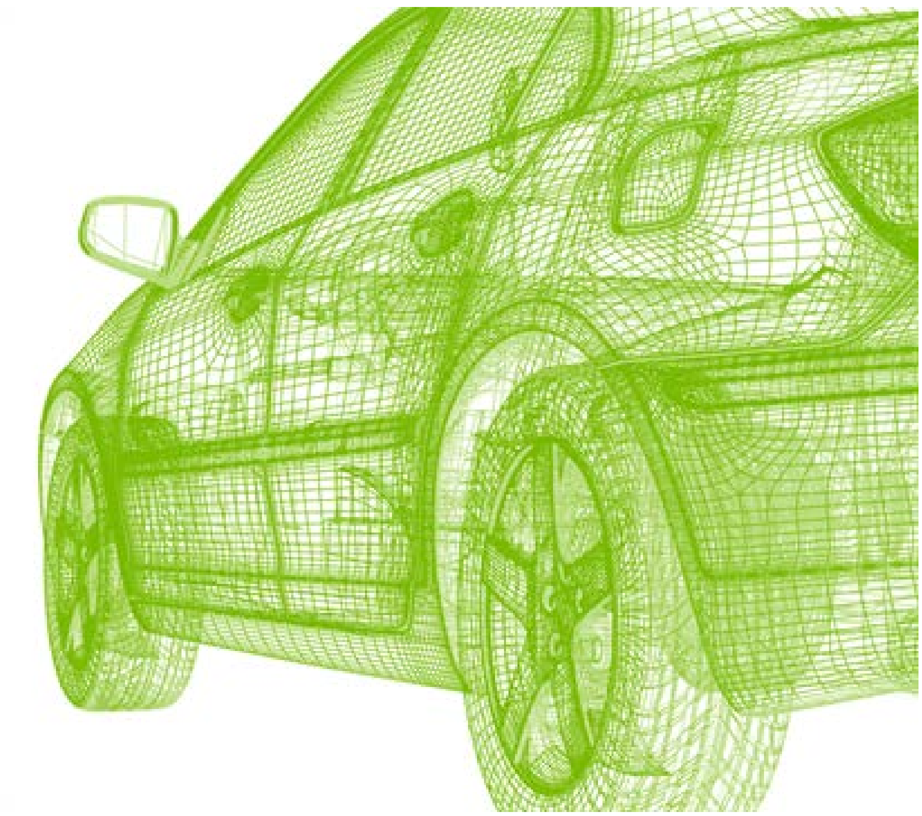

Energy
Systems
Division

VEHICLE MODELING FOR USE IN THE CAFE MODEL
PROCESS DESCRIPTION AND MODELING ASSUMPTIONS

Ayman Moawad, Namdoo Kim and Aymeric Rousseau

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June 2016

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Acronyms and Abbreviations

ABS	absolute
AER	all-electric range
APRF	Argonne Advanced Powertrain Research Facility
AU	Automatic
BEV	battery electric vehicle
BISG	belt-integrated starter generator
BMEP	brake mean effective pressure
BSFC	brake-specific fuel consumption
C1,2,3,4	Clutches 1 through 4
CAFE	Corporate Average Fuel Economy
CISG	crank-integrated starter generator
CVT	continuously variable transmission
DOT	U.S. Department of Transportation
EOL	end of life
EPA	U.S. Environmental Protection Agency
EREV	extended range electric vehicle
EV	electric vehicle
EV2	two-motor electric vehicle
FTP	Federal Test Procedure
GVW	gross vehicle weight
HEV	hybrid electric vehicle
HFET	Highway Fuel Economy Test
Hi Mode	compound mode
HV	hybrid vehicle
I/O	input(s)/output(s)
IACC1,2	improved accessories package 1, 2
ICE	internal combustion engine
INC	incremental
IVM	Initial vehicle movement
Lo Mode	input-split mode
MC1,2	Electric Machines 1 and 2MHEV micro hybrid electric vehicle
MY	model year
NHTSA	National Highway Traffic Safety Administration

PEV	pure electric vehicle
PHEV	plug-in hybrid electric vehicle
SAE	Society of Automotive Engineers
SOC	state of charge
SUV	sport utility vehicle
CAFE model	CAFE Compliance and Effects Modeling System
VPA	vehicle powertrain architecture

Units of Measure

Ah	ampere-hour(s)
h	hour(s)
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
m^2	square meter(s)
mpg	mile(s) per gallon
mph	mile(s) per hour
rad	radian(s)
rpm	rotation(s) per minute
s, sec	second(s)
V	volt(s)
W	watt(s)
Wh	watt-hour(s)

1. Introduction

In 1975, Congress passed the Energy Policy and Conservation Act (EPCA), requiring standards for Corporate Average Fuel Economy (CAFE), and charging the U.S. Department of Transportation's (DOT) with the establishment and enforcement of these standards. The Secretary of Transportation has delegated these responsibilities to the National Highway Traffic Safety Administration (DOT/NHTSA). Following an extended period of stable CAFE standards, NHTSA increased standards in 2003 for light trucks produced during 2005-2007 and developed new attribute-based standards in 2006 for light trucks produced during 2008-2011. In 2007, Congress passed the Energy Independence & Security Act (EISA), which updated EPCA by requiring, among other things, maximum feasible attribute-based CAFE standards that achieve at least 35 mpg by 2020. Rulemakings completed in 2009 and 2012 established new fuel economy standards for light vehicles produced during 2012-2016 and 2017-2021, respectively.

The Volpe Center provides analytical support for NHTSA's regulatory and analytical activities related to fuel economy standards, which, unlike long-standing safety and criteria pollutant emissions standards, apply to manufacturers' overall fleets rather than to individual vehicle models. In developing the standards, DOT/NHTSA made use of the CAFE Compliance and Effects Modeling System (the "Volpe model" or the "CAFE model"), which was developed by DOT's Volpe National Transportation Systems Center for the 2005-2007 CAFE rulemaking and continuously updated since. The model is the primary tool used by the agency to evaluate potential CAFE stringency levels by applying technologies incrementally to each manufacturer's fleet until the requirements under consideration are met. The CAFE model relies on numerous technology-related and economic inputs such as a market forecasts, technology cost, and effectiveness estimates; these inputs are categorized by vehicle classification, technology synergies, phase-in rates, cost learning curve adjustments, and technology "decision trees". The Volpe Center assists NHTSA in the development of the engineering and economic inputs to the CAFE model by analyzing the application of potential technologies to the current automotive industry vehicle fleet to determine the feasibility of future CAFE standards and the associated costs and benefits of the standards.

Part of the model's function is to estimate CAFE improvements that a given manufacturer could achieve by applying additional technology to specific vehicles in its product line. To inform decisions regarding the design of specific vehicles, manufacturers may apply techniques such as vehicle and component testing, combustion simulation, powertrain simulation, computational fluid dynamics simulation (CFD), and full vehicle simulation. Because CAFE standards apply to the average fuel economy across manufacturers' entire fleets of new passenger cars and light trucks, the model, when simulating manufacturers' potential application of technology, considers the entire range of each manufacturer's product line. This typically involves accounting for more than 1,000 distinct vehicle models and variants, many more than can be practically examined using full vehicle simulation (or the other techniques mentioned above). Instead, the model uses estimates of the effectiveness of specific technologies for a representative vehicle in each vehicle class, and arranges technologies in decision trees defining logical progressions from lower to higher levels of cost, complexity, development requirements, and/or implementation challenges.

DOT/NHTSA has made use of vehicle simulation results to update technology effectiveness estimates used by the model. In recent rulemakings, the decision trees have been expanded so that DOT/NHTSA is better able to track the incremental and net/cumulative cost and effectiveness associated with each technology, which substantially improves the "accounting" of costs and effectiveness for CAFE rulemakings. A detailed description of the CAFE model can be found in NHTSA's Final Regulatory Impact Analysis (FRIA) supporting the 2012 rule establishing CAFE standards applicable beginning MY 2017. The FRIA and all other rulemaking documents, the model, source code, model documentation, and all model inputs and outputs are available at http://www.nhtsa.gov/fuel-economy.

A significant number of inputs to Volpe's decision tree model are related to the effectiveness (fuel consumption reduction) for each fuel-saving technology. Because the model is intended for fleet-level analysis, precision in vehicle-level results is less important than in, for example, the vehicle design process. However, even in this fleet-level context, minimization of systematic bias is important. Because some combinations of technology are likely to yield overall fuel savings different from levels that would be applied by simply multiplying factors applicable to individual technologies, the model uses "synergy factors" to make corresponding adjustments. Although vehicle testing could be used to estimate these factors, vehicle testing spanning many vehicle types and technology combinations could be prohibitively resource-intensive. Another alternative, either as a substitute for or a complement to vehicle testing, would be to make greater use of vehicle simulation. Full vehicle simulation tools use physics-based mathematical equations, engineering characteristics (e.g., including engine maps, transmission shift points, hybrid vehicle control strategy), and explicit drive cycles to predict the effectiveness of individual fuel-saving technologies and the effectiveness of combinations of fuel-saving technologies.

Argonne National Laboratory, a DOE national laboratory, has developed a full-vehicle simulation tool named Autonomie. Autonomie has become one of the industry's standard tools for analyzing vehicle energy consumption and technology effectiveness.

The objective of this project is to develop and demonstrate a process that, at a minimum, provides more robust information that can be used to calibrate inputs applicable under the CAFE model's existing structure. The project will be more fully successful if a process can be developed that minimizes the need for decision trees and replaces the synergy factors by inputs provided directly from a vehicle simulation tool. The report provides a description of the process that was developed by Argonne National Laboratory and implemented in Autonomie.

2. Project Statement

The CAFE model currently relies on multiple decision trees to represent component technology options, including:

- Powertrain Electrification
- Engine
- Transmission
- Light-weighting
- Aerodynamics
- Rolling resistance

Figure 1 shows an example of the vehicle electrification decision tree. During the simulation, the CAFE model walks through each decision tree to find the technology that should be selected next to provide the best fuel energy improvement at the lowest cost.

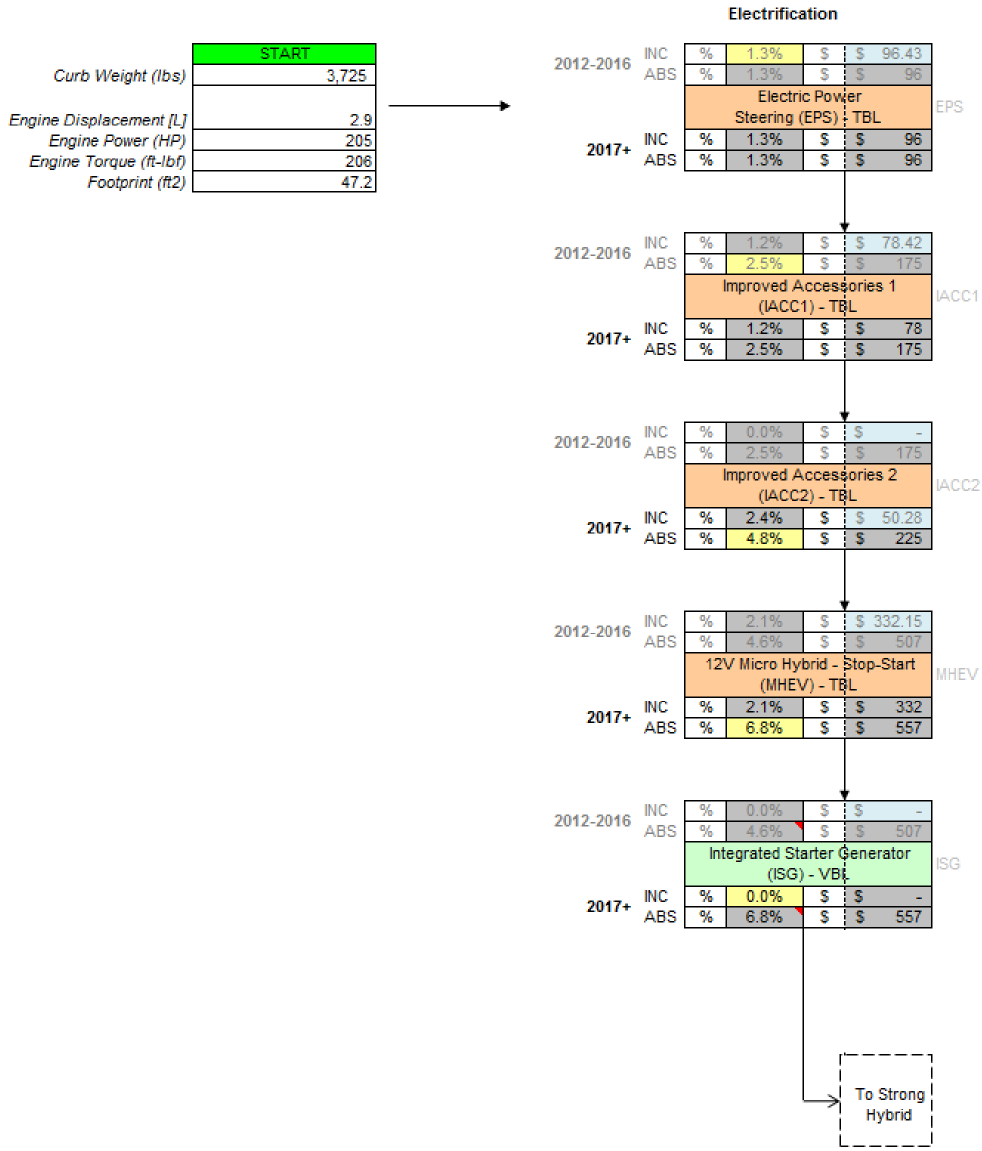


Figure 1 – Hybrid Technology Decision Tree

Figure 2 shows example decision trees selected equivalent to the number of technology combinations adapted to represent current and future potential technologies.

