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

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Overall Process Overview

ANL APRF’s Test Data for Validation

Vehicle Technology Assumptions

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

• 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

Autonomie’s main requirement:
Accelerate the development and introduction of advanced technologies via a Plug&Play modeling architecture and framework through Math-Based Systems Engineering (MBSE).
Autonomie is Composed of Two Distinct Entities

System Navigation, Integration and Simulation

Empty Interface

XML structure

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

Low level and high level controls available for most powertrains

Dozens of plant models and >100 initializations

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

>60 pre-defined LD and MD&HD vehicles

Large Number of Post-processing Tools
Autonomie is Open (Matlab/Simulink Based)

Component Models in Simulink

Initialization Files in Matlab

\begin{verbatim}
% consumption table

\end{verbatim}

Pre & Post-processing Files in Matlab

\begin{verbatim}
// Efficiency maps in terms of speed and power (used for plots)

\end{verbatim}

Controls in Simulink / StateFlow

\begin{verbatim}
\end{verbatim}
Users Can Customize Autonomie by Changing

Any Parameter

Any Initialization File

Any Use Case

Any Post-processing
Developers Can Customize Autonomie by Adding / Modifying

Models & Control
- Simulink
- GTPower
- LMS AMESim...

Vehicle, Powertrain and Component Configurations

Use Cases

Pre & Post-processing
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.

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

Simulation results analysis in the GUI
PSAT & Autonomie Have Been Used to Evaluate Technologies’ Energy Benefits for More Than 20 Years

Impact of Powertrain Configurations

- Series
- Voltec

Impact of Component Technologies

- 1.6L DI Turbo
- 2.0L DI VL
- Large Scale Simulations

Impact of Advanced Control / Optimization

- GPS
- Itinerary Computation
- Existing technology

- Driver’s Input
- Current Position
- Destination

- OR
- Pattern Recognition
- Average traffic speed

- Detailed/segment-by-segment information
- Speed & grade
- Route-based Optimization

- Energy Management

- Vehicle Classes
- Timeframes
- Powertrain Configurations
- Fuels
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...)

List of References

Software

- S. Halbach, P. Sharer, S. Pagerit, C. Folkerts, A. Rousseau, “Model Architecture, Methods, and Interfaces for Efficient Math-Based Design and Simulation of Automotive Control Systems”, SAE 2010-01-0241, SAE World Congress, Detroit, April 2010
List of References

Advanced Powertrains

- N. Kim, J. Kwon, A. Rousseau, “Comparison of Powertrain Configuration Options for Plug-in HEVs from a Fuel Economy Perspective”, SAE 2012-01-1027, SAE World Congress, Detroit, Apr12
List of References
Advanced Component Technologies


- A. Rousseau, N. Shidore, R. Carlson, D. Karbowski, "Impact of Battery Characteristics on PHEV Fuel Economy,” AABC08. (pdf)


List of References
Advanced Control

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- Vehicle Powertrain Sizing Algorithms and Validation
- Vehicle Simulation Results Quality Check Process
Vehicle energy consumption application developed with low frequency component models simulating longitudinal acceleration

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**
  ![Engine Performance Map]

- **Transmission (per gear)**
  ![Transmission Graph]

- **Electric Machine**
  ![Electric Machine Performance Map]

- **Energy Storage**
  ![Energy Storage Graph]

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

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

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.

