulations



file:///U:/Analysis/GPRA_QC_Report_141208_095744.html

Percent Time Trace Missed By More Than 2 mph [0 0.02] 5

Powertrain	Class	Year	Case	Fuel Type	Transmission	# of Gears	Values
EREV PHEV40	Midsize	2020	low	E85	Voltec		0.070141
EREV PHEV40	Midsize	2020	low	SI	Voltec		0.070141
EREV PHEV40	Midsize	2025	high	CI	Voltec		0.070101
EREV PHEV40	Midsize	2025	low	E85	Voltec		0.070148
Conventional	Midsize_SUV	2045	low	SI	Automatic	7	0.60532

Engine Percentage ON (Split HEV) [0.5 0.9] 4

Engine Number of Starts (Conv and mild hybrids) [0 3] 99

Engine Power (Conv and mild hybrids) [50000 150000] 36

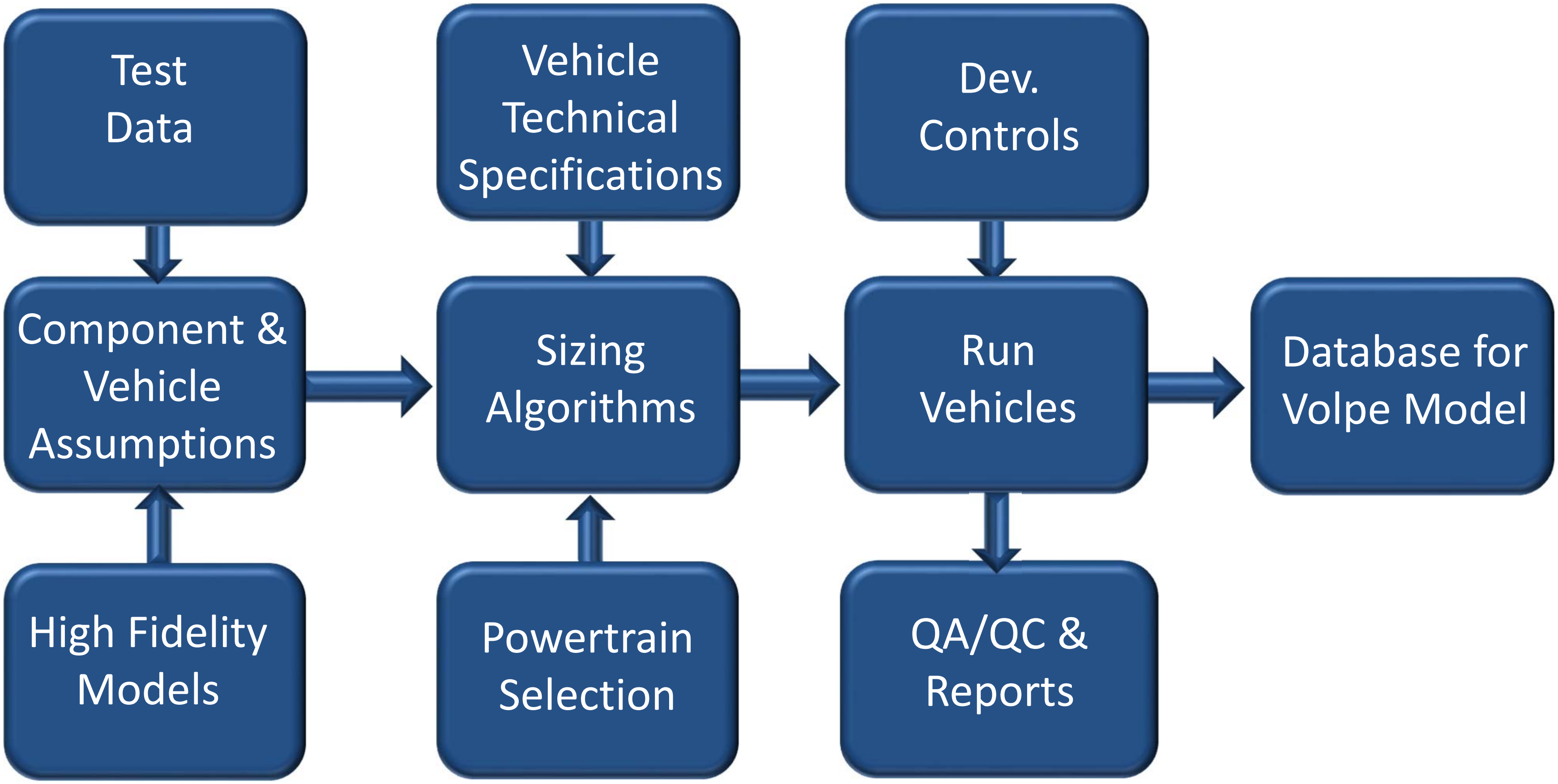
Engine Power (Split HEV) [50000 100000] 70

Vehicle Mass [600 3200] 4

- Fields of interest are extracted from simulation results and imported into the database.
- An Interactive HTML report is generated listing the results that need to be examined.

Conclusion

Final Process Overview



Test Data

Vehicle Technical Specifications

Dev. Controls

Component & Vehicle Assumptions

Sizing Algorithms

Run Vehicles

Database for Volpe Model

High Fidelity Models

Powertrain Selection

QA/QC & Reports

Process Advantages

- Full vehicle simulations used directly as inputs to the Volpe/CAFE model.
- All vehicles have performance comparable to the baseline vehicle.
- Order of technology applications does not matter since all combinations are simulated.
- Provides detailed information for every vehicle to calculate cost (technology, power, energy, weight…).

Outline

- Autonomie Overview
- Model Development and Validation
- Process to Estimate Technologies Effectiveness with Full Vehicle Simulation
- Vehicle Powertrain Sizing Algorithms and Validation
- Vehicle Simulation Results Quality Check Process

Vehicle Technical Specifications (VTS)

- Initial Vehicle Movement – 60 mph at least 9 sec (+/- 0.1 sec)
- Minimum grade of 6% at 65 mph at GVW (engine / fuel cell only)
- Maximum vehicle speed >= 100 mph
- Max grade launch from a stop forward and reverse >= 30%

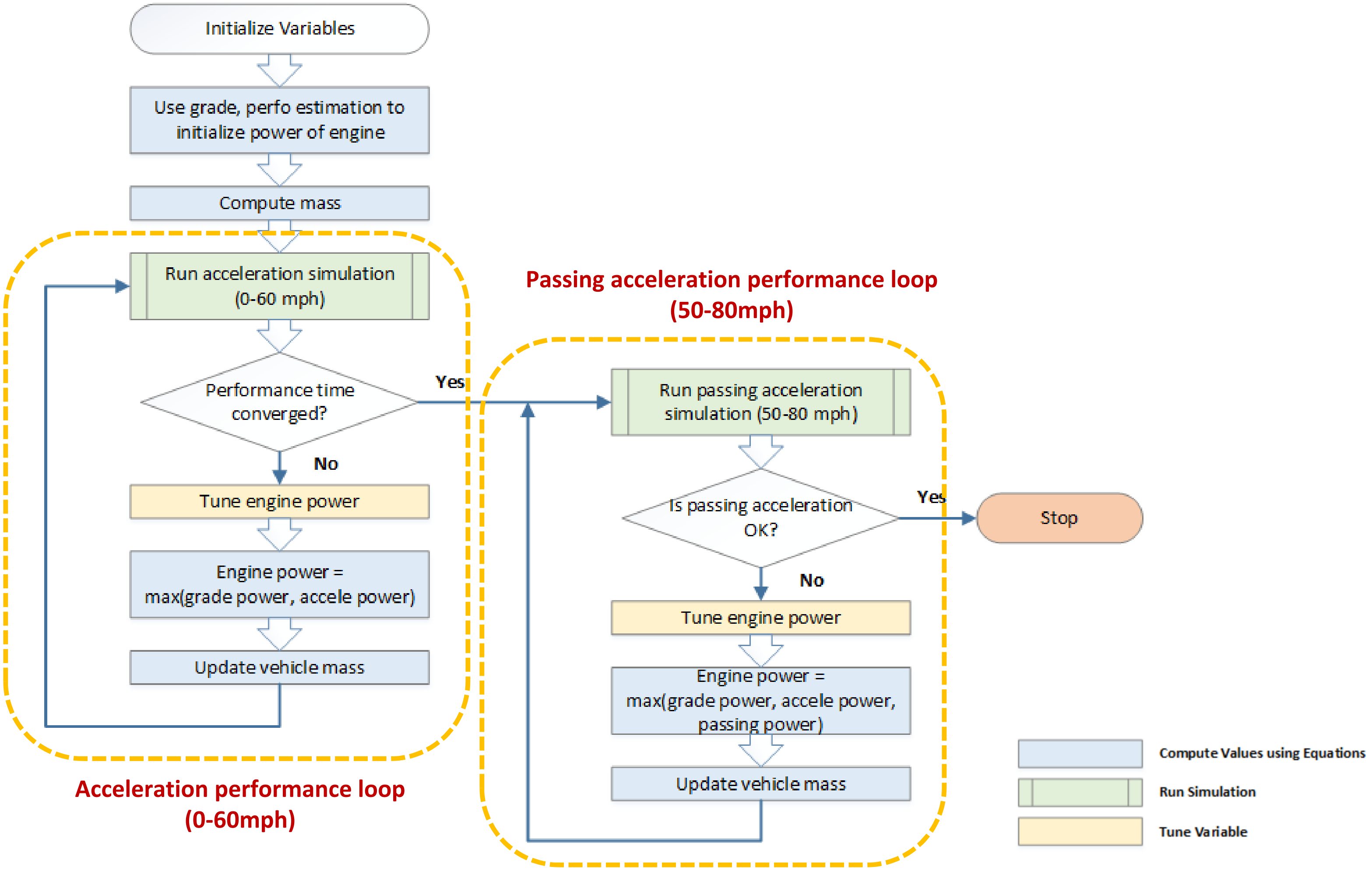
=> Automated sizing algorithms used to ensure that simulations results for multiple technologies are comparable