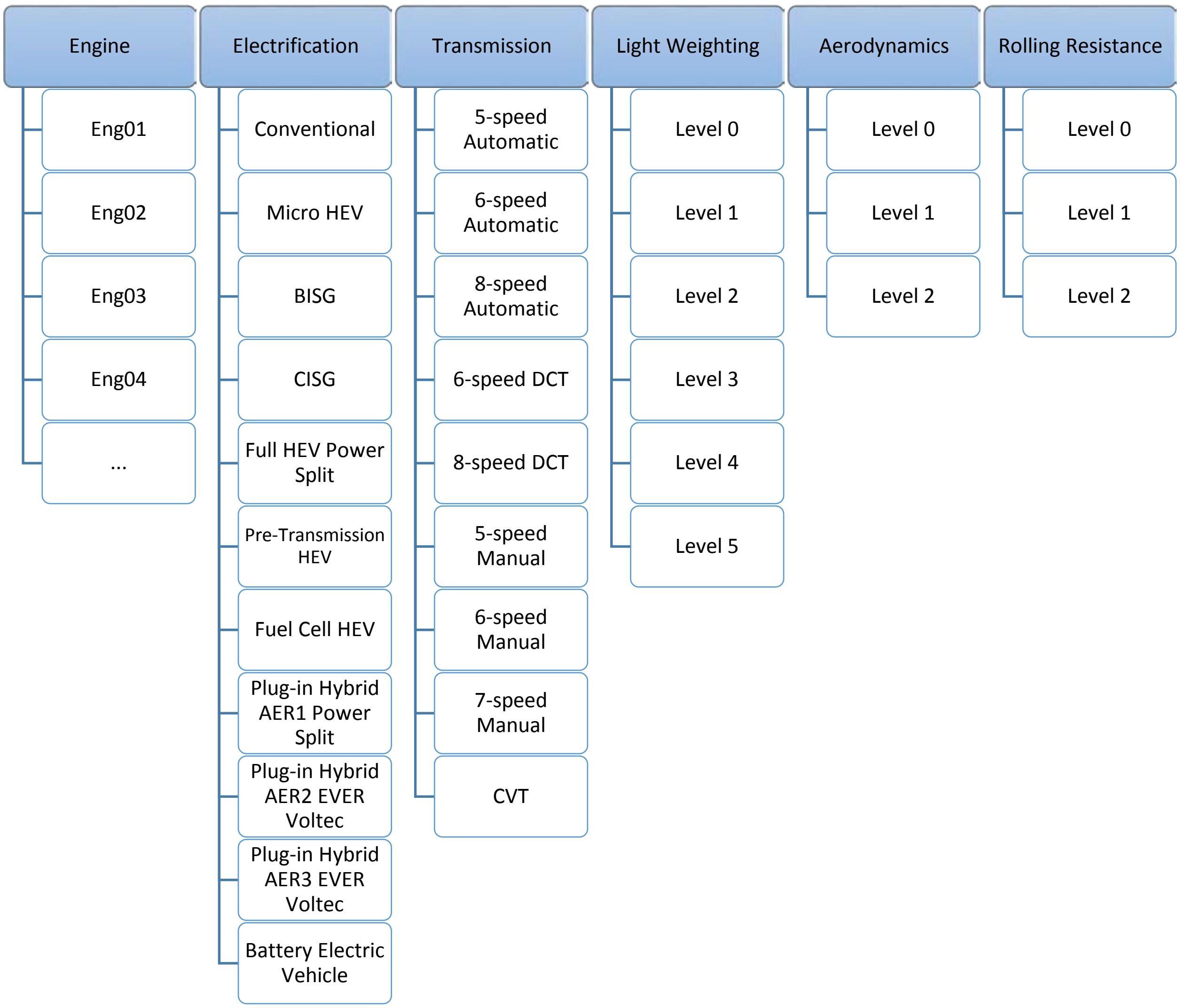


Figure 2 – Example Technological Decision Trees in the CAFE Model

In addition to the numerous decision trees, the CAFE model currently relies on estimates of synergies between technologies, recognizing that multiple technologies can address the same inefficiencies of the component. For example, if an engine technology provides 5% fuel consumption improvement and an advanced transmission 4%, the combination of both technologies may not provide 9% improvement – the actual improvement could be lower (negative synergy) or higher (positive synergy). Developing the relationships between multiple component technologies is challenging, but quantifying it is even more difficult, especially when more than one technology is involved. As the number of technologies increases, the number of technology combinations increases exponentially. Thus, a large number of simulations may be required in order to calculate the complete set of synergy factors for a modest number of technologies.

3. Process Overview

The main objective is to reduce the need for decision trees and replace the synergy factors by individual vehicle simulations as shown in Figure 3.

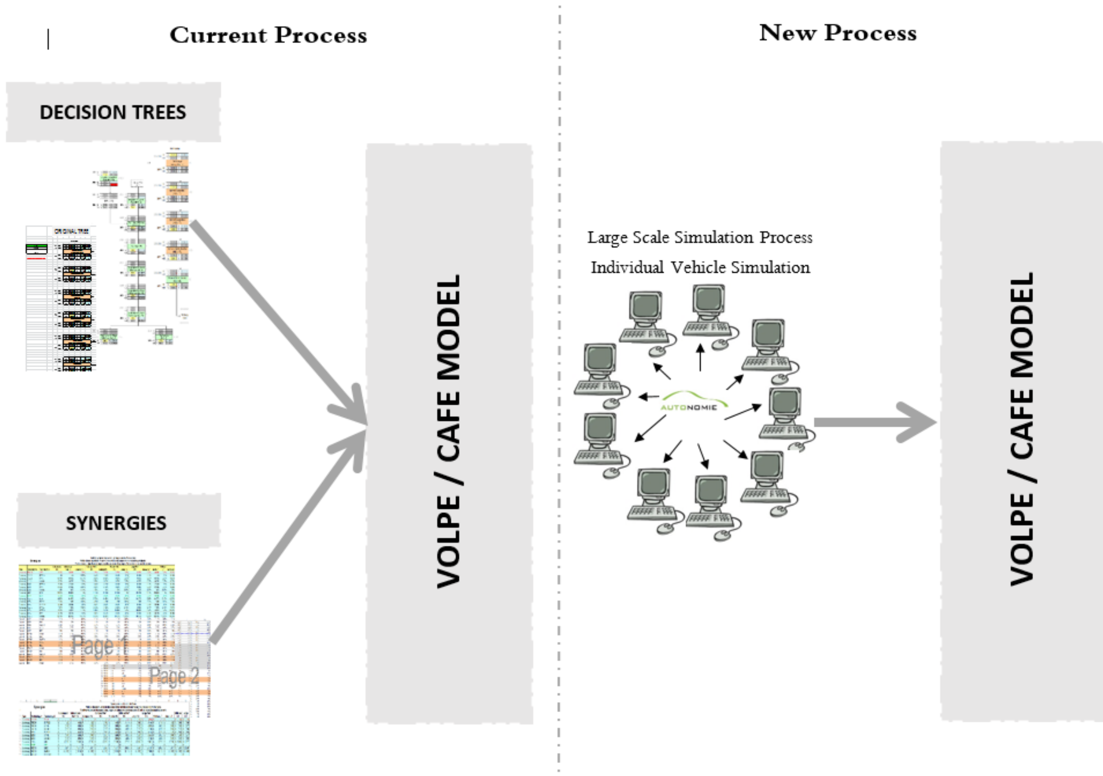


Figure 3 – Model Input: Replacing Decision Trees and Synergies with Individual Simulations

To do so, individual vehicles have to be simulated to represent every combination of vehicle, powertrain, and component technologies. The preliminary decision trees evaluated here include:

- 5 vehicles Classes (Compact, Midsize, Small SUV, Midsize SUV, Pickup)
- 14 engine technologies
- 11 electrification levels (Conventional equivalent to no electrification level)
- 9 transmissions technologies (applied to Low Electrification Level Vehicles only)
- 6 Light Weighting levels
- 3 Rolling Resistance levels
- 3 Aerodynamics levels

For one vehicle class:

4 Low Electrification Level Vehicles x 14 Engines Levels x 9 Transmissions Levels x 6 Light-Weighting Levels x 3 Rolling Resistance Levels x 3 Aerodynamics Levels = 27,216 vehicles

+

7 hybridized vehicles x 6 light weighting x 3 rolling resistance x 3 aerodynamics = 378 vehicles

=

~27,600 vehicles for each vehicle class

The combination of the technologies from each decision tree leads to ~27,600 simulations for a single vehicle class (or ~140,000 for 5) in order to fully populate inputs to the CAFE model. It is explained later that each vehicle combination needs to go through sizing algorithm routines + procedure runs => over a million simulations are required.

The process developed includes the following steps as shown in Figure 4:

1. Collect/develop all the technology assumptions.
2. Develop a process to automatically create the vehicle models.
3. Size the individual vehicles to all meet the same vehicle technical specifications.
4. Run each vehicle model on the specified driving cycles.
5. Create a database with all the required input for the CAFE model.
6. Create post-processing tool to validate the database content.

Since this process has to be performed in an acceptable amount of time, several additional processes were developed and implemented:

- Use of distributed computing for vehicle sizing and simulation
- Use of statistical analysis to minimize the number of simulations that need to be performed

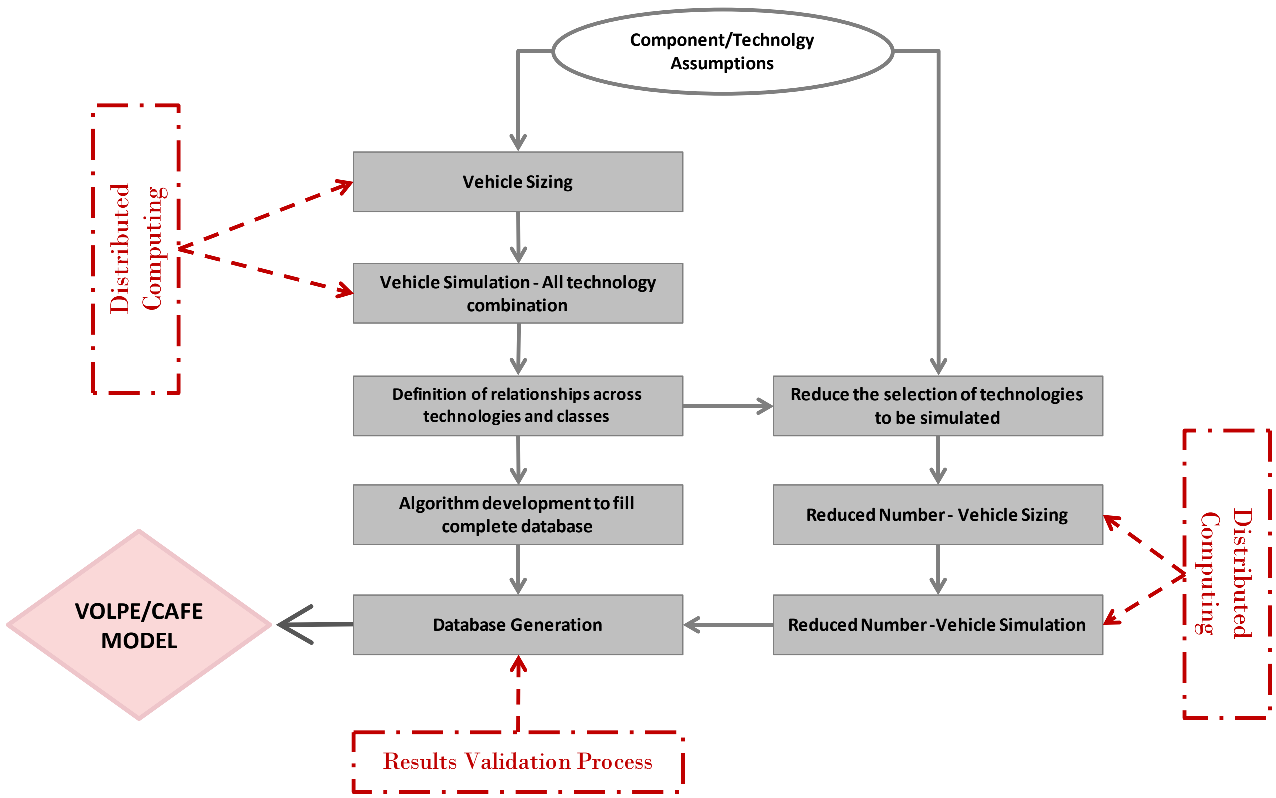


Figure 4 – Overview of Large-Scale Simulation Process (LSSP) Overview

The following sections of the report will describe each step in detail.