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

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
### Shifting Algorithm Validation Leveraging Multiple APRF Data Sets

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

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

- Gear1
- Gear2
- Gear3
- Gear4
- Gear5
- Gear6

Engine Speed vs Gear Number

1. Gear1
2. Gear2
3. Gear3
4. Gear4
5. Gear5
6. Gear6

Shifting Algorithm

1. $\omega_{eco}^1 \rightarrow 2$
2. $\omega_{eco}^5 \rightarrow 6$
3. $\omega_{eco}^2 \rightarrow 1$

Engine Speed Range in Economical Driving

APRF Test Data Analysis

1. Gear Shifting Up - Engine Speed vs Acceleration position
2. Gear Shifting Down - Engine Speed vs Acceleration position
3. Up and Down-shifting maps (Simulation 1)

- $\alpha_{perf}$
- $\alpha_{eco}$
- $\alpha_{dn}$
- $\alpha_{up}$
Automatic Transmission Shifting Logic

Automatic Transmission Example

- 2013 Hyundai Sonata Conv. 6ATX Example
Shifting Algorithm Calibration Process

- Example: 2013 Hyundai Sonata Conv. I4 6ATX

- gb.ctrl.dmd.init.eng_spd_upshift_highest_gear
- gb.ctrl.dmd.init.eng_spd_upshift_lowest_gear
- gb.ctrl.dmd.init.eng_spd_dnshift_highest_gear
- gb.ctrl.dmd.init.eng_spd_dnshift_lowest_gear
- gb.ctrl.dmd.init.acc_above_perfo
- gb.ctrl.dmd.init.acc_below_eco_dn
- gb.ctrl.dmd.init.acc_below_eco_up
Automatic Transmission Shifting Validation

2013 Hyundai Sonata Conv. 6ATX – UDDS Driving Cycle

![Graph showing performance comparison between simulation and test data for 2013 Hyundai Sonata Conv. 6ATX – UDDS Driving Cycle with NCCP = 0.983]

2012 Chrysler 300 V6 8ATX – UDDS Driving Cycle

![Graph showing performance comparison between simulation and test data for 2012 Chrysler 300 V6 8ATX – UDDS Driving Cycle with NCCP = 0.962]

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

![Diagram of Clutch and Gear-train](image)

<table>
<thead>
<tr>
<th></th>
<th>N1</th>
<th>N2</th>
<th>S1</th>
<th>N2</th>
<th>N1</th>
<th>S2</th>
<th>S1</th>
<th>S2</th>
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<tbody>
<tr>
<td>CL1 – X</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CL2 – X</td>
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<td>CL1 – O</td>
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<tr>
<td>CL2 – O</td>
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<tr>
<td>CL1 – X</td>
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<tr>
<td>CL2 – O</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

O – clutch locked
X – clutch open
N – neutral
S – synchronized

Example of gear shifting: 1\(^{st}\) $\rightarrow$ 2\(^{nd}\)
- Odd gear $\rightarrow$ Pre-selection $\rightarrow$ Shifting $\rightarrow$ 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)

\[ J_{c1} + J_{c1} + J_{odd} \]
\[ S_e \cdot T_{e} \]
\[ \omega_e = \omega_s1 \]
\[ N_{odd} \cdot TF \]
\[ 1 \]
\[ \omega = \omega_s1 \]

\[ J_{c2} + J_{even} \]
\[ S_e \cdot T_{c2} \]
\[ \omega_s2 \]
\[ N_{even} \cdot TF \]

\[ S_e \cdot T_{loss2} \]

\[ \omega_e = \omega_s1 = N_{odd} \cdot \omega_{out} \]
\[ \omega_s2 = N_{even} \cdot \omega_{out} \]

\[ T_{out} = N_{odd} \cdot \{ T_e - (J_e + J_{c1} + J_{odd}) \cdot \dot{\omega}_e \} \]
\[ + N_{even} \cdot \{ T_{c2} - T_{loss2} - (J_{c2} + J_{even}) \cdot \dot{\omega}_s2 \} - J_{out} \cdot \dot{\omega}_{out} \]
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: $1^{st} \rightarrow 2^{nd}$

**Par HEV Dual Clutch Trans**

![Graph showing acceleration and clutching events during a shift](image-url)

- CL1 declutching
- CL2 clutching
- Shaft 1 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.
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

Battery power is constrained by the battery temperature.