Overall Sizing Philosophies

- Engine/fuel cell sized to meet 70% of peak power required to meet Vehicle Technical Specifications (VTS)
- HEV
  - Battery power sized to recuperate 100% energy on UDDS
  - Electric machine power sized to meet performance
- Low Energy PHEVs (blended)
  - Battery energy sized to meet All Electric Range (AER) on UDDS based on unadjusted values
  - Electric machine & battery power sized to be able to follow the UDDS in electric vehicle (EV) mode across entire charge depleting range (CD)
- High Energy PHEVs (extended range)
  - Battery energy sized to meet AER on UDDS based on unadjusted values
  - Electric machine & battery power sized to be able to follow the US06 in EV mode across entire charge depleting range (CD)
- BEV
  - Battery energy sized to meet range on UDDS based on unadjusted value

Automated Sizing Algorithm

Conventional Vehicle Example



Initialize Variables

Use grade, perfo estimation to initialize power of engine

Compute mass

Run acceleration simulation (0-60 mph)

Performance time converged?

Yes

No

Tune engine power

Engine power = max(grade power, accele power)

Update vehicle mass

Acceleration performance loop (0-60mph)

Passing acceleration performance loop (50-80mph)

Run passing acceleration simulation (50-80 mph)

Is passing acceleration OK?

Yes

Stop

No

Tune engine power

Engine power = max(grade power, accele power, passing power)

Update vehicle mass

🟦 Compute Values using Equations

🟩 Run Simulation

🟨 Tune Variable

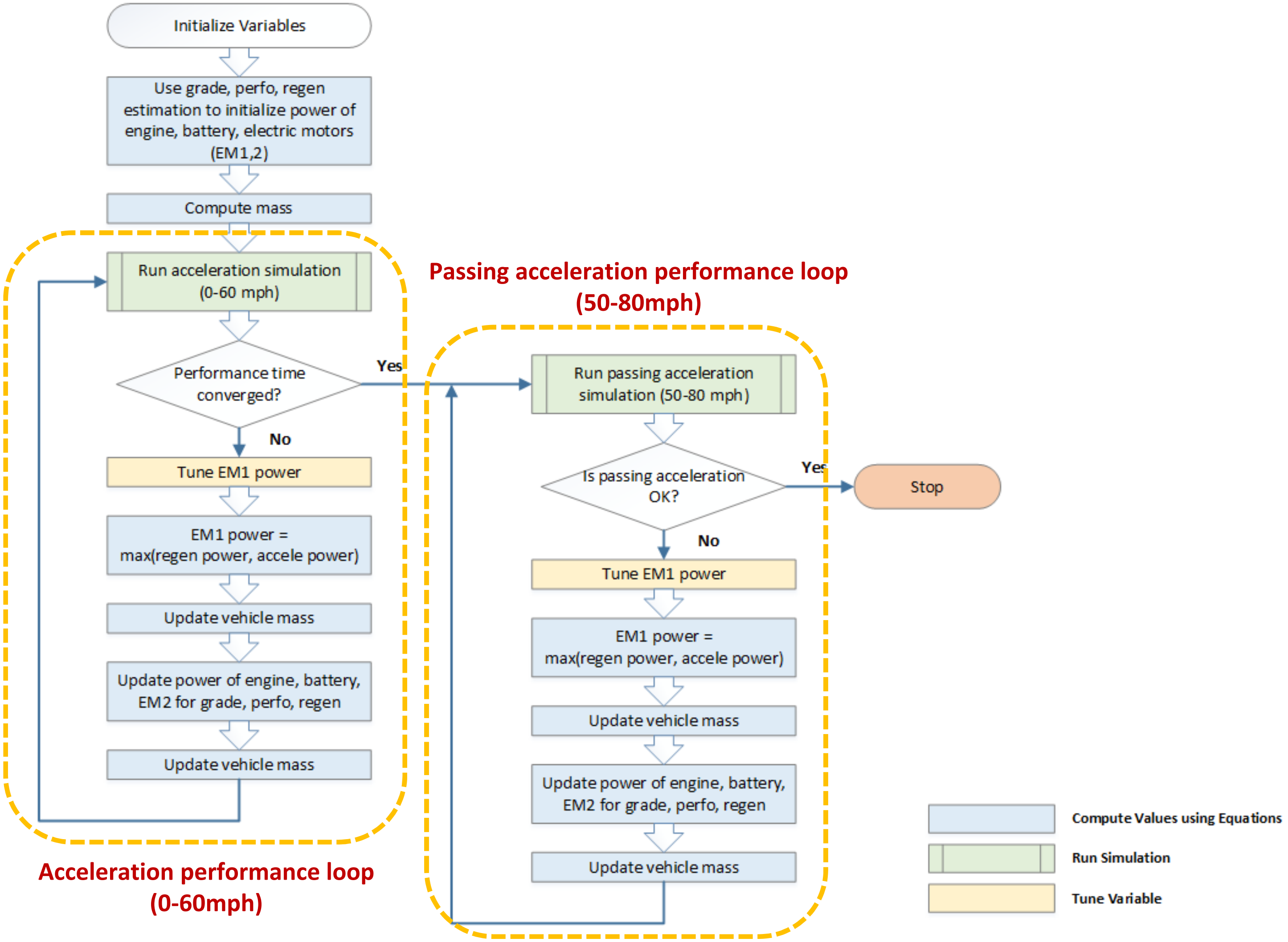
Automated Sizing Algorithm

Power Split HEV Example

- Main algorithm philosophy
  - Engine sized to meet 70% of peak power required to meet VTS (acceleration performance or grade): engine peak power is a function of the vehicle weight.
  - Battery power sized to recuperate 100% energy on UDDS: battery cell number is function of the vehicle weight.
  - Electric machine (EM1) power sized to recuperate 100% energy on UDDS or to meet the requirement of acceleration performance.
  - Electric machine (EM2) sized as followed:
    1) Start ICE at Vmax (~57mph for UDDS) ICE should be ON (i.e., EM2 peak power for engine start at top speed on UDDS cycle)
    2) Control maximum power of engine at Vspd=0 (i.e., EM2 peak power for engine control on performance)
    3) Control ICE at max grade (i.e. EM2 continuous power for engine control on grade, engine power fraction going through electro-mechanical power path)

Automated Sizing Algorithm

Power Split HEV Example



Initialize Variables

Use grade, perfo, regen estimation to initialize power of engine, battery, electric motors (EM1,2)

Compute mass

Run acceleration simulation (0-60 mph)

Performance time converged?