4. Autonomie

4.1. Overview

Autonomie is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. The tool, sponsored by the U.S Department of Energy Vehicle Technologies Program, is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity), abstraction (from subsystems to systems to entire architectures), and processes (e.g., calibration, validation). Developed by Argonne in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineers throughout the development process — from modeling to control. Autonomie was built to accomplish the following:

- Support proper methods, from model-in-the-loop, software-in-the-loop (SIL), and hardware-in-the-loop (HIL) to rapid-control prototyping (RCP);
- Integrate math-based engineering activities through all stages of development — from feasibility studies to production release;
- Promote re-use and exchange of models industry-wide through its modeling architecture and framework;
- Support users' customization of the entire software package, including system architecture, processes, and post-processing;
- Mix and match models with different levels of abstraction to facilitate execution efficiency with higher-fidelity models, for which analysis and high-detail understanding are critical;
- Link with commercial off-the-shelf software applications, including GT-POWER©, AMESim©, and CarSim©, for detailed, physically based models;
- Provide configuration and database management; and
- Protect proprietary models and processes.

By building models automatically, Autonomie allows the simulation of a very large number of component technologies and powertrain configurations. Autonomie offers the following capabilities:

- Simulate subsystems, systems, or entire vehicles;
- Predict and analyze fuel efficiency and performance;

- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;
- Support system hardware and software requirements;
- Link to optimization algorithms; and
- Supply libraries of models for propulsion architectures of conventional powertrains, as well as electric-drive vehicles.

Autonomie is used in this study to assess the fuel consumption of advanced powertrain technologies in numerous vehicle categories and configurations. Autonomie has been validated for several powertrain configurations and vehicle classes using vehicle test data from Argonne's Advanced Powertrain Research Facility (APRF).[1]

With more than 400 different pre-defined powertrain configurations, Autonomie is an ideal tool to analyze the advantages and drawbacks of the different options within each vehicle category, including conventional, parallel, series, and power-split hybrid vehicles.

Autonomie allows users to evaluate the impact of component sizing on fuel consumption for different powertrain technologies, as well as to define the component requirements (e.g., power, energy) to maximize fuel displacement for a specific application. This is important for the current study because the use of validated plant models, vehicle controls, and complete vehicle models is critical to properly evaluating the benefit of any specific technology. The vehicle-level control algorithms (e.g., engine ON/OFF logic, component operating conditions algorithm) are critical to properly evaluating any powertrain configuration or component-sizing impact, especially for electric drives. Argonne has extensive experience in developing shifting algorithms for conventional vehicles based on the different component characteristics (e.g., engine fuel rate, gear ratios).

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support a large number of studies, focusing on fuel efficiency, cost-benefit analysis, or greenhouse gases.

More than 150 companies and research entities, including major automotive companies and suppliers, are also using Autonomie to support advanced vehicle development programs.

[1] Autonomie Model Validation http://www.autonomie.net/projects/model_valid_21.html

4.2. Structure

Autonomie was designed for full plug-and-play support. Models in the standard format create building blocks, which are assembled at run time into a simulation model of a vehicle, system, or subsystem. All parts of the user interface are designed to be flexible to support architectures, systems, subsystems, and processes not yet envisioned. The software can be molded to individual uses, so it can grow as requirements increase and technical knowledge expands. This flexibility also allows for implementation of legacy models, including plant and controls.

Autonomie is based on standardized modeling architecture, on-demand model building, associated extendible markup language (XML) definition files, and user interfaces for managing models, including a file-versioning database (Figure 5).

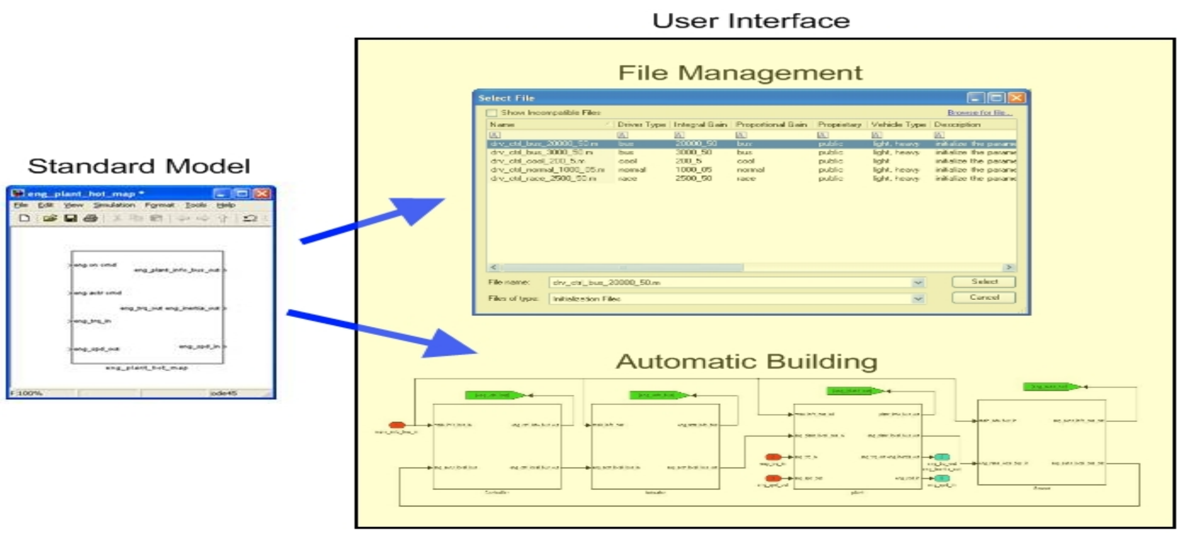


Figure 5 – Simulation Management Concepts

All systems in the vehicle architecture can be logically categorized as either a “containing system” or a “terminating system” (Figure 6). Containing systems consist of one or more subsystems, as well as optional files to define that system. They do not contain models; they only describe the structure of the interconnections among systems and subsystems. Terminating systems consist of a model that defines the behavior of the system and any files needed to provide inputs or calculate outputs. Terminating system models contain the equations that describe the mathematical functions of a system or subsystem.

Both types of systems are arranged in a hierarchical fashion to define the vehicle to be simulated. To avoid confusion, it is a best practice to mimic the structure of the hardware as much as possible. For example, low-level component controllers should be grouped with the components that they control, at different levels of the hierarchy (where applicable). Only systems that actually appear in the vehicle should be represented; in other words, there is no need for unused components or empty controllers. In addition to simplifying the architecture, this philosophy will allow for easy transfer of systems among users and will fully support HIL, SIL, and RCP.

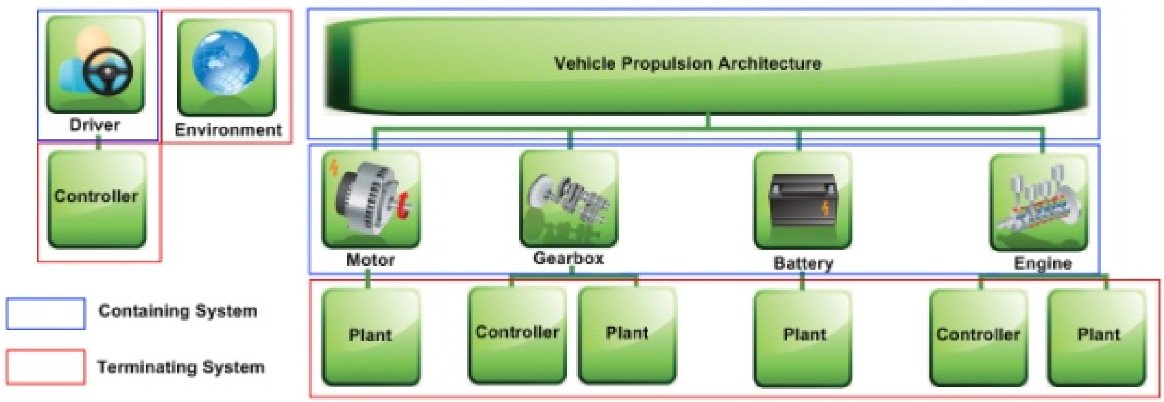


Figure 6 – Class Diagram of Container and Terminating Systems

At the top level is a vehicle system containing the following systems: environment; driver; vehicle propulsion controller for advanced powertrain vehicles such as hybrid electric vehicles (HEVs) or plug-in hybrid electric vehicles (PHEVs), which require a vehicle level controller; and vehicle propulsion architecture (VPA) (Figure 7). The VPA system will contain the powertrain components that are required to simulate the vehicle, such as engine, battery, and wheels.

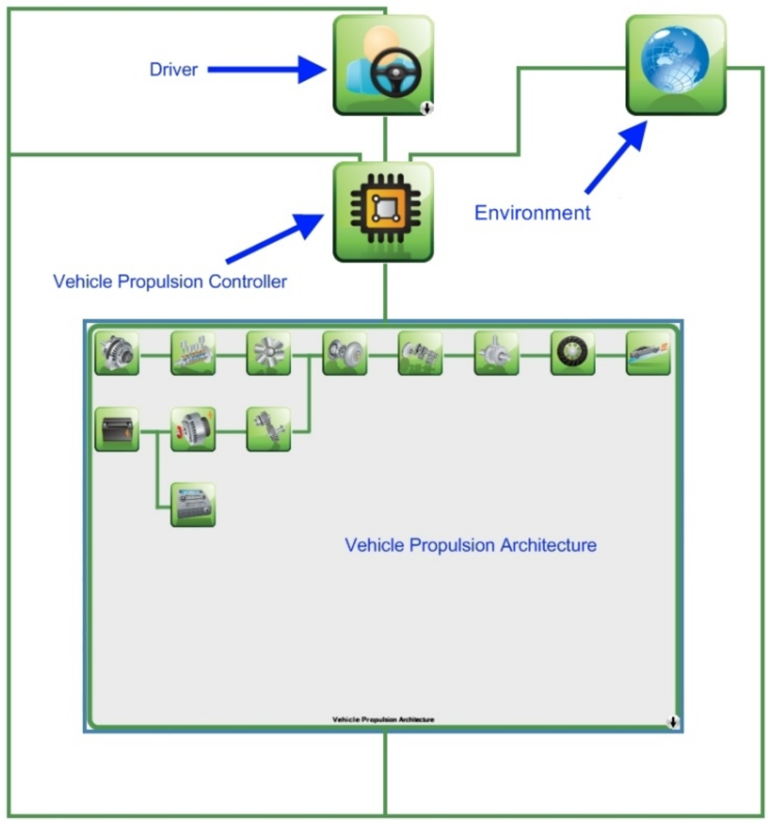


Figure 7 – Top-Level Vehicle Layout

The model files created for the terminating systems need to be combined in a way that allows simulation in Simulink. One option is to create every possible combination of the systems and save each complete vehicle as a separate model file. Because of the staggering number of possible combinations, this option is not feasible. Combinations involve not only many different components, but also different levels of fidelity and model versions for each component. Changing the version of a single component model would result in a new version of the entire vehicle. This method is clearly storage intensive and impractical.