Vehicle speed (m/s) [x 10]
Engine speed (rad/s)
Engine torque (N.m)
Coolant temperature (C)

Only when engine is on
Control concept based on the analyzed results

Vehicle Level Controls Logic Reverse Engineered
2010 Prius PHEV Example

Target generating

- Driver power demand
- SOC
- Thermal conditions

- Mode decision (Engine on/off)
- Energy management (SOC balancing)

- Engine target generating
- Engine power demand
- Engine on/off demand
- Engine torque demand
- Engine speed demand

- Battery power demand

Target tracking

- Control signals
- Engine on/off demand
- Engine torque demand
- Engine speed demand
- Motor 2 torque demand
- Motor torque demand
- Motor: torque target generation

- Motor 2: Engine speed tracking
- Driver power demand
Component Operating Conditions Validated
Prius HEV Validation on HWFET

Highway (HWFET)

- Vehicle speed (m/s) [Test]
- Vehicle speed (m/s) [Simulation]

- Engine speed (rad/s) [Test]
- Engine speed (rad/s) [Simulation]

- Engine torque (Nm) [Test]
- Engine torque (Nm) [Simulation]
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

- N. Kim, J. Jeong, A. Rousseau, and H. Lohse-Busch, “Control Analysis and Thermal Model Development of PHEV”, SAE 2015-01-1157, SAE World Congress, Detroit, April 15
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 GT-Power 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 technology.

- 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

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

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

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

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
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

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

...
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

<table>
<thead>
<tr>
<th>Transmission &amp; vehicle type</th>
<th>Span</th>
<th>Final drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 spd AU, conventional</td>
<td>&gt;6</td>
<td>&gt;2</td>
</tr>
<tr>
<td>8 speed AU, conventional</td>
<td>&gt;7</td>
<td>&gt;2</td>
</tr>
<tr>
<td>8 speed DCT, conventional</td>
<td>&gt;7 &amp; &gt;8-speed AU</td>
<td>&gt;2</td>
</tr>
<tr>
<td>6 speed AU, BISG</td>
<td>&gt;6</td>
<td>Lower than 6 speed AU***</td>
</tr>
<tr>
<td>8 speed AU, BISG</td>
<td>&gt;7</td>
<td>Lower than 8 speed AU***</td>
</tr>
<tr>
<td>8 speed DCT, BISG</td>
<td>&gt;7 &amp; &gt;8-speed AU</td>
<td>Lower than 8 speed DCT***</td>
</tr>
</tbody>
</table>

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:

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

Where

- \( Z = \) total number of gears.
- \( n = \) gear number in consideration for design (varies from 1 to \( z \)).
- \( \phi_2 = \) progression factor (independent variable – normally between 1 and 1.2).
- \( i_z = \) top gear ratio
- \( i_n = \) nth gear ratio

- Variation of \( \phi_2 \) between 1 and 1.2 is a trade-off between performance and FE.
- For this study, \( \phi_2 \) which maximizes FE, has been chosen, for each transmission.
- Algorithm validated against transmissions for several compact cars.

Gear Selection Algorithm Validation

- Using Least Squares Error method, $\phi_2$ was determined for a number of 6 speed transmissions in the market.

\[ \text{R Square} = 0.99861 \]

\[ \text{R Square} = 0.99961 \]

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

- Variation of $\phi_2$ 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

<table>
<thead>
<tr>
<th></th>
<th>Focus</th>
<th>Cruze</th>
<th>Mazda 3</th>
<th>Golf</th>
<th>Average</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_2$</td>
<td>1.09</td>
<td>1.04</td>
<td>1.08</td>
<td>1.08</td>
<td>1.07</td>
<td><strong>1.07</strong></td>
</tr>
</tbody>
</table>

Table 2: Market Vehicle $\phi_2$ interpolation the compare the simulation Phi2 Value
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

\[ V_{\text{dn perf}} \quad V_{\text{up perf}} \]

Performance Shifting Speeds

\[ V_{\text{dn eco}} \quad V_{\text{up eco}} \]