Yes

No

Tune EM1 power

EM1 power = max(regen power, accele power)

Update vehicle mass

Update power of engine, battery, EM2 for grade, perfo, regen

Update vehicle mass

Acceleration performance loop (0-60mph)

Passing acceleration performance loop (50-80mph)

Run passing acceleration simulation (50-80 mph)

Is passing acceleration OK?

Yes

Stop

No

Tune EM1 power

EM1 power = max(regen power, accele power)

Update vehicle mass

Update power of engine, battery, EM2 for grade, perfo, regen

Update vehicle mass

🟦 Compute Values using Equations

🟩 Run Simulation

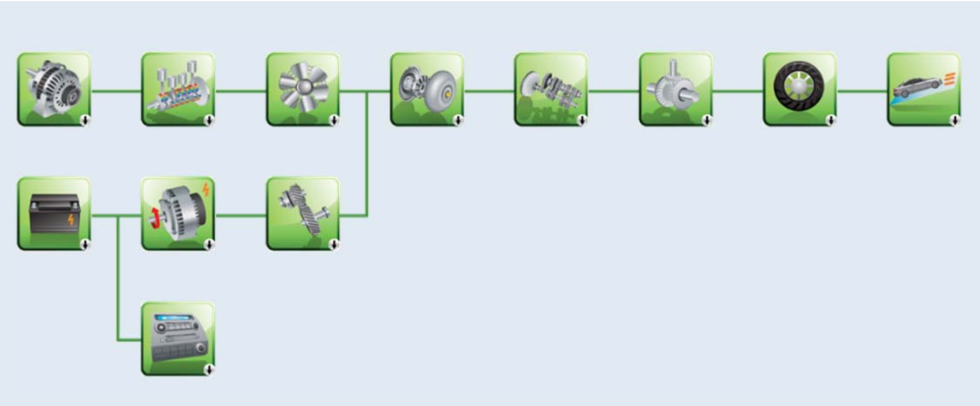
🟨 Tune Variable

Vehicle Sizing Algorithm Validation

Conventional Vehicle Example

- Conv. auto trans 2wd vehicle : Hyundai Sonata 6 ATX MY2013

Conventional Sonata 6 ATX

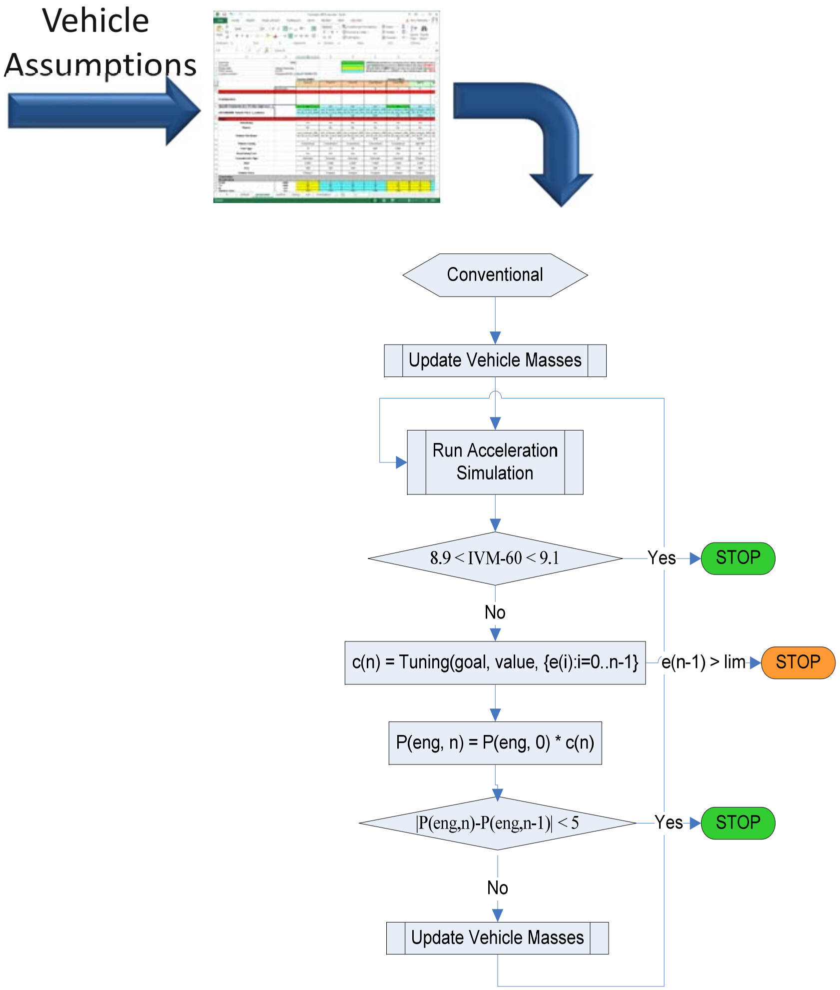


Spec.

Gear ratio	Final drive	Wheel radius
4.21, 2.64, 1.80, 1.39, 1.00 0.77	2.89	0.3218 m
Drag coefficient	Front area	0-60 mph
0.32 *	2.18 m^2 *	7.9 sec **

* http://ecomodder.com/wiki/index.php/Vehicle_Coefficient_of_Drag_List

** https://en.wikipedia.org/wiki/Hyundai_Sonata



Vehicle Assumptions

Conventional

Update Vehicle Masses

Run Acceleration Simulation

8.9 < IVM-60 < 9.1

Yes

STOP

No

c(n) = Tuning(goal, value, {e(i):i=0..n-1})

e(n-1) > lim

STOP

P(eng, n) = P(eng, 0) * c(n)

|P(eng,n)-P(eng,n-1)| < 5

Yes

STOP

No

Update Vehicle Masses

Vehicle Sizing Algorithm Validation

Conventional Vehicle Example

- Sizing comparison results for conv. auto trans 2wd vehicle

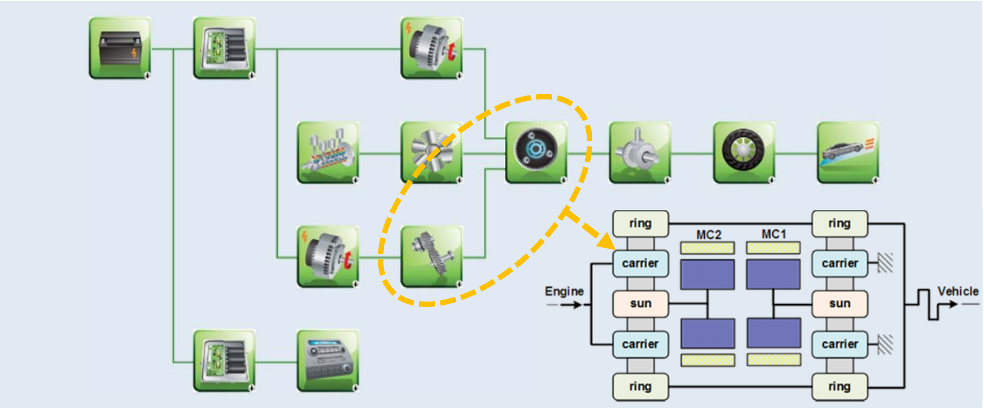
	OEM Source : Hyundai Sonata 6 ATX MY2013	Sizing results from Autonomie	Comparison
Vehicle weight	1588 kg	1593 kg	0.3 %
Engine Power	154 kW	144 kW	-6.4 %
Acceleration Performance: 0-60 mph	7.90 sec	7.89 sec	-
- Baseline vehicle specification : Hyundai Sonata 6 ATX MY2013 - Sizing results from the same acceleration constraint - Individual component performance data not available (estimated)			

Vehicle Sizing Algorithm Validation

Power Split HEV Example

- Split HEV 2wd vehicle : Toyota Prius HEV MY2010

Toyota Prius HEV MY2010

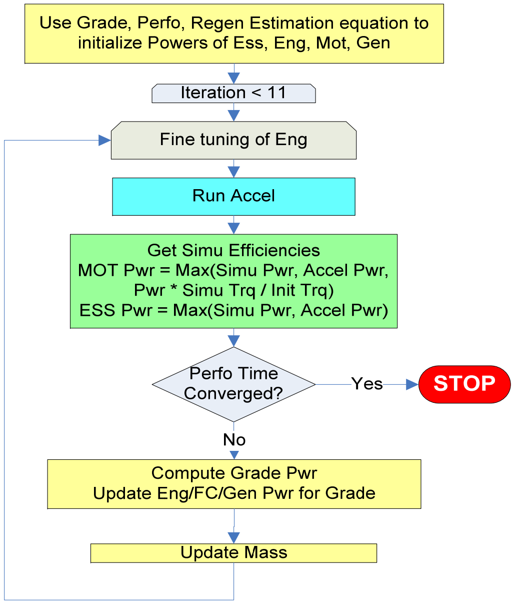


Spec.