A second option is to save every model in its own file and manage a library of the models. This would be an improvement over the first option; however, it still presents some difficulties. When users wish to create a new vehicle, they must select all of the appropriate models from the library and connect them by hand into a vehicle context. Not only is this manual process time consuming, but it introduces many opportunities for error. Consider an engine control unit model for auto code generation that can have more than 2,000 inputs and outputs (I/Os). Manually connecting all I/Os almost guarantees errors. It also requires some outside solution for model library management (e.g., searching, versioning, and ensuring compatibility).

Autonomie uses a novel approach that combines the second option with an automated building process, giving the user the flexibility of saving and versioning models independently without the potential pitfalls of manual connections. Users select the correct files in a user interface, and the automatic building uses metadata associated with the models to create the correct connections, as shown in Figure 8.

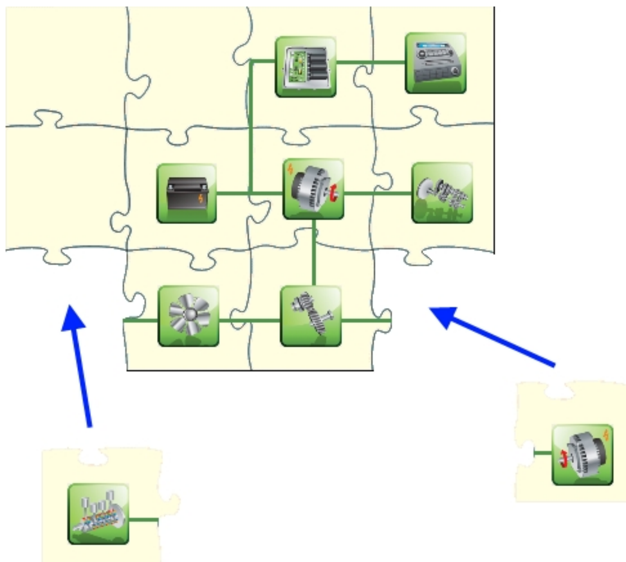


Figure 8 – Models are Automatically Built

5. Technology Selection

Manufacturers have been considering many technology options for improving vehicle energy efficiency. The objective of this phase is to define and collect, if necessary, the performance assumptions for each technology that were in the original CAFE decision trees.

5.1. Engine

Figure 9 shows the original engine decision tree provided by the Volpe Center.

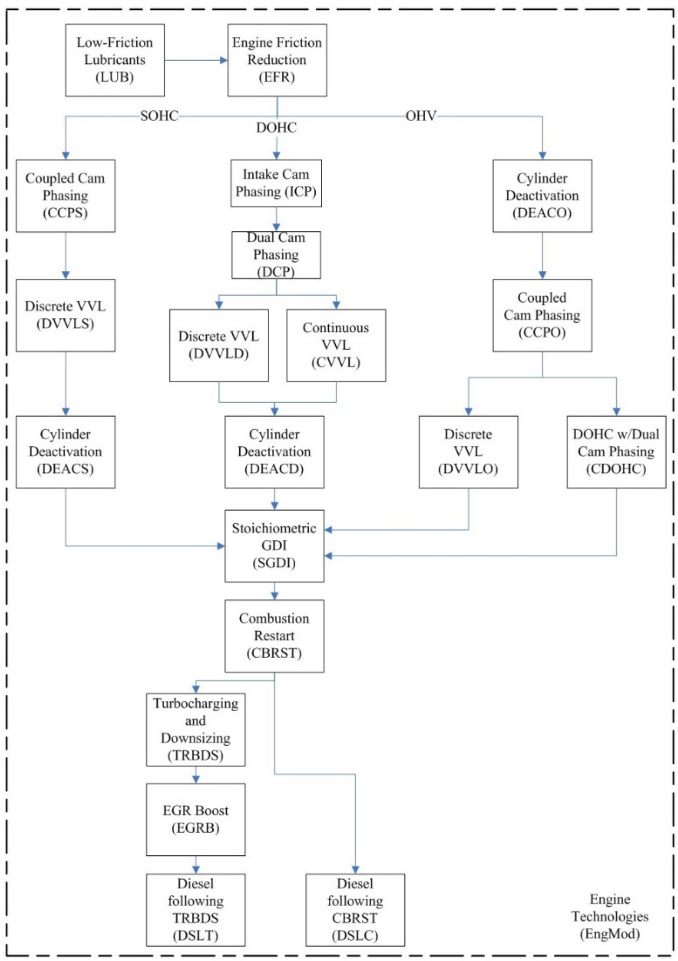
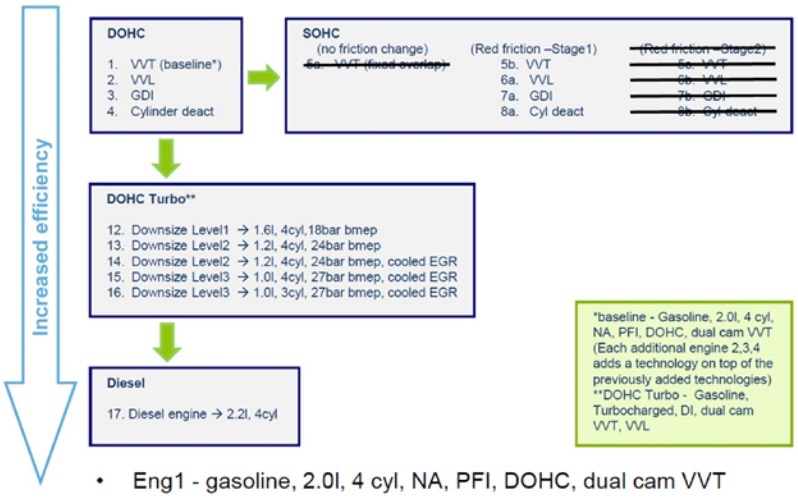


Figure 9 – Original CAFE Model Engine Decision Tree

A consulting contract has been completed for obtaining a wide range of different engine maps with technological breakdown, as shown in Figure 10. The contractor has provided wide-open-throttle engine performance values and brake-specific fuel consumption (BSFC) maps for future engine concepts. In order to provide sufficient and realistic results, the list of incremental technologies have been modeled using GT-POWER©, and validated with existing dynamometer measurements. The models were trained over the entire engine operating range and have predictive combustion capability. This is essential, since the BSFC prediction needs to be accurate while the engine setup is subject to change. These maps are used in the process described herein.



- Eng1 - gasoline, 2.0l, 4 cyl, NA, PFI, DOHC, dual cam VVT
  - Calibrations fully optimized for best bsfc and maximum torque (comb. phasing, valve timing, lambda, etc)
- Eng2* - VVL system was added to the intake valves on Eng1
  - Valve lift and timing optimized
  - Benefit (1) Reduced pumping work at low loads (2) More torque at low speeds from reduced intake duration
- Eng3* - Eng2 (PFI) converted to direct injection
  - Comp ratio raised from 10.2 to 11.0 and injection timing optimized
  - Benefit - DI provides greater knock tolerance, allowing higher comp ratio and increased efficiency over entire map
- Eng4* - Cylinder deactivation added to engine Eng3
  - Engine fires only 2 cylinders at low loads and at speeds below 3000 RPM by deactivating valves on 2 cylinders
  - Benefit - Effective load doubled on 2 cylinders providing less pumping work and higher efficiency
- Eng5b/ Eng6a/ Eng7a/ Eng8a* - Reduced friction from Eng5a/ Eng2/ Eng3/ Eng4 respectively
  - Engine FMEP reduced by 0.1 bar over entire operation range to understand friction benefit from SOHC
  - Benefit (1) Reduced friction improves efficiency at all load points (2) Raises full load line
- Eng12 - gasoline, 1.6l, 4 cyl, turbocharged, DI, DOHC, dual cam VVT, intake VVL
  - Calibrations fully optimized for best bsfc (comb. phasing, valve timing, lambda, etc)
- Eng13* - Eng12 downsized to 1.2l
  - Turbocharger maps scaled to improve torque at low engine speeds
- Eng14* - High pressure cooled EGR added to Eng13
  - Cooled EGR target set points optimized
- Eng15* - Eng14 downsized to 1.0l
  - Cooled EGR target set points re-optimized and turbocharger maps re-scaled
- Eng16* - Eng15 converted to 3cyl, 1.0l concept
  - Intake and exhaust piping scaled to account for larger mass flows through each cylinder and cooled EGR target set points re-optimized

Benefits summarized on the following page

*All inputs/parameters are held constant unless specifically mentioned

Figure 10 – Example Engine Technologies

For this example, 14 different BSFC engine maps were developed and selected to be used to evaluate the fuel consumption benefits of advanced engines. The baseline engine technology is the PFI 2.0-L gasoline engine with VVT. The baseline BSFC engine map (Engine 1) was generated from engine dynamometer data. Each subsequent engine (BSFC map) represents an incremental increase in technology advance over the previous technology. For example, Engine 2 is a 2.0-L engine with Variable Valve Lift (VVL) in addition to VVT for a PFI engine. Engine 3 is a direct injection (DI) engine with VVT and VVL, and so on. Figure 10 lists the four NA technologies considered.

Friction reduction has been shown to offer significant improvements in vehicle fuel consumption. Therefore, in order to evaluate the potential of friction reduction, each of the above engine technologies was subjected to two levels of reduction in friction mean effective pressure (FMEP).

1. A reduction in FMEP by 0.1 bar across the entire engine speed range.
2. An extreme friction reduction (25% FMEP) across the entire speed range.

For this example the first level of friction reduction has been considered.

In addition to the naturally aspirated engines, maps for turbo technologies were also developed using GT-POWER©. With turbo engines, there is a 'lag' in torque delivery due to the operation of the turbo charger. This impacts vehicle performance, and could impact the vehicle shifting on aggressive cycles. Turbo lag has been modelled for the turbo systems based on principles of a first order delay, where the turbo lag kicks in after the naturally aspirated torque limit of the turbo engines has been reached.

Figure 11 below shows the response of the turbo engine model for a step command.

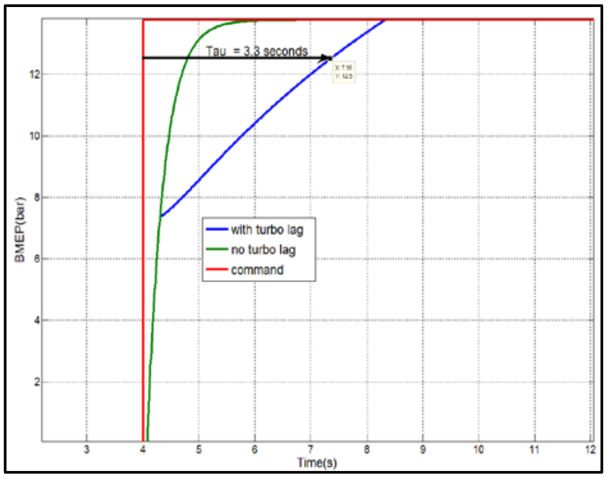


Figure 11 – Turbo charged engine response for the one liter engine

It should be noted that the turbo response changes with engine speed, i.e. at higher speeds, the turbo response is faster due to higher exhaust flow rates.

It should also be noted that the baseline engine maps (Engine 1 and Engine 12) for the naturally aspirated and the turbo engines were generated using test data. The baseline GT-POWER© models were hence validated against test data.

Assumptions for cylinder deactivation

Due to NVH considerations in production vehicles, cylinder deactivation operation is not performed in several vehicle operation modes, like vehicle warm-up, lower gear operation, idle, and low engine speed. In order to provide a realistic evaluation of the benefits of cylinder deactivation technology, cylinder deactivation has not been used under the following vehicle and engine conditions:

1. Cylinder deactivation is disabled if the engine is at idle or any speed below 1000 RPM or above 3000 RPM.
2. Cylinder deactivation is disabled if the vehicle is in the 1st of the 2nd gear.
3. Cylinder deactivation is disabled if the engine load is above half the max BMEP of the engine (and a certain hysteresis is maintained to prevent constant activation and deactivation).