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).
Vehicle Control Logic
Example of Power Split HEV

Control concept based on the analyzed results
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

Engine on/off demand

Engine power demand

Engine torque demand

Engine speed demand

Motor 2: Engine speed tracking

Motor 2 torque demand

Motor: torque target generation

Engine on (HEV mode)

Engine off (PEV mode)

Fuel cut

Idling

Cranking

Demand or Cold

Hot

Cold

Engine on/off demand

Engine torque demand

Motor torque demand

Battery power demand

All points
Selected points

Wheel speed (rad/s)
Vehicle speed (m/s)

Wheel torque demand (Nm)

Vehicle speed (m/s)
Wheel torque demand (Nm)
Vehicle Control Development
Example of Power Split HEV

- Driver power demand
- Engine on/off demand
- Engine speed demand
- Motor 2 torque demand
- Motor torque demand
- Battery power demand
- Thermal conditions
- SOC

Energy management (SOC balancing)

Mode decision (Engine on/off)

Engine target generating

Motor: torque target generation

Motor 2: Engine speed tracking

Instant power
Rating power
Regenerative power

SOC

Energy management (SOC balancing)

Engine on/off demand

Engine torque demand

Motor 2 torque demand

Motor torque demand

Driver power demand

Engine power demand
Vehicle Control Development
Example of Power Split HEV

Engine idling control

Under cold conditions

Driver power demand
SOC
Mode decision (Engine on/off)

Energy management (SOC balancing)

Engine target generating

Engine on/off demand

Engine torque demand

Motor 2 torque demand

Motor: torque target generation

Engine speed demand

Motor 2: Engine speed tracking

Battery power demand

Thermal conditions

SOC

Engine power demand

Engine target generating

Engine on/off demand

Engine torque demand

Motor 2 torque demand

Motor: torque target generation

Driver power demand

Energy management (SOC balancing)
Vehicle Control Development

Example of Power Split PHEV

CD mode
- Engine off (EV)
- Brake signal & Vehicle speed < Thresh
- Engine on
  - Vehicle speed < X m/s
    - Engine only mode
      - \( P_{\text{bat}} = 0 \)
  - Vehicle speed > X m/s
    - Battery supporting mode
      - \( P_{\text{bat}} = X \text{ kW} \)
- Required power > Max. electric power

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

SOC < 28%
SOC > 30%
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

Process Overview

Results Checking (Level 2): Statistical Analysis

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

Database Analysis

Multi-simulation analysis

Analysis functions specific to the database

New calculations for trade-off analysis (i.e., cost)

Export for analysis/check

Launch GUI

Component Assumptions

Vehicle Assumptions

Vehicle Setup

Vehicle String

Vehicle Simulation

Time Based Analysis

Individual Simulation Results

Vehicle Simulations
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

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

User Select Options in GUI

Patented Algorithm

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

- 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.

Select Driving Cycles

Build Each Vehicle

From template vehicle definition to all vehicles
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 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 Consumption
- Combined Fuel Consumption
- Combined Electrical Consumption
Database Analysis (2/2)

Graphical User Interface Created to Check Simulation Results

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

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

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

- 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
- Component & Vehicle Assumptions
  - High Fidelity Models
- Vehicle Technical Specifications
  - Sizing Algorithms
- Dev. Controls
  - Powertrain Selection
- Run Vehicles
  - QA/QC & Reports
- Database for Volpe Model
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

Acceleration performance loop (0-60 mph)

- Initialize Variables
  - Use grade, performance estimation to initialize power of engine
  - Compute mass
- Run acceleration simulation (0-60 mph)
  - Performance time converged?
    - Yes
    - Stop
    - No
      - Tune engine power
      - Engine power = max(grade power, accelerate power)
      - Update vehicle mass
- Passing acceleration performance loop (50-80 mph)
  - Run passing acceleration simulation (50-80 mph)
    - Is passing acceleration OK?
      - Yes
      - Stop
      - No
      - Tune engine power
      - Engine power = max(grade power, accelerate 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