Gear ratio	Final drive	Wheel radius
RG1/SG1 = 2.6, RG2/SG2 = 2.64	3.268	0.317 m
Drag coefficient	**Front area**	**0-60 mph**
0.25 *	2.25 m^2 *	9.7 sec **

* http://ecomodder.com/wiki/index.php/Vehicle_Coefficient_of_Drag_List
** http://www.zeroto60times.com/vehicle-make/toyota-0-60-mph-times/

Vehicle Assumptions



Use Grade, Perfo, Regen Estimation equation to initialize Powers of Ess, Eng, Mot, Gen

Iteration < 11

Fine tuning of Eng

Run Accel

Get Simu Efficiencies
MOT Pwr = Max(Simu Pwr, Accel Pwr, Pwr * Simu Trq / Init Trq)
ESS Pwr = Max(Simu Pwr, Accel Pwr)

Perfo Time Converged?

Compute Grade Pwr
Update Eng/FC/Gen Pwr for Grade

Update Mass

Run Simulation
Tune Variable
Update Values using Simulation Results
Update Values using Equation

Vehicle Sizing Algorithm Validation

Power Split HEV Example

- Here is the sizing comparison results for Split HEV 2wd vehicle

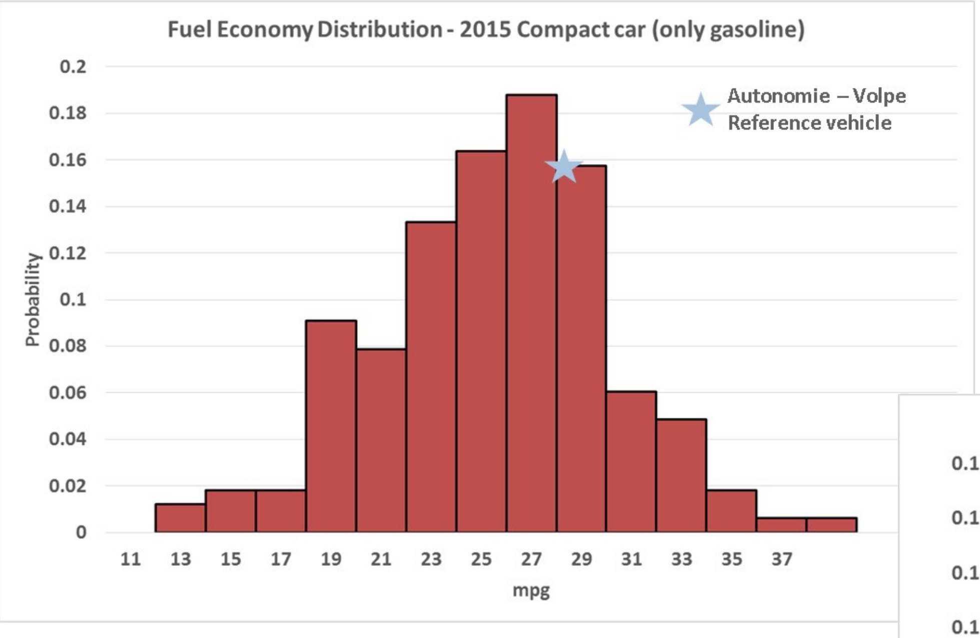
	OEM Source : Toyota Prius HEV MY2010	Sizing results form Autonomie
Vehicle weight	1530 kg	1463 kg
Engine Power	73 kW	75 kW
Motor1 Power	60 kW	66 kW
Motor2 Power	40 kW	43 kW
Battery Power	27 kW	36 kW
Acceleration Performance: 0-60 mph	9.7 sec	9.74 sec

- Baseline vehicle specification : Toyota Prius HEV MY2010
- Specific power for electric motor and battery is from DOE assumptions
- Individual component performance data not available (estimated)

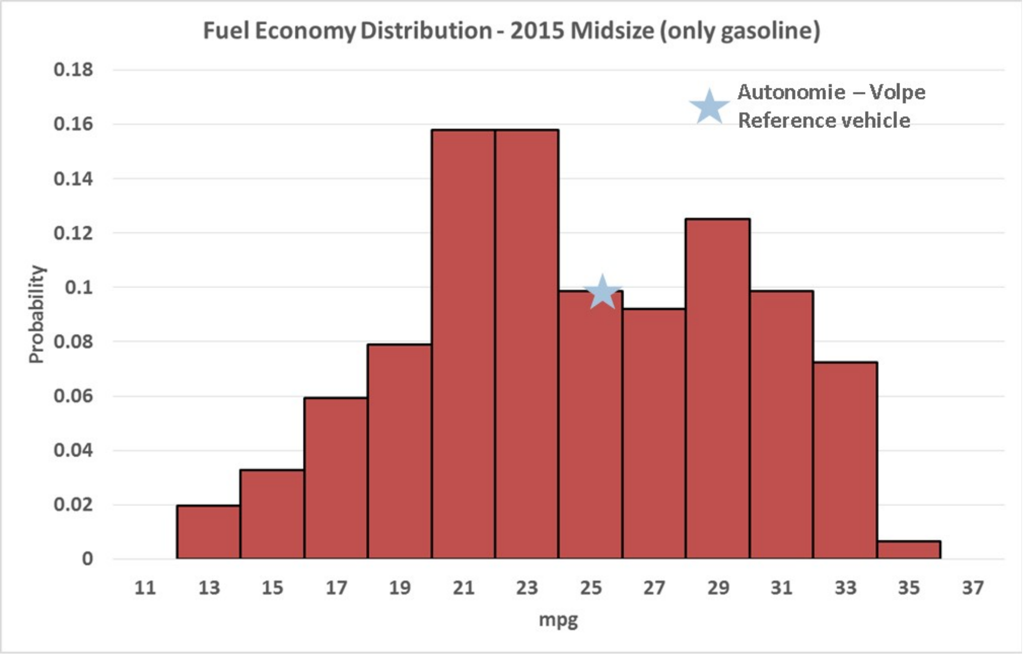
Outline

- Autonomie Overview
- Model Development and Validation
- Process to Estimate Technologies Effectiveness with Full Vehicle Simulation
- Vehicle Powertrain Sizing Algorithms and Validation
- Vehicle Simulation Results Quality Check Process