Typically, cylinder deactivation is not performed during the vehicle warm up phase, i.e. for a cold start. Since all the simulations considered in this study assume a 'hot start', where in the engine coolant temperature is steady around 95 degrees C, the cold start condition was not a factor for the simulations.[2]

[2] See section 6.10.

In addition, changes in the transmission shifting calibration (like lugging speed limits) and additional torque converter slippage during cylinder deactivation have also been disregarded.

5.2. Transmission

To provide more fuel-efficient vehicles to customers, manufacturers have introduced a number of transmission improvements over the past couple of years, including incorporating a higher number of gears and new technologies such as the dual-clutch transmission. The following configurations are used in this example eV, to represent market need:

- 5-speed automatic (reference vehicle)
- 6-speed automatic
- 8-speed automatic
- 6-speed dual-clutch
- 8-speed dual-clutch
- Continuously variable
- 5-speed manual
- 6-speed manual
- 7-speed manual

Progressive transmission gear ratios have been designed for each transmission type considering trends in gear span and ratios, as well as expected differences in vehicle performance and fuel consumption based on the transmission technology. In order to properly evaluate engine operation for different component technologies and powertrain configurations, a rigorous selection of transmission gear ratios, final drive ratios, and gear shift parameters is important. On the basis of a literature review and evaluation of chassis dynamometer test data for conventional vehicles, the following criteria were selected for the design of transmission gear ratios, final drive ratios, and shift parameters.

1. The vehicle should shift to top gear around 45 mph.
2. In top gear, the engine should operate at or above 1,250 rpm to prevent engine lugging.
3. The number of gear shifts for a 6-speed transmission, Urban Dynamometer Driving Schedule (UDDS) cycle, should be around 110 to 120 based on a review of chassis dynamometer test data to balance operating at best engine efficiency and shift frequency which impacts customer satisfaction.
4. Gear span and final drive ratios should be based on industry trends for the compact vehicle class.

5. Engine operation will be restricted in the low-speed/high torque region to prevent noise, vibration, and harshness (NVH) issues and ensure drive quality.
6. The span of the 8-speed transmissions is higher than that of the 6-speed transmission.
7. The span of the 8-speed DCT is slightly higher than the span of the 8-speed AU to compensate for the lack of torque multiplication of the torque converter for the AU.
8. The vehicle should be able to meet or exceed Vehicle Technical Specifications (VTSs) related to grade (in first and top gear) and passing performance for a compact car.

Figure 12 shows the expected fuel economy and performance differences between the 6- and 8-speed AU and 8-speed DCT based on the literature survey.

Transmission	6 Speed Auto	8 Speed Auto	8 Speed DCT
Performance	+	++	+
Fuel Economy	+	++	+++

Figure 12 – Expected Differences in Performance and Fuel Economy for the Different Engines.

The 8-speed automatic is expected to have a better performance in Initial Vehicle Movement (IVM) -60 mph) test when compared to a 6–speed automatic (AU) given that the “ideal” tractive effort parabola is better matched by an 8-speed than a 6-speed. Naturally, the higher number of shifts in an IVM-60 test for an 8-speed could reduce the performance difference. An 8-speed DCT with the same gear ratios and final drive as an 8-speed AU is expected to have slower performance because of the absence of the initial torque multiplication of the torque converter.

The 8-speed AU is expected to provide better fuel efficiency than a 6-speed because of its higher gear span, and therefore, a lower engine speed range of operation. The 8-speed DCT provides the highest fuel economy because of the absence of torque converter losses when it is in the unlocked state.

Dual clutch transmissions with torque converters are being introduced in the market. But, based on the 2014 EPA Report on light –duty vehicles, a significant majority of the DCT transmissions in the market today are without the use of a torque converter device. Therefore, in this example, it is assumed that the torque converter is not used with the DCT.

Based on publicly available data, the gear spans, transmission gear ratios, and final drive ratios for several vehicles in the compact car segment for MY 2013 were reviewed. Table 1 lists the minimum and maximum values for gear ratio span, final drive ratio, and engine speed in top gear at 45 mph (indicator of top gear ratio). The table also lists the selected values for the 6-speed transmission. A similar selection was made for the 8-speed case, as well.

Table 1 – Gear Ratio, Final Drive Information for Sample 6-Speed Automatic Transmission Vehicles – MY 2013.

	Minimum Value	Maximum Value	Selected Value for Study
Span	5.6	6.15	6.00
Final Drive	3.2	4.58	3.74
Engine Speed (45 mph)	1,234 RPM	1,604 RPM	1,420 RPM

A gear span of 6 has been selected for the 6-speed case, because current trends in transmission technology reflect increasing gear spans, thus driving selection of a span closer to the maximum observed value.

Similarly, span and final drive ratios for the 8-speed AU transmission were chosen, considering available transmissions in the market today as well as the criteria listed above. It should be noted that there are very few compact cars currently in the market with 8-speed transmissions, and most of the available data suggest the use of 8-speed transmissions in the large sedan (and higher) segments, luxury cars, and sports cars. Therefore, the decision on gear span and final drive ratio was made so as to meet the criteria listed above.

Table 2 lists the span, final drive ratio, and engine speed at 45 mph for the 6-speed AU, 8-speed AU, and 8-speed DCT transmissions. With a start-stop (BISG) powertrain configuration, the electric motor provides additional torque during vehicle launch, thus aiding in vehicle acceleration and performance. Therefore, it is possible to have a final drive ratio lower than one for a conventional powertrain with the same transmission. A very small final drive ratio would result in increased transmission gear ratios to attain the same performance and grade ability requirements, and therefore, an inherent trade-off exists between higher transmission gear ratio and final drive ratio. Finding an optimum trade-off between transmission gear ratio and final drive ratio for the BISG is not included in this example.

Table 2 – Gear Span, Final Drive and Engine Speed in Top Gear at 45 mph for 6-Speed AU, 8-Speed AU, and 8-Speed DCT.

	6-speed AU	8-speed AU	8-speed DCT
Span	6	7.5	7.7
Final Drive	3.7	3.5	3.5

Engine Speed (45 mph)	1,420 RPM	1,290 RPM	1,290 RPM

With the gear span, final drive ratio, and expected engine speed at 45 mph in top gear all preselected, the progressive gear ratios were calculated for each transmission type using the following formula from:

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

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, and

i_n = nth gear ratio.

The independent variable φ_2 can normally take a value between 1 and 1.2 based on industry trends. The selection of φ_2 causes a trade-off between fuel consumption and performance. For this example, the independent variable, for each transmission, was chosen so as to minimize the fuel consumption over a combined UDDS (Urban) and HWFET (Highway) drive cycle. Figure 13 shows the fuel economy and performance (IVM-60 mph) for different values of the independent variable for a UDDS cycle.

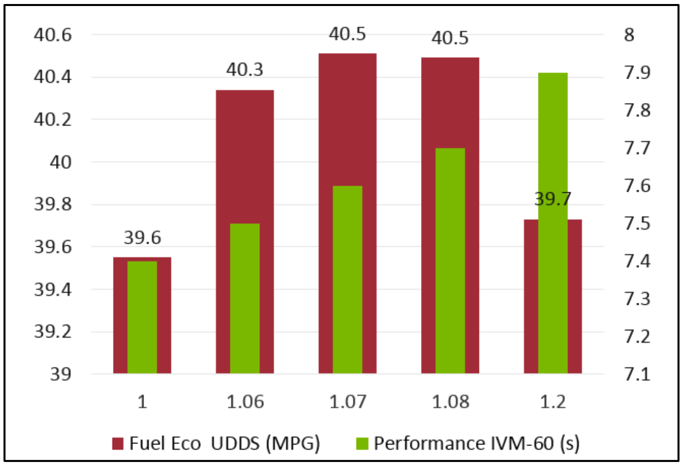


Figure 13 – Fuel Economy and Performance Variations with Choice of Progression Factor for a 6-Speed Transmission.

As shown, a value of 1.07 provides the maximum fuel economy and was therefore chosen to decide the gear ratios of the 6-speed transmission for the example. Figure 14 shows the gear ratios obtained with three different values of φ_2 .

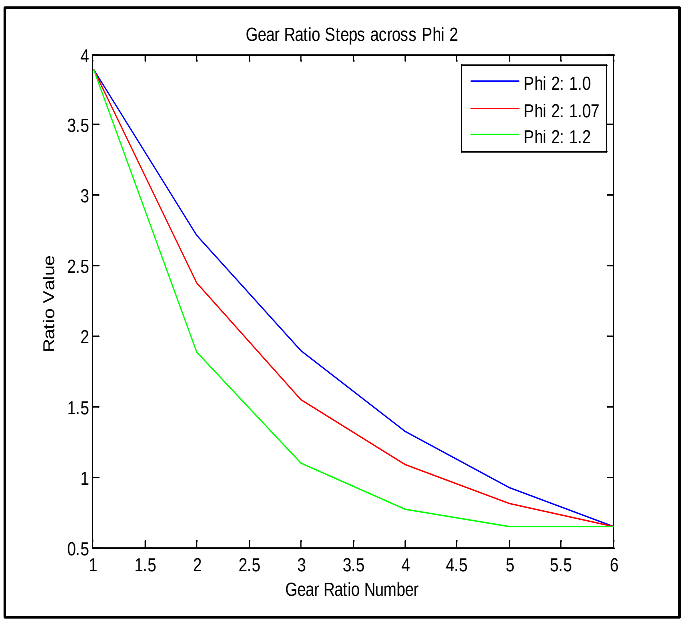


Figure 14 – Gear Ratios Obtained with Three Values of Progression Factor for a 6-Speed Transmission.

A similar exercise was conducted for the 8-speed transmissions, as well.

The transmission ratios thus designed may not meet the necessary criteria for practical transmission ratio design, where decisions on number of planetary gear sets, clutches, and kinematic combinations of different transmission elements have to be considered. It is assumed that with actual transmissions, the ratios would be slightly different and would have a minimal implication on vehicle fuel consumption. To validate the approach described above for selection of the intermediate gear ratios, the intermediate gear ratios calculated by the algorithm were compared to actual vehicles for two vehicles in the compact class. Gear span, final drive ratio, and top gear ratio were inputs to the equation above. As Figure 15 and Figure 16 show, with proper selection of the independent variable φ_2, the calculated gear ratios are very close to the actual gear ratios.

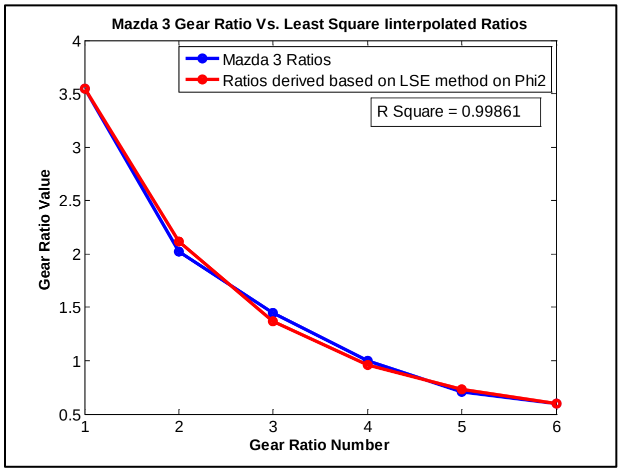


Figure 15 – Comparison of Actual Gear Ratios and Gear Ratios Calculated

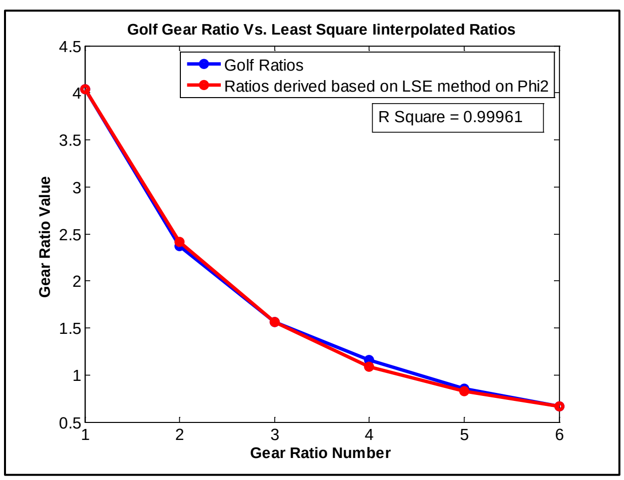


Figure 16 – Comparison of Actual Gear Ratios and Gear Ratios Calculated

A similar validation was performed with the Ford Focus and the Chevy Cruze. Table 3 shows the value of φ_2, which was calculated to minimize the LSE (Least Square Error) between calculated and actual gear ratios for the vehicles, in comparison to the value of φ_2 chosen for the study.