Acceleration performance loop (0-60 mph)
- Initialize Variables
  - Use grades, 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
      - Pass acceleration performance loop (50-80 mph)
      - Run passing acceleration simulation (50-80 mph)
  - No
    - Tune EM1 power
      - EM1 power = max(regen power, accele power)
    - Update vehicle mass
    - Update power of engine, battery, EM2 for grade, perfo, regen
- Stop

Passing acceleration performance loop (50-80 mph)
- 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
Vehicle Sizing Algorithm Validation
Conventional Vehicle Example

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

**Conventional Sonata 6 ATX**

<table>
<thead>
<tr>
<th>Spec.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear ratio</td>
<td>4.21, 2.64, 1.80, 1.39, 1.00, 0.77</td>
</tr>
<tr>
<td>Final drive</td>
<td>2.89</td>
</tr>
<tr>
<td>Wheel radius</td>
<td>0.3218 m</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>0.32 *</td>
</tr>
<tr>
<td>Front area</td>
<td>2.18 m^2 *</td>
</tr>
<tr>
<td>0-60 mph</td>
<td>7.9 sec **</td>
</tr>
</tbody>
</table>

** https://en.wikipedia.org/wiki/Hyundai_Sonata
Vehicle Sizing Algorithm Validation
Conventional Vehicle Example

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

<table>
<thead>
<tr>
<th></th>
<th>OEM Source : Hyundai Sonata 6 ATX MY2013</th>
<th>Sizing results from Autonomie</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle weight</td>
<td>1588 kg</td>
<td>1593 kg</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Engine Power</td>
<td>154 kW</td>
<td>144 kW</td>
<td>-6.4 %</td>
</tr>
<tr>
<td>Acceleration Performance: 0-60 mph</td>
<td>7.90 sec</td>
<td>7.89 sec</td>
<td>-</td>
</tr>
</tbody>
</table>

- 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.

<table>
<thead>
<tr>
<th>Gear ratio</th>
<th>Final drive</th>
<th>Wheel radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG1/SG1 = 2.6, RG2/SG2 = 2.64</td>
<td>3.268</td>
<td>0.317 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Drag coefficient</th>
<th>Front area</th>
<th>0-60 mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 *</td>
<td>2.25 m^2</td>
<td>9.7 sec **</td>
</tr>
</tbody>
</table>


** [http://www.zeroto60times.com/vehicle-make/toyota-0-60-mph-times/](http://www.zeroto60times.com/vehicle-make/toyota-0-60-mph-times/)
## Vehicle Sizing Algorithm Validation

### Power Split HEV Example

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

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

- 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

Fuel Economy Distribution - 2015 Compact car (only gasoline)

Fuel Economy Distribution - 2015 Midsize (only gasoline)
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

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

### Sample QA/QC Checks for Simulations with Engines

<table>
<thead>
<tr>
<th>Check</th>
<th>Drive Cycle on which check is performed</th>
<th>Component/Vehicle/Powertrain</th>
<th>Source of Reference Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Efficiency Relative Check (e.g. diesel average efficiency greater than gasoline)</td>
<td>Performed on database of results</td>
<td>Engine, Conventional and Start-Stop Vehicles for a given vehicle class.</td>
<td></td>
</tr>
<tr>
<td>Check of trends across engine technologies: engine efficiency, vehicle fuel economy, peak engine power.</td>
<td>Performed on database of results</td>
<td>Comparison across same class and powertrain type (e.g. conventional SI, compact class) across different engine technologies.</td>
<td>Engineering judgement.</td>
</tr>
</tbody>
</table>

# Sample QA/QC Checks for Simulations with Batteries

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

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.
Component and Vehicle Checks Loaded in Database with Other Simulation Results
QA/QC Report Generated

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