Reference Vehicle Energy Consumption Compared to Today's Vehicles



Compact Car

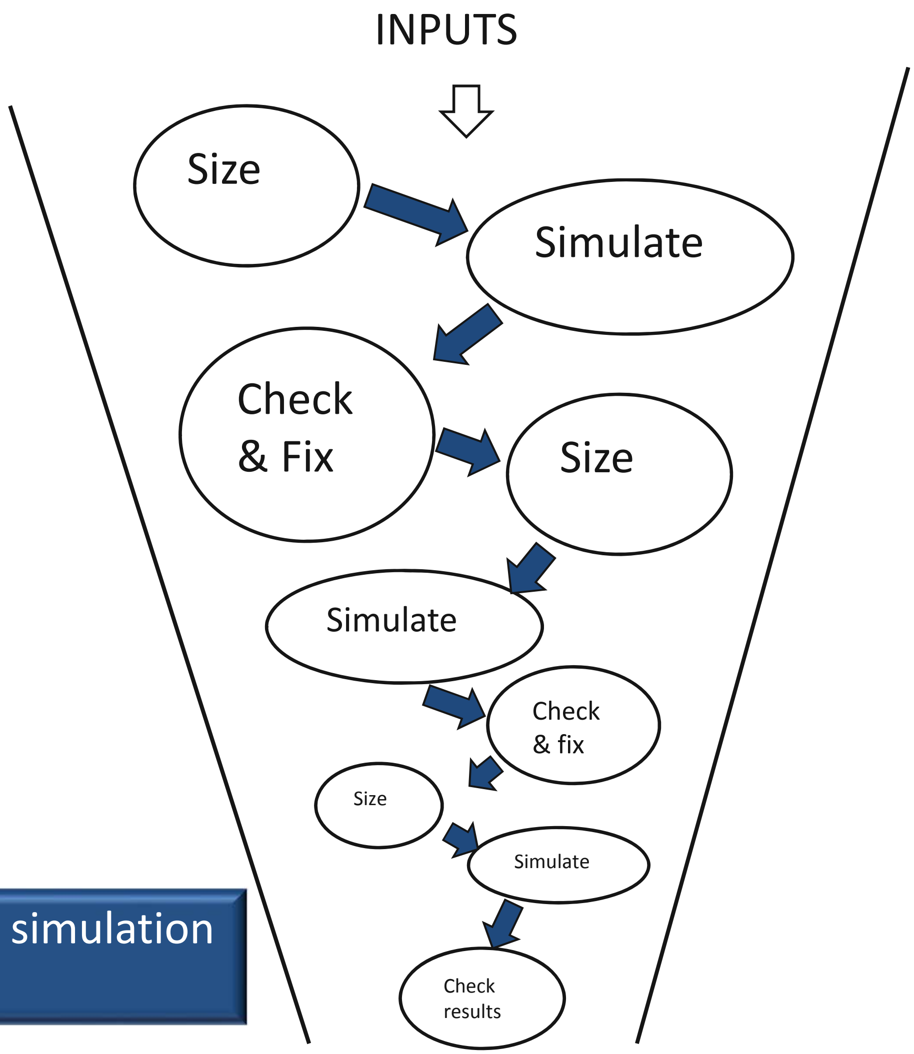


Midsize Car

Vehicle Results QA/QC Motivation

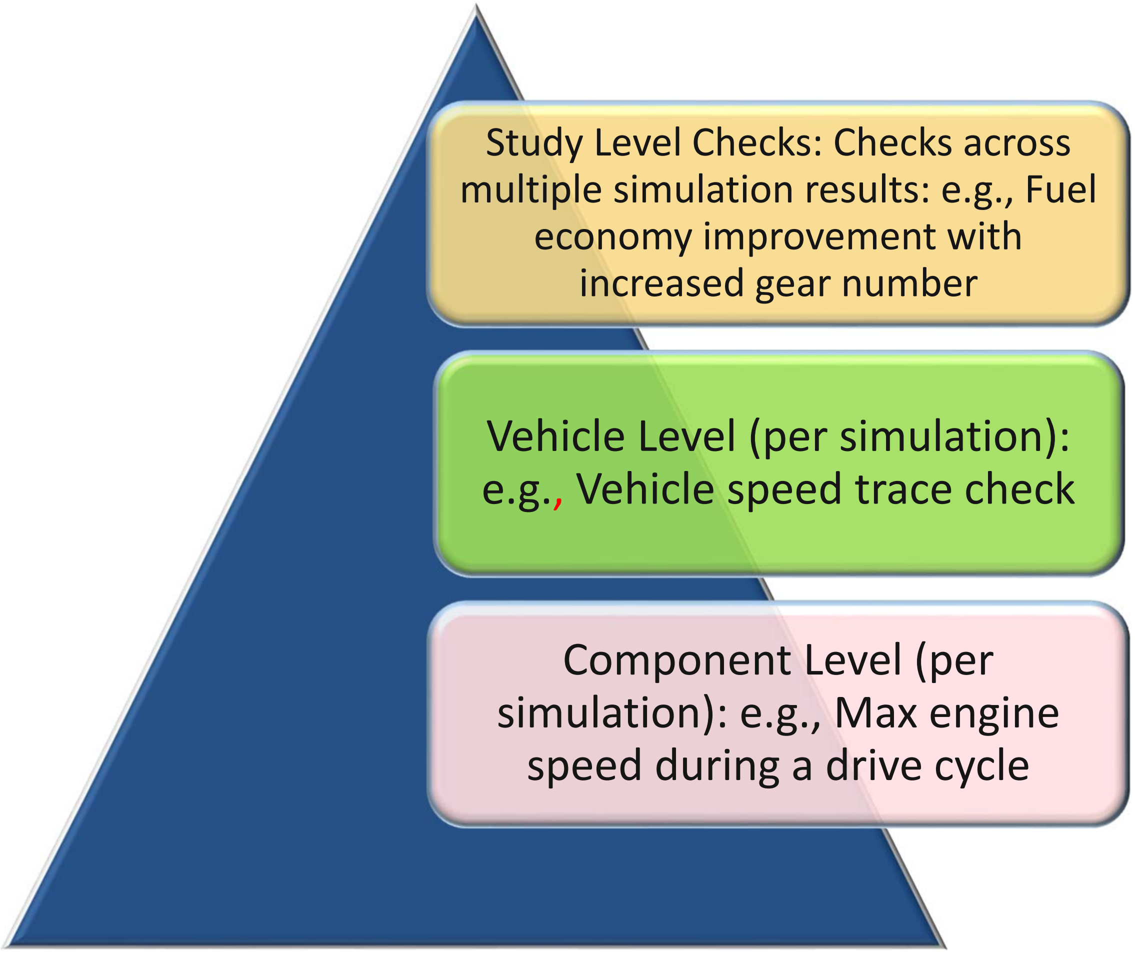
- Hundreds of thousands of vehicles are simulated

- Due to the large number of results, this could result in:
  1. Increased number of iterations.
  2. Erroneous results propagating to further steps of the study.
  3. Delays in generating results.



Automated checking process can greatly reduce simulation iterations and improve quality of results.

Three Levels of Checks Performed on Simulation Results



Study Level Checks: Checks across multiple simulation results: e.g., Fuel economy improvement with increased gear number

Vehicle Level (per simulation): e.g., Vehicle speed trace check

Component Level (per simulation): e.g., Max engine speed during a drive cycle

Multiple Sources of Data Used to Generate Limits or Performance Quotients for the Checks.

Vehicle Test Data

- Compare simulation results against chassis dynamometer benchmarking of state of the art vehicles and vehicle specifications
- Example check: Number of shifts of a 6 speed automatic for a conventional midsize car on the UDDS cycle.

Peer Reviewed Publications and Reports

- Compare trends from simulation results against trends predicted in peer reviewed publications and Journals (e.g. assessment of fuel economy technologies for light-duty vehicles, National Academy of Science).
- Example check: Fuel economy ratio between diesel and gasoline technology (~1.2).

Engineering Judgement

- Fuel consumption should decrease when advanced technologies are introduced
- Example Check: With increase transmission gear number, fuel consumption should decrease.

Sample QA/QC Checks for Vehicles with Engines

Check	Drive Cycle on which check is performed	Component/Vehicle/Powertrain	Source of Reference Data
Max Engine Speed should be lower than XX.	UDDS (part of 2 cycle procedure)	Engine, Conventional and Start-Stop Vehicle.	Chassis dyno test data for each vehicle class, fuel type.
Average Engine Efficiency	UDDS (part of 2 cycle procedure)	Engine – SI , Conventional, and Charge Sustaining Hybrid Vehicle (power split) for Baseline Simulation Case.	Chassis dyno test data for each powertrain type (conventional , power split) .
Ratio of gasoline to diesel fuel economy	2 cycle procedure.	Engine SI and DI, Conventional Powertrain.	EPA fuel economy report for current technology, peer reviewed reports.

Color Code – Red: Component Checks, Green: Vehicle checks, Yellow: Checks across multiple simulations.

Sample QA/QC Checks for Simulations with Engines

Check	Drive Cycle on which check is performed	Component/Vehicle/Powertrain	Source of Reference Data
Engine HP/Vehicle weight	Sizing Process in Autonomie	Engine, Conventional and Start-Stop Vehicle , for each vehicle class.	EPA Vehicle Fuel Economy Trends Report.
Average Efficiency Relative Check (e.g. diesel average efficiency greater than gasoline)	Performed on database of results	Engine, Conventional and Start-Stop Vehicles for a given vehicle class.	
Check of trends across engine technologies: engine efficiency, vehicle fuel economy, peak engine power.	Performed on database of results	Comparison across same class and powertrain type (e.g. conventional SI, compact class) across different engine technologies.	Engineering judgement.

Color Code – Red: Component Checks, Green: Vehicle checks, Yellow: Checks across multiple simulations.