Table 3 – Progression Ratio for Numerous Vehicles with 6-speed AU.

	Ford Focus	Chevy Cruze	Mazda 3	Volkswagen Golf	Study
φ_2	1.09	1.04	1.08	1.08	1.07

In order to meet the criteria listed above, proper selection of shift parameters is equally important to the selection of gear ratios. Figure 17 shows the shape of the upshift and downshift curves for a 6-speed transmission. Of particular importance are shift parameters, which determine the upshift to top gear around 45 mph and downshift from top gear to prevent lugging.

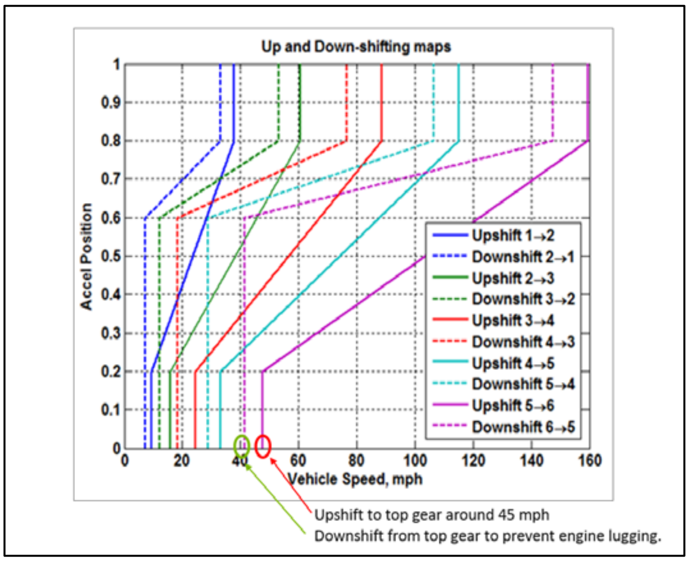


Figure 17 – Shifting Speed Curves for a 6-Speed Transmission Vehicle in Autonomie.

More shifting control details are described later on in this report.

Torque Converter Lock-up Assumptions

A quasi-static model is used to represent the torque converter. The torque converter is used as a start-up device in the first gear, with very low slip (torque ratio of 0.95) at higher speeds, in the first gear. Recent trends in torque converter technology suggest operation in locked or controlled slip mode, in the 2nd and higher gears. In general, the torque converter is in controlled slip or mechanically locked based on vehicle speed and pedal position, for each gear apart from the 1st. In order to suggest advances in torque converter technology, it was assumed that the torque converter would be in a mechanically locked state for the 2nd and higher gears.

5.3. Light-weighting

Light-weighting will be associated with the glider weight. Its secondary effect (such as downsizing) will be taken into account as part of the vehicle sizing algorithm. In this example, the base vehicle and the vehicles with higher levels of mass reduction are sized (10, 15 and 20%) are sized to meet the vehicle technical performance. Vehicles with lower levels of mass reduction inherit sizing characteristics from their respective baseline. The glider percentage mass reduction values selected for the example are:

- 0% (reference vehicle)
- 5% reduction
- 7.5% reduction
- 10% reduction
- 15% reduction
- 20% reduction

5.4. Rolling Resistance

The following rolling resistance reduction values were selected:

- 0% (reference vehicle)
- 10% reduction
- 20% reduction

These values were chosen to bound the possible rolling resistance improvements expected in future vehicles. No sizing is performed on this dimension.

5.5. Aerodynamic

The following aerodynamic reduction values were selected:

- 0% (reference vehicle)
- 10% reduction
- 20% reduction

These values were chosen to bound the possible rolling resistance improvements expected in future vehicles. No sizing is performed on this dimension.

5.6. Electric Drive Vehicles

Interest in electric drive vehicle technologies is growing, and their development accelerating, in the automotive industry. This growth represents a shift of focus from market entry and environmental drivers to mainstream, customer-committed development.

Hybrid Vehicles (HEVs) combine at least two energy sources, such as an internal combustion engine (ICE) or fuel cell system with an energy storage system. Electric drive vehicles have the potential to reduce fuel consumption in several ways, including the following:

- Regenerative braking: A regenerative brake is an energy mechanism that reduces the vehicle's speed by converting some of its kinetic energy into a storable form of energy for future use instead of dissipating it as heat, as with a conventional friction brake. Regenerative braking can also reduce brake wear and the resulting fine particulate dust.
- Engine shutoff under various driving conditions (e.g., vehicle stopped, low power demand).
- Engine downsizing, which may be possible to accommodate an average load (not a peak load), would reduce the engine and powertrain weight. Higher torque at low speed from the electric machine also allows the vehicle to achieve the same performance as conventional vehicles with a lower vehicle specific power (W/kg).
- Optimal component operating conditions: For example, the engine can be operated close to its best efficiency line.
- Accessory electrification allows parasitic loads to run on as-needed basis.
- The energy storage systems of PHEVs and battery electric vehicles (BEVs) can also be recharged, further improving fuel displacement.

However, vehicle electrification also have disadvantages that could affect fuel consumption, including increased vehicle weight due to additional components.

Two major types of hybrids have been considered for transportation applications: electrical and hydraulic. Since Hydraulic Hybrid Vehicles have been studied almost exclusively for medium- and heavy-duty applications, only HEVs have been used in this example.

HEVs combine electric and mechanical power devices. The main components of HEVs that differentiate them from conventional vehicles are the electric machine (motor and generator), energy storage (e.g., battery or ultra-capacitors), and power electronics. The electric machine absorbs braking energy, stores it in the energy storage system, and uses it to meet acceleration and peak power demands.

5.6.1. Electric Drive Powertrain Configurations

The various HEV powertrain configurations can be classified on the basis of their hybridization degree, as shown in Figure 18. The hybridization degree is defined as the percentage of total power that can be delivered electrically. The higher the hybridization degree, the greater is the ability to propel the vehicle using electrical energy.

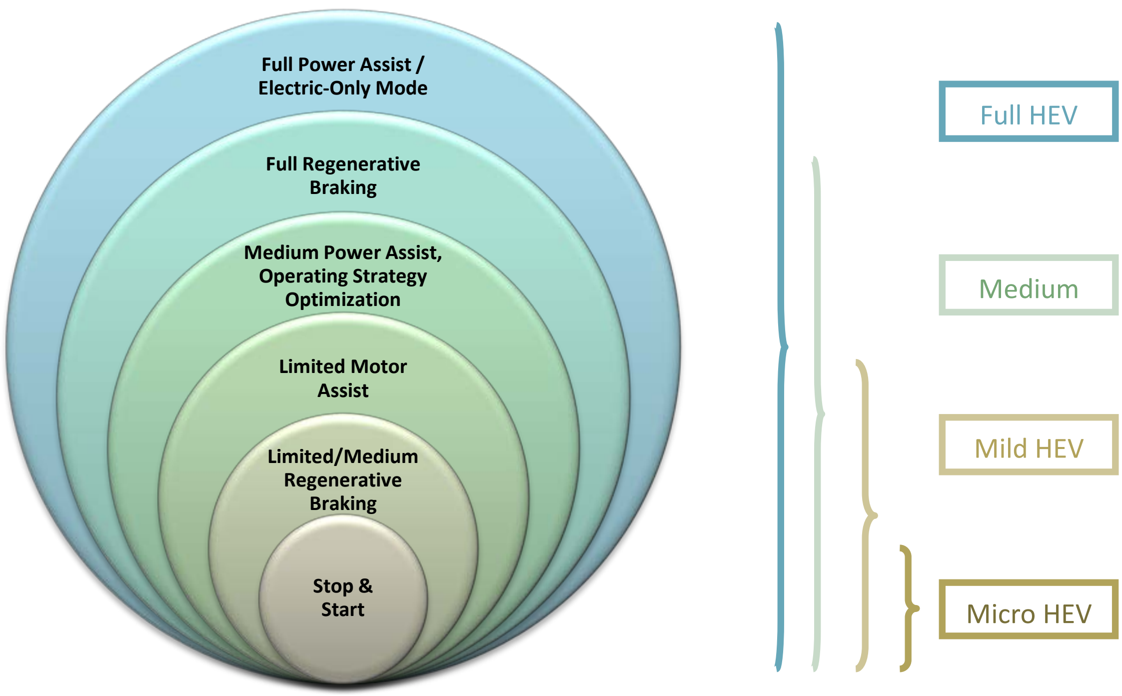


Figure 18 – Electric Drive Configuration Capabilities

A number of different powertrain architectures have been considered and introduced in the market for different applications. These architectures are usually classified into three categories: series, parallel, and power split. The following sections describe some of the possible powertrain configurations for each architecture.

5.6.2. Series Hybrid Vehicle

The first hybrids were generally based on a series configuration. As shown in Figure 19, series hybrid vehicles are propelled solely by electrical energy. When the engine is used, it provides a generator with mechanical power, which is then converted into electricity. In the case of a fuel-cell system, the electrical energy is directly used by the electric machine. The main advantage is that the engine speed is decoupled from the vehicle speed, allowing operating conditions at or close to the engine's most efficient operating point. The main drawback is that the main components have to be oversized to be able to maintain a uniform performance, leading to higher vehicle weight. Finally, the large number of components and the energy conversion from chemical to mechanical to electrical leads to lower powertrain efficiency.

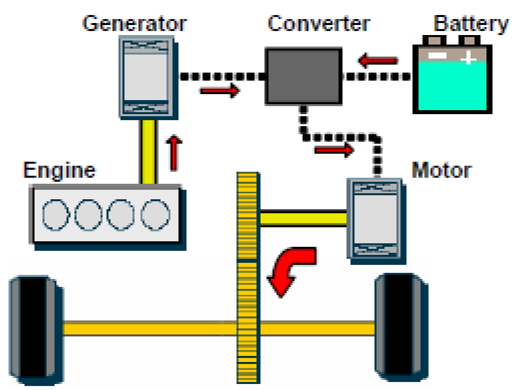


Figure 19 – Series Hybrid Electric Vehicle

Several variations of the series configuration have been considered. One of the important considerations in the design of a series HEV is related to the use of a single gear ratio versus a two-speed transmission. Using a single gear ratio usually leads to low maximum vehicle speed and poor performance at high speed due to the low electric machine torque in that operating regime. When applications require better performance at high speeds, a two-speed transmission is considered. If electric machines are used at each of the wheels, instead of one single electric machine, torque vectoring is possible, improving vehicle stability.

Currently, for light-duty vehicles, series configurations are essentially considered only for PHEV applications.

5.6.3. Parallel Hybrid Vehicle

In a parallel configuration, the vehicle can be directly propelled by either electrical or mechanical power. Direct connection between the power sources and the wheels leads to lower powertrain losses compared to the pure series configuration. However, since all of the components' speeds are linked to the vehicle's speed, the engine cannot routinely be operated close to its best efficiency curve.

Several subcategories exist within the parallel configuration:

- MHEV: A small electric machine is used. Control system turns the engine off when the vehicle is stopped and restarts the engine when the brake pedal is released. Examples include the Citroen C3.

- Starter-alternator: This configuration is based on a small electric machine directly connected to the engine (usually 5 to 15 kW) located between the engine and the transmission. Because of the low electric-machine power, this configuration is mostly focused on reducing consumption by eliminating idling. While some energy can be recuperated through regenerative braking, most of the negative electric-machine torque available is usually used to absorb the engine's negative torque. Since the electric machine speed is linked to the engine, the vehicle cannot operate in electric mode other than for extremely low speeds (e.g., creep). In addition, the electric machine is used to smooth the engine torque by providing power during high transient events to reduce emissions. The electric machine can be connected to the engine either through a belt or directly on the crankshaft. Examples include the Buick E-Assist (belt integrated), Honda Civic (crankshaft integrated), and Honda Accord (Crankshaft integrated).

- Pre-transmission: This configuration has an electric machine in between the engine and the transmission. The electric machine power ranges from 20 to 50kW for light duty applications, which allows the driver to propel the vehicle in electric-only mode as well as recover energy through regenerative braking. The pre-transmission configuration can take advantage of different gear ratios that allow the electric machine to operate at higher efficiency and provide high torque for a longer operating range. This configuration allows operation in electric mode during low and medium power demands, in addition to the ICE on/off operation. The main challenge for these configurations is being able to maintain a good drive quality because of the engine on/off feature and the high component inertia during shifting events. Examples of pre-transmission HEVs currently in production include the Hyundai Sonata Hybrid and the Infiniti M35 Hybrid.

- Post-transmission: This configuration shares most of the same capabilities as the pre-transmission. The main difference is the location of the electric machine, which in this case is after the transmission. The post-transmission configuration has the advantage of maximizing the regenerative energy path by avoiding transmission losses, but the electric machine torque must be higher because it cannot take advantage of the transmission torque multiplication.

5.6.4. Power Split Hybrid Vehicle

As shown in Figure 20, power split hybrids combine the best aspects of both series and parallel hybrids to create an extremely efficient system. The most common configuration, called an input split, is composed of a power split device (planetary gear transmission), two electric machines and an engine. Within this architecture, all these elements can operate differently. Indeed, the engine is not always on and the electricity from the generator may go directly to the wheels to help propel the vehicle, or go through an inverter to be stored in the battery. The operational phases for an input split configuration are the following:

- During vehicle launch, when driving, or when the state of charge (SOC) of the battery is high enough, the ICE is not as efficient as electric drive, so the ICE is turned off and the electric machine alone propels the vehicle.
- During normal operation, the ICE output power is split, with part going to drive the vehicle and part used to generate electricity. The electricity goes either to the electric machine, which assists in propelling the vehicle, or to charge the energy storage system. The generator also acts as a starter for the engine.
- During full-throttle acceleration, the ICE and electric machine both power the vehicle, with the energy storage device (e.g., battery) providing extra energy.
- During deceleration or braking, the electric machine acts as a generator, transforming the kinetic energy of the wheels into electricity to charge the energy storage system.

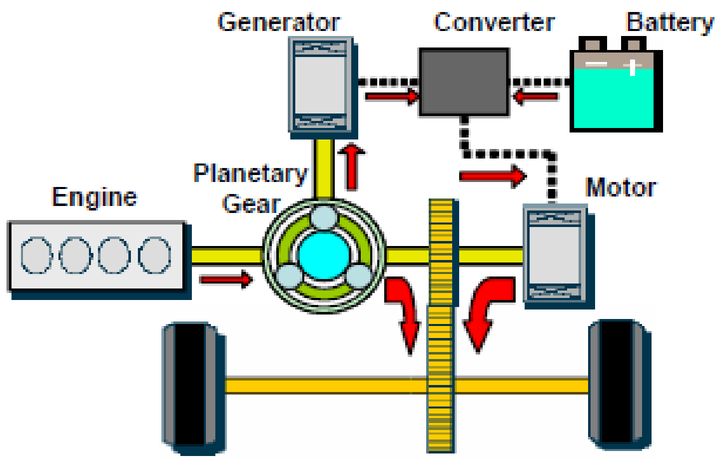


Figure 20 – Power Split Hybrid Electric Vehicle

Several variations of the power split have been implemented, including single-mode and multi-mode power splits. The Two-Mode Hybrid is a full hybrid system that enables significant improvement in composite fuel economy while providing uncompromised performance and towing capability. In city driving and stop-and-go traffic, the vehicle can be powered either by the two electric motors or by the ICE, or by both simultaneously. As shown in Figure 21, the Two-Mode Hybrid can also drive the vehicle using an input power-split range, a compound power-split range, or four fixed-ratio transmission gears. The system is flexible and efficient, with smaller motors, inverter module and battery that enable numerous cost advantages.

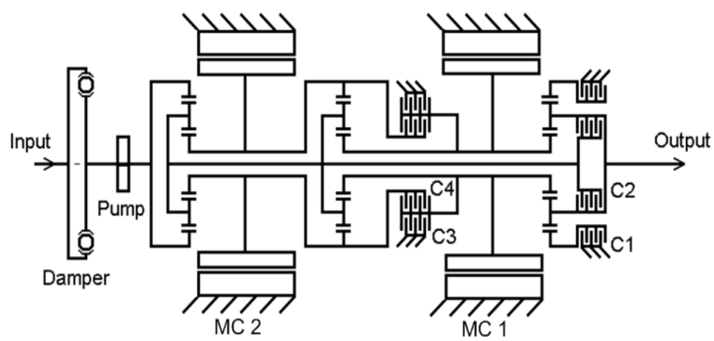


Figure 21 – Two Mode Transmission with Four Fixed Gears

The advantages of the Two-Mode Hybrid configuration are as follows:

- Transmits more power mechanically, which is more efficient and less costly.
- Delivers engine power with motors that are “right-sized” for regenerative braking and acceleration assist.

- Maintains high efficiency over a wider range.
- Has at least one fixed gear ratio available (shift ratio).
- Allows a synchronous shift between two modes.
- Uses two planetary gear sets: one for input power split and torque multiplication and both for compound power split.
- Allows high power density for an electro-mechanical infinitely variable transmission.

However, the addition of clutches to the transmission increases spin and pump losses and the engine may not be at its optimum point in the fixed-gear mode.

Examples of single-mode power split hybrids include the Toyota Prius and Ford Fusion Hybrid. An example of a multi-mode power split hybrid is the General Motors Chevrolet Tahoe.

5.6.5. Voltec Hybrid Vehicle

In the past couple of years, configurations allowing different operating modes (e.g., series and parallel, parallel and power split) have been introduced in the market. The Voltec configuration from General Motors is an example of these configurations. The Voltec powertrain architecture (Figure 22), also called the EREV (Extended Range Electric Vehicle), provides four modes of operating, including two that are unique and maximize the powertrain efficiency and performance. The electric transaxle has been specially designed to enable patented operating modes, both to improve the vehicle’s electric driving range when operating as a BEV and to reduce fuel consumption when extending the range by operating with an ICE. The EREV powertrain introduces a unique two-motor electric-vehicle (EV) driving mode that allows both the driving motor and the generator to provide tractive effort while simultaneously reducing electric motor speeds and the total associated electric motor losses. For HEV operation, the EREV transaxle uses the same hardware that enables one-motor and two-motor operation to provide both the completely decoupled action of a pure series hybrid and a more efficient flow of power with decoupled action for driving under light load and at high vehicle speed.

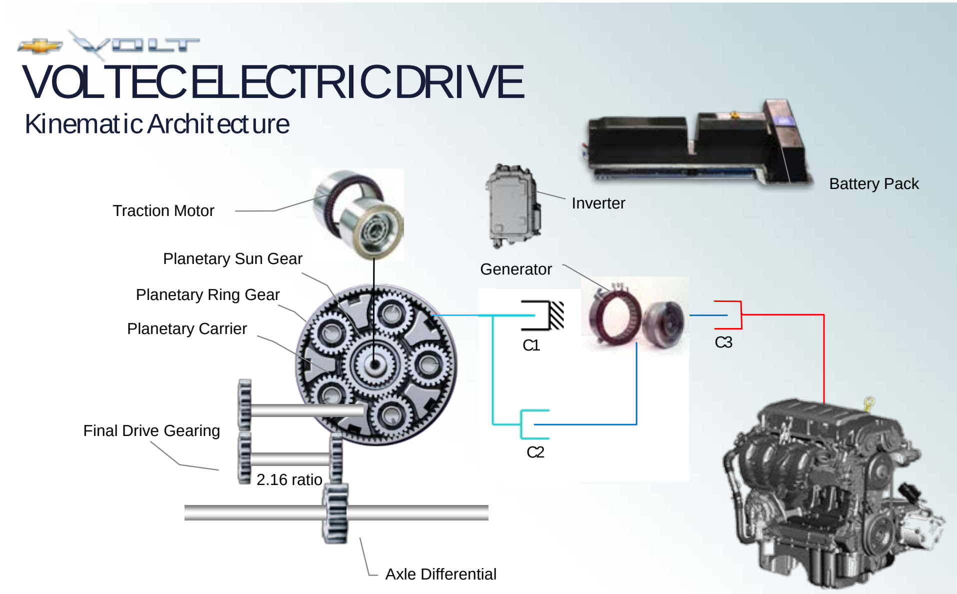


Figure 22 – Voltec Hybrid Electric Vehicle [source: www.gm.com]

It is important to note that many different variations exist within each configuration (i.e., power-split configurations can be single-mode, two-mode, three-mode, etc.) and between configurations (i.e., several configurations are considered to be a mix of series, parallel and/or power-split). Overall, several hundred configurations are possible for electric-drive vehicles.

5.6.6. Plug-in Hybrid Electric Vehicle

PHEVs differ from HEVs in their ability to recharge the energy storage system through the electric grid. PHEVs energy storage systems have usually a higher total energy compared to HEVs and they also use a larger portion of it (e.g., when most HEVs use 10 to 15% of their total battery energy, PHEVs use from 60 to 70%). Since the vehicle is designed to have a high capacity energy storage, electrochemical batteries are usually used for this application. All the HEV configurations described above can be used as PHEVs. In most cases, because of the desire to propel the vehicle using electrical energy from the energy storage system, the electric machine power is greater for a PHEV compared to an HEV.

5.7. Vehicle-Level Control

The task of achieving fuel savings with a hybrid architecture depends on the vehicle performance requirements and the type of powertrain selected as well as the component sizes and technology, the vehicle control strategy, and the driving cycle. The overall vehicle-level control strategy is critical to minimize fuel consumption while maintaining acceptable drive quality. Figure 23 illustrates a simple acceleration, cruising and braking cycle for a full HEV, demonstrating the best usage of different power sources based on the vehicle's power demand. During small accelerations, only the energy storage power is used (EV mode) and during braking, some of the energy is absorbed and stored. The engine does not start to operate during low power demands, owing to its poor efficiency compared to the electrical system. The engine is only used during medium and high power demands, where its efficiency is higher.

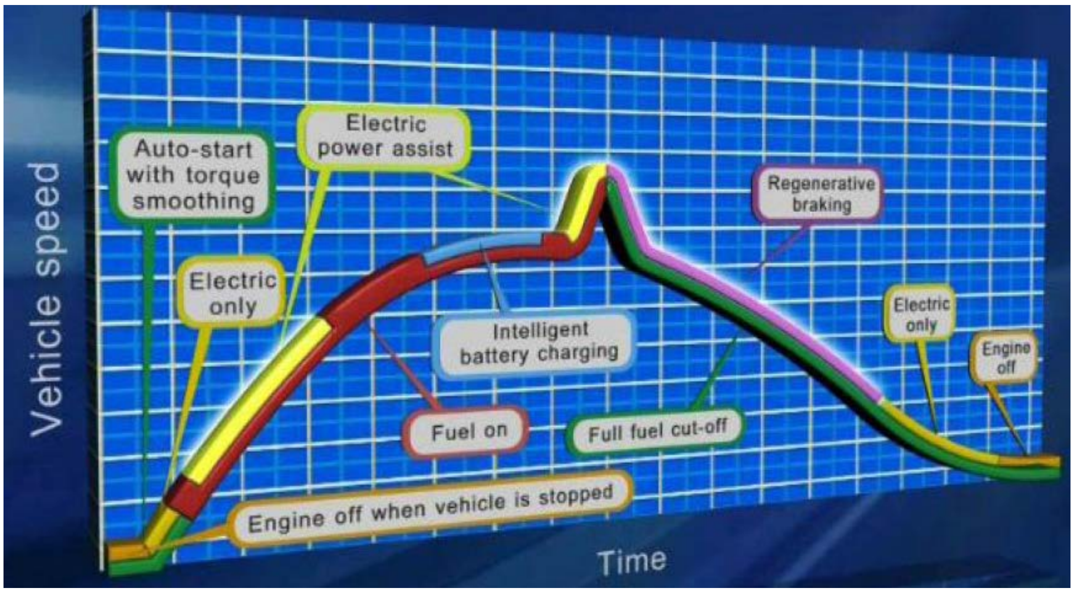


Figure 23 – Hybrid Electric Vehicle Principles [source: www.gm.com]

While different vehicle-level control strategy approaches have been studied for electric drive vehicles (e.g., rule based, dynamic programming, instantaneous optimization), the vast majority of current and future electric drive vehicles are using and expected to use rule-based control strategies. The vehicle level control strategies used in this example will be described later in the report.