Sample QA/QC Checks for Simulations with Batteries

Check	Drive Cycle on which check is performed	Component/Vehicle/Powertrain	Source of Reference Data
Ratio of battery energy to vehicle mass	Sizing Process	BEV 100, 200, 300.	Specifications for vehicles in the market today.
% Regen Energy recovered at the battery	UDDS cycle	HEV, PHEVs in charge sustaining mode.	Chassis dyno test data for each powertrain type.
BEV range check	SAE J1634 procedure.	BEV 100, 200, 300, any vehicle class.	Engineering Judgement – Actual range should be close to target range.

Color Code – Red: Component Checks, Green: Vehicle checks, Yellow: Checks across multiple simulations.

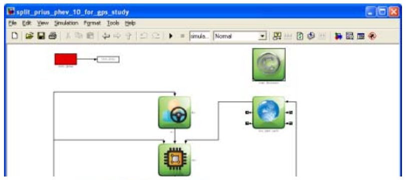
Checks have been Similarly Generated for Additional Powertrain Components/Systems

- Transmissions
- Fuel Cell, Hydrogen Tanks and Fuel Cell Vehicles
- PEEM (Power Electronics and Electrical Machines)
- Checks common to all vehicle types: Example Vehicle Speed band check.

Sample List of Checks

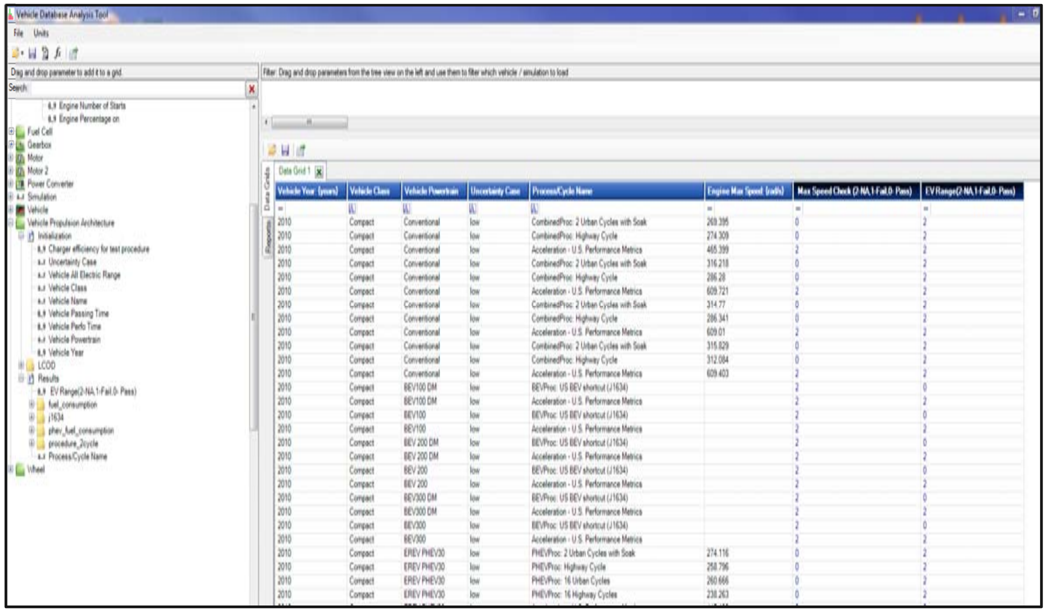
- Trace
- Vehicle Weight
- Engine Percentage ON
- Engine Number of Starts
- Engine/Fuel Cell Average Efficiency
- Engine/Fuel Cell Power
- Engine Speed
- Motor Average Efficiency
- Motor Power
- Motor Speed
- Motor Max Current
- Number of Shifts
- Time Fraction in Top Gear
- Battery SOC
- HEV Delta SOC
- Percentage Regeneration Recovered
- Electric Consumption
- Fuel Consumption Ratios
- :
- :

Component and Vehicle Checks Loaded in Database with Other Simulation Results



Component Checks
Vehicle Checks
On each simulation

Database of Simulation Results: Each check has a pass/fail flag.



Drag and drop parameter to add it to a grid.

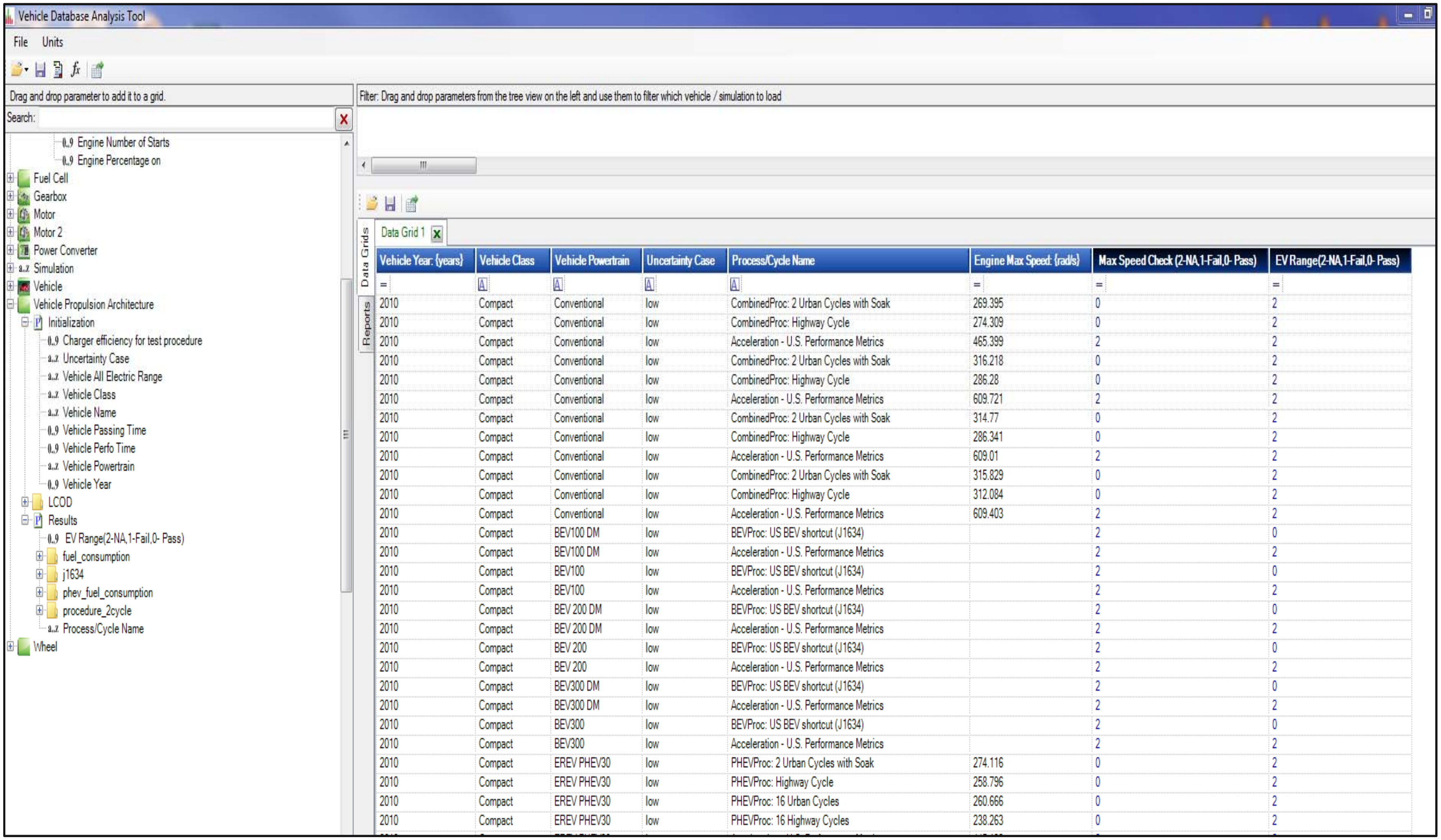
Search:

- Engine Number of Starts
- Engine Percentage on
- Fuel Cell
- Gearbox
- Motor
- Motor 2
- Power Converter
- Simulation
- Vehicle
- Vehicle Propulsion Architecture
  - Initialization
    - Charger efficiency for test procedure
    - Uncertainty Case
    - Vehicle All Electric Range
    - Vehicle Class
    - Vehicle Name
    - Vehicle Passing Time
    - Vehicle Perfo Time
    - Vehicle Powertrain
    - Vehicle Year
  - LCOD
  - Results
    - EV Range(2-NA,1-Fail,0- Pass)
    - fuel_consumption
    - j1634
    - phev_fuel_consumption
    - procedure_2cycle
    - Process/Cycle Name
- Wheel

Filter: Drag and drop parameters from the tree view on the left and use then to filter which vehicle / simulation to load

Vehicle Year (years)	Vehicle Class	Vehicle Powertrain	Uncertainty Case	Process/Cycle Name	Engine Max Speed (rad/s)	Max Speed Check (2-NA,1-Fail,0- Pass)	EV Range(2-NA,1-Fail,0- Pass)
=					=	=	=
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	269.395	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	274.309	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	465.399	2	2
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	316.218	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	286.28	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	609.721	2	2
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	314.77	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	286.341	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	609.01	2	2
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	315.829	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	312.084	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	609.403	2	2
2010	Compact	BEV100 DM	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV100 DM	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV100	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV100	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV 200 DM	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV 200 DM	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV 200	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV 200	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV300 DM	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV300 DM	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV300	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV300	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	EREV PHEV30	low	PHEVProc: 2 Urban Cycles with Soak	274.116	0	2
2010	Compact	EREV PHEV30	low	PHEVProc: Highway Cycle	258.796	0	2
2010	Compact	EREV PHEV30	low	PHEVProc: 16 Urban Cycles	260.666	0	2
2010	Compact	EREV PHEV30	low	PHEVProc: 16 Highway Cycles	238.263	0	2

Component and Vehicle Checks Loaded in Database with Other Simulation Results



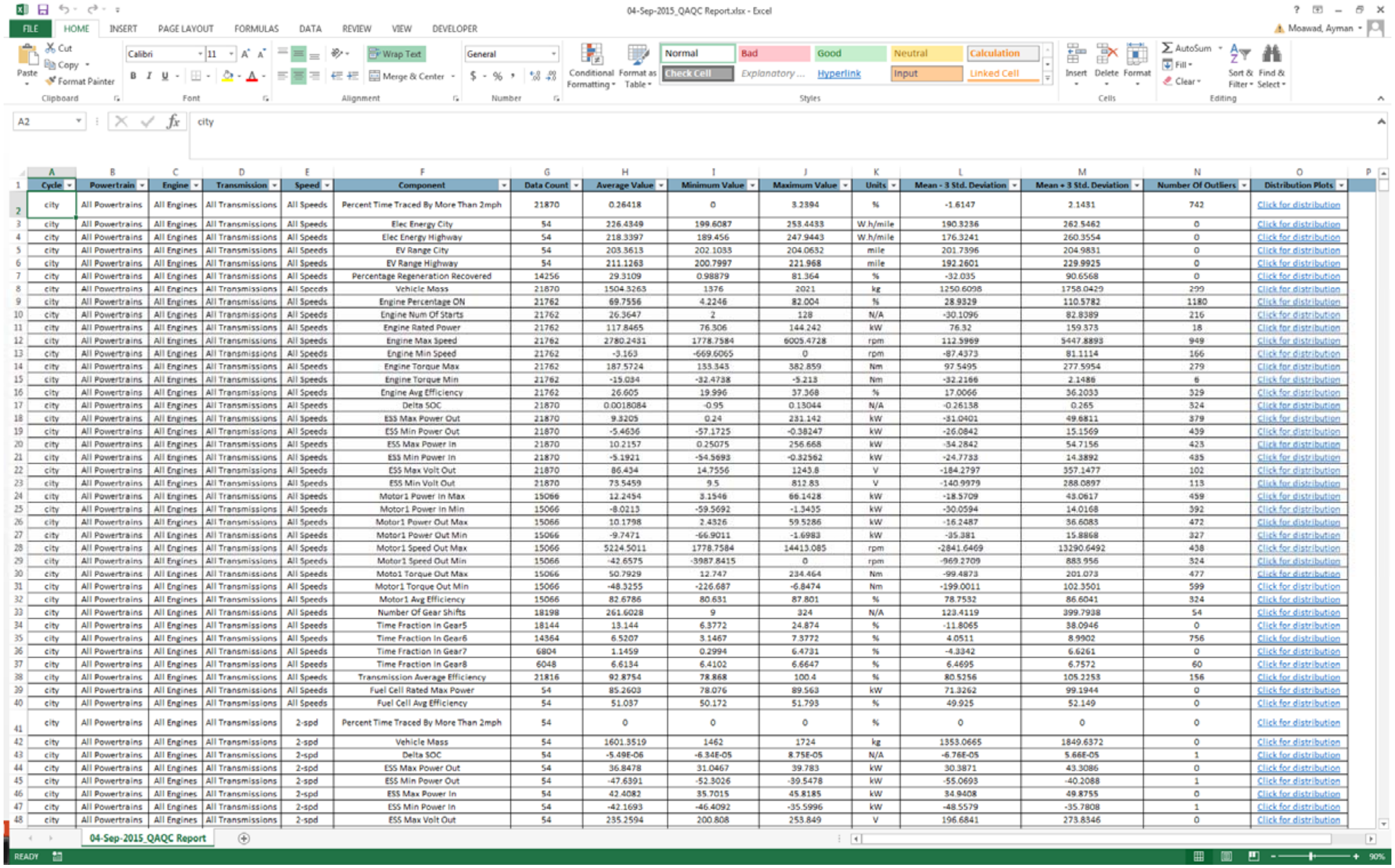
Drag and drop parameter to add it to a grid.

Filter: Drag and drop parameters from the tree view on the left and use them to filter which vehicle / simulation to load

Vehicle Year: {years}	Vehicle Class	Vehicle Powertrain	Uncertainty Case	Process/Cycle Name	Engine Max Speed: {rad/s}	Max Speed Check (2-NA,1-Fail,0- Pass)	EV Range(2-NA,1-Fail,0- Pass)
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	269.395	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	274.309	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	465.399	2	2
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	316.218	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	286.28	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	609.721	2	2
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	314.77	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	286.341	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	609.01	2	2
2010	Compact	Conventional	low	CombinedProc: 2 Urban Cycles with Soak	315.829	0	2
2010	Compact	Conventional	low	CombinedProc: Highway Cycle	312.084	0	2
2010	Compact	Conventional	low	Acceleration - U.S. Performance Metrics	609.403	2	2
2010	Compact	BEV100 DM	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV100 DM	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV100	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV100	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV 200 DM	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV 200 DM	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV 200	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV 200	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV300 DM	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV300 DM	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	BEV300	low	BEVProc: US BEV shortcut (J1634)		2	0
2010	Compact	BEV300	low	Acceleration - U.S. Performance Metrics		2	2
2010	Compact	EREV PHEV30	low	PHEVProc: 2 Urban Cycles with Soak	274.116	0	2
2010	Compact	EREV PHEV30	low	PHEVProc: Highway Cycle	258.796	0	2
2010	Compact	EREV PHEV30	low	PHEVProc: 16 Urban Cycles	260.666	0	2
2010	Compact	EREV PHEV30	low	PHEVProc: 16 Highway Cycles	238.263	0	2

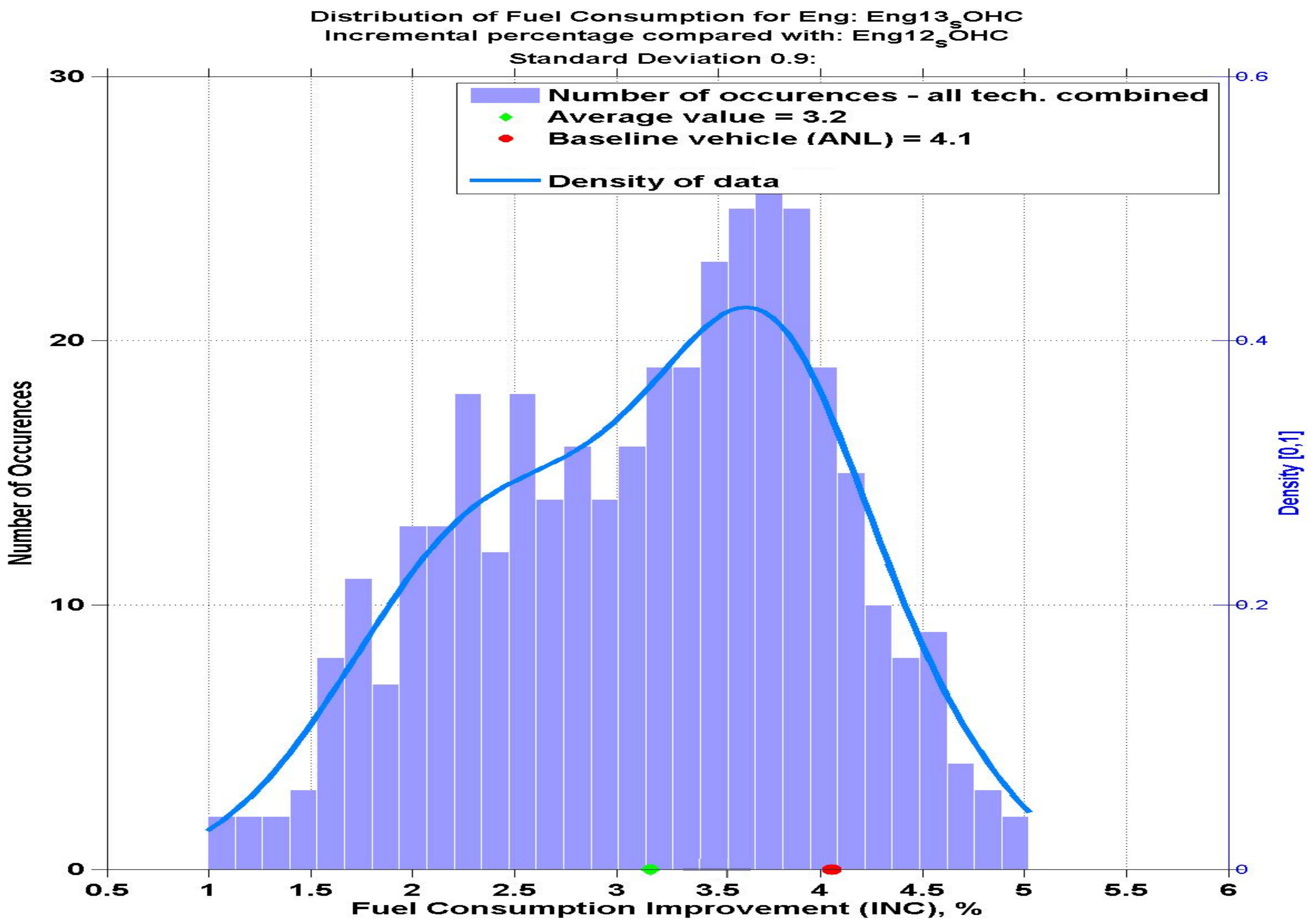
QA/QC Report Generated

- Statistical procedures are applied to flag erroneous results.
- Methods are developed to have the ability to trace invalid results.



Cycle	Powertrain	Engine	Transmission	Speed	Component	Data Count	Average Value	Minimum Value	Maximum Value	Units	Mean - 3 Std. Deviation	Mean + 3 Std. Deviation	Number Of Outliers	Distribution Plots
city	All Powertrains	All Engines	All Transmissions	All Speeds	Percent Time Traced By More Than 2mph	21870	0.26418	0	3.2394	%	-1.6147	2.1481	742	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Elec Energy City	54	226.4349	199.6087	253.4433	W.h/mile	190.3236	262.5462	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Elec Energy Highway	54	218.3397	189.456	247.9443	W.h/mile	176.3241	260.3554	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	EV Range City	54	203.3613	202.1033	204.0632	mile	201.7396	204.9831	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	EV Range Highway	54	211.1263	200.7997	221.968	mile	192.2601	229.9925	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Percentage Regeneration Recovered	14256	29.3109	0.98879	81.364	%	-32.035	90.6568	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Vehicle Mass	21870	1504.3263	1376	2021	kg	1250.6098	1758.0429	299	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Percentage ON	21762	69.7556	4.2246	82.004	%	28.9329	110.5782	1180	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Num Of Starts	21762	26.3647	2	128	N/A	-30.1096	82.8389	216	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Rated Power	21762	117.8465	76.306	144.242	kW	76.32	159.373	18	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Max Speed	21762	2780.2431	1778.7584	6005.4728	rpm	112.5969	5447.8893	949	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Min Speed	21762	-3.163	-669.6065	0	rpm	-87.4373	81.1114	166	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Torque Max	21762	187.5724	133.343	382.859	Nm	97.5495	277.5954	279	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Torque Min	21762	-15.034	-32.4738	-5.213	Nm	-32.2166	2.1486	6	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Engine Avg Efficiency	21762	26.605	19.996	37.368	%	17.0066	36.2033	329	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Delta SOC	21870	0.0018084	-0.95	0.13044	N/A	-0.26138	0.265	324	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	ESS Max Power Out	21870	9.3205	0.24	231.142	kW	-31.0401	49.6811	379	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	ESS Min Power Out	21870	-5.4636	-57.1725	-0.38247	kW	-26.0842	15.1569	439	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	ESS Max Power In	21870	10.2157	0.25075	256.668	kW	-34.2842	54.7156	423	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	ESS Min Power In	21870	-5.1921	-54.5693	-0.32562	kW	-24.7733	14.3892	435	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	ESS Max Volt Out	21870	86.434	14.7556	1243.8	V	-184.2797	357.1477	102	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	ESS Min Volt Out	21870	73.5459	9.5	812.83	V	-140.9979	288.0897	113	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Power In Max	15066	12.2454	3.1546	66.1428	kW	-18.5709	43.0617	459	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Power In Min	15066	-8.0213	-59.5692	-1.3435	kW	-30.0594	14.0168	392	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Power Out Max	15066	10.1798	2.4326	59.5286	kW	-16.2487	36.6083	472	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Power Out Min	15066	-9.7471	-66.9011	-1.6983	kW	-35.381	15.8868	327	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Speed Out Max	15066	5224.5011	1778.7584	14413.085	rpm	-2841.6469	13290.6492	438	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Speed Out Min	15066	-42.6575	-3987.8415	0	rpm	-969.2709	883.956	324	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Moto1 Torque Out Max	15066	50.7929	12.747	234.464	Nm	-99.4873	201.073	477	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Torque Out Min	15066	-48.3255	-226.687	-6.8474	Nm	-199.0011	102.3501	599	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Motor1 Avg Efficiency	15066	82.6786	80.631	87.801	%	78.7532	86.6041	324	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Number Of Gear Shifts	18198	261.6028	9	324	N/A	123.4119	399.7938	54	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Time Fraction In Gear5	18144	13.144	6.3772	24.874	%	-11.8065	38.0946	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Time Fraction In Gear6	14364	6.5207	3.1467	7.3772	%	4.0511	8.9902	756	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Time Fraction In Gear7	6804	1.1459	0.2994	6.4731	%	-4.3342	6.6261	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Time Fraction In Gear8	6048	6.6134	6.4102	6.6647	%	6.4695	6.7572	60	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Transmission Average Efficiency	21816	92.8754	78.868	100.4	%	80.5256	105.2253	156	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Fuel Cell Rated Max Power	54	85.2603	78.076	89.563	kW	71.3262	99.1944	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	All Speeds	Fuel Cell Avg Efficiency	54	51.037	50.172	51.793	%	49.925	52.149	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	Percent Time Traced By More Than 2mph	54	0	0	0	%	0	0	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	Vehicle Mass	54	1601.3519	1462	1724	kg	1353.0665	1849.6372	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	Delta SOC	54	-5.49E-06	-6.34E-05	8.75E-05	N/A	-6.76E-05	5.66E-05	1	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	ESS Max Power Out	54	36.8478	31.0467	39.783	kW	30.3871	43.3086	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	ESS Min Power Out	54	-47.6391	-52.3026	-39.5478	kW	-55.0693	-40.2088	1	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	ESS Max Power In	54	42.4082	35.7015	45.8185	kW	34.9408	49.8755	0	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	ESS Min Power In	54	-42.1693	-46.4092	-35.5996	kW	-48.5579	-35.7808	1	Click for distribution
city	All Powertrains	All Engines	All Transmissions	2-spd	ESS Max Volt Out	54	235.2594	200.808	253.849	V	196.6841	273.8346	0	Click for distribution

Distribution Plots Generated as Part of the Report for Visual Perspectives.



Summary

- A new process has been developed to use full vehicle simulation results as input to the Volpe/CAFE model.
- This process leverages Autonomie, a tool developed and validated by the U.S. DOE over the past 20+ years.
- All the models and controls are open to users.
- All the assumptions and results will be made available as part of the project.