5.8. Powertrain Electrification

The selection of hybridization degree and powertrain configuration is complex, since numerous options exist. On the basis of current production vehicles as well as anticipated near-future trends, the following powertrain configurations were selected for this example:

- 12-V micro-hybrid electric vehicle (micro-HEV/start-stop system – no regenerative braking.)
- Belt-integrated starter generator (BISG)
- Crank-integrated starter generator (CISG)
- Full hybrid electric vehicle (HEV), single-mode power split configuration with fixed ratio

- Full hybrid electric vehicle (HEV), Pre-Transmission configuration with 6-speed DCT.
- Fuel cell HEV, series configuration, with 320-mile range on the FTP drive cycle
- PHEV, single-mode power split configuration with fixed ratio, with 20 AER on the FTP (standard urban) drive cycle
- PHEV, Voltec extended-range electric vehicle (EREV) configuration with 30 AER on the FTP drive cycle
- PHEV, Voltec EREV configuration, with 50 AER on the FTP drive cycle
- Battery electric vehicle (BEV), with 200 AER on the FTP drive cycle

Note that the AER values are based on unadjusted electrical consumptions. In addition, the belt losses were included for both the micro-HEV and BISG cases. The pre-transmission parallel configuration was not selected for PHEVs because the single-mode power split configuration is expected to represent the highest volume of vehicles in the timeframe considered and provide a lower fuel consumption.

6. Vehicle and Component Assumptions

The purpose of this study is to demonstrate the feasibility of the Large Scale Simulation Process (LSSP) rather than to generate final simulation results. Therefore, the vehicle and component assumptions will only be briefly described in this section. Future studies in the next phase of this project will provide additional detail on the technology and control strategy specifications.

6.1. Reference Vehicle

To demonstrate feasibility of the process, a single vehicle class will be presented: Midsize vehicle. The reference vehicle is a midsize car with conventional powertrains and the specifications summarized below in Table 4.

Table 4 – Reference Vehicle Main Specifications

Baseline Vehicle Specification	Values
Glider mass (kg)	1,000
Drag coefficient	0.31
Frontal area (m^2)	2.3
Rolling resistance coefficient 1	0.008
Rolling resistance coefficient 2 (speed term)	0.00012

All the mechanical losses of the components required to run the engine on the dynamometer are included in the engine maps.

6.2. Transmission

As shown previously, the transmission ratios were selected to represent typical values for high-volume vehicles currently on the market.

Power-split HEV and PHEV 20 AER transmissions have a planetary gear set with 78 ring teeth and 30 sun teeth, similar to the Toyota Prius. The PHEV 40 AER has a planetary gear set with 83 ring teeth and 37 sun teeth, similar to the GM Voltec. Fuel cell vehicles use a two-speed manual transmission to increase the powertrain efficiency as well as allow them to achieve a maximum vehicle speed of at least 100 mph. BEVs are fixed gear.

The transmission shifting logic has a significant impact on vehicle fuel economy and should be carefully designed to maximize the powertrain efficiency while maintaining acceptable drive quality. The logic used in the simulated conventional light-duty vehicle models relies on two components: (1) the shifting controller, which provides the logic to select the appropriate gear during the simulation; and (2) the shifting initializer, the algorithm that defines the shifting maps (i.e., values of the parameters of the shifting controller) specific to a selected set of component assumptions.

Figure 24 shows an example of a complete set of shifting curves for a light-duty vehicle. Two curves of the same color (i.e., upshifting and downshifting curves) never intersect, thus ensuring that there are no shift oscillations, which is important for drivability.

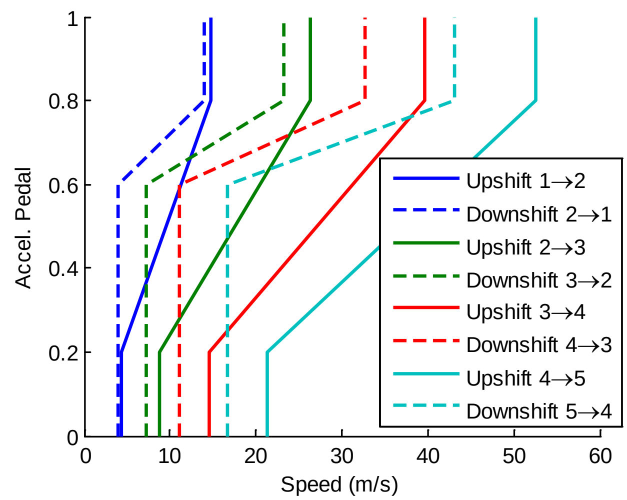


Figure 24 – Shifting Speed Curves for Light-Duty Vehicle in Autonomie

The shifting control algorithm used for the simulation is explained in the following section.

6.3. Control Algorithm

6.3.1. Shifting Control Algorithms

The transmission shifting logic has a significant impact on vehicle fuel economy and should be carefully designed to maximize the powertrain efficiency while maintaining acceptable drive quality. The logic used in the simulated conventional light-duty vehicle models relies on two components:

- The shifting controller, which provides the logic to select the appropriate gear during the simulation; and
- The shifting initializer, the algorithm that defines the shifting maps (i.e., values of the parameters of the shifting controller) specific to a selected set of component assumptions.

6.3.1.1. Shifting Controller

The shifting controller determines the appropriate gear command at each simulation step. A simplified schematic of the controller is shown in Figure 25. The letters and numbers in the discussion that follows correspond to those shown in the figure.

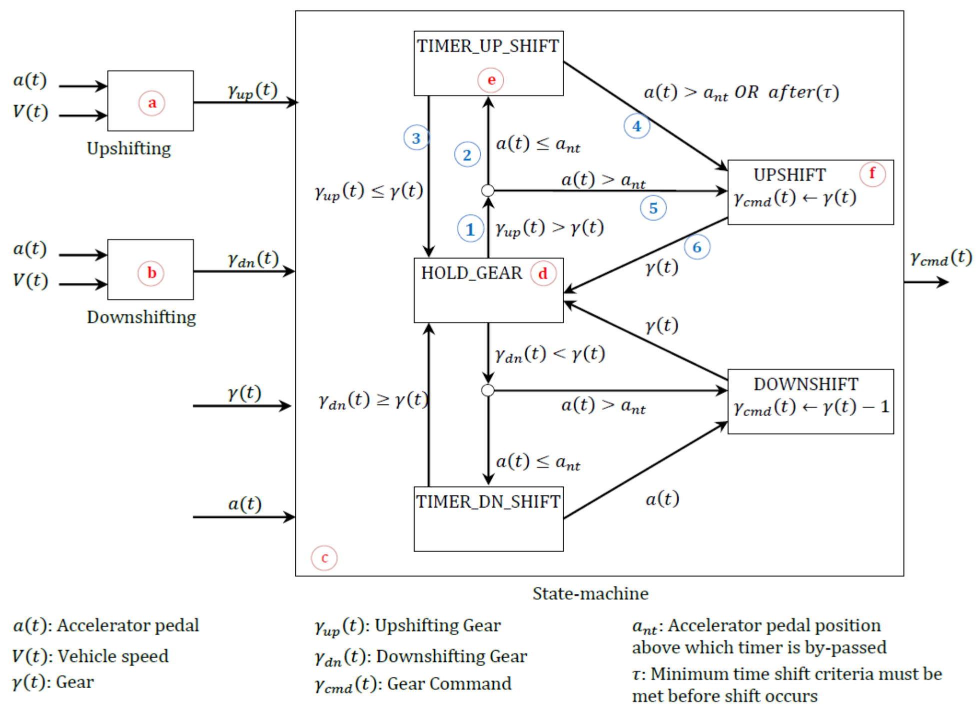


Figure 25 – Shifting Controller Schematic

The controller is based on two main shifting maps — one for upshifting (a), moving from a lower gear to a higher gear, and another one for downshifting (b), moving from a higher gear to a lower gear — as well as a state-machine (c) that defines the status of the system (e.g., no shifting, upshifting). Each shifting map outputs a next-gear command $\gamma_{dn}(t)$ and $\gamma_{up}(t)$ based on the current accelerator pedal position *a(t)* and vehicle speed *V(t)*. The state machine is composed of different states, of which only one is active at any time step; a change in state occurs whenever a transition condition from the active state becomes true (i.e., an upshift will occur only if a set of conditions is true). The state that is active most of the time is the hold-gear state (d), which makes sense because, most of the time, the vehicle should be in gear and not shifting for drivability reasons. An upshift occurs when the upshifting gear $\gamma_{up}(t)$ is strictly higher than the current gear $\gamma(t)$ (1) (e.g., $\gamma_{up}(t) = 5\ and\ \gamma(t) = 4$). For all vehicles, the shift does not necessarily happen instantly when the command to shift is given, depending on the current pedal position. In aggressive driving, i.e., at high accelerator-pedal positions (5), the shift happens as soon as the gear transition (1) becomes true, ensuring optimal performance. In contrast, in "normal" driving, i.e., at low pedal positions (2), there is an intermediate state (e) that allows the shift only when the gear condition (1) is true for a minimum time τ. This constraint is imposed to avoid an excessive number of shifting events, which would lead to unacceptable drive quality and increased fuel consumption. The upshifting itself is executed in state (f), in which the shift command $\gamma_{cmd}(t)$ is incremented (i.e., the next upper gear is selected); once the shifting is completed (6), the state machine comes back to the hold-gear state (d). Downshifting occurs in a similar way.

Currently, in Autonomie, a shifting event can only result in moving one gear up or one gear down: there is no gear-skipping. Gear skipping is usually used under very specific conditions that are not encountered during the standard FTP and HFET drive cycles considered in the study. As an additional level of robustness in the Autonomie control algorithm, an upshift or downshift cannot occur if the resulting engine speed would be too low or too high, respectively. This approach ensures that the engine is not operated below idle or above its maximum rotational speed.

6.3.1.2. Shifting Initializer

Shifting Maps

The shifting controller uses shifting maps to compute the gear command. In the controller, the shift map is a two-dimensional (2-D) look-up table indexed by vehicle speed and accelerator-pedal position. Defining such a map is equivalent to defining the "boundaries" of each gear area; those boundaries are the shifting speeds. Figure 26 illustrates that equivalence.

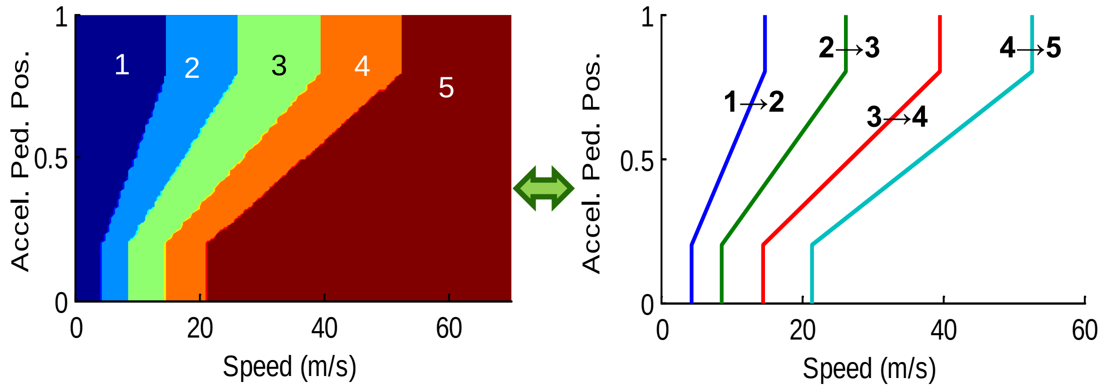


Figure 26 – Upshifting Gear Map (left), Upshifting Vehicle Speeds (right)

For each shifting curve, there are two key points: the "economical" shifting speed (at very low pedal position) and the "performance" shifting speed (at high pedal position). The objective of the control engineer is to combine both goals of the shifting control to fulfill the driver expectations: minimization of fuel consumption on the one hand and maximization of vehicle performance on the other.

Economical Shifting Speeds

The economical shifting speed for an upshift or a downshift is the speed at which the upshift/downshift occurs when the accelerator pedal position is very lightly pressed. $V_{eco}^{k\to k+1}$ is the economical vehicle speed for upshifting from gear *k* to gear *k*+1. $V_{eco}^{k+1\to k}$ is the downshifting speed for this same set of gears. The vehicle speed shift points are computed from the engine shift points $\omega_{eco}^{k\to k+1}$ and $\omega_{eco}^{k+1\to k}$. Figure 27 shows the engine speed shift points for an engine associated with a 5-speed transmission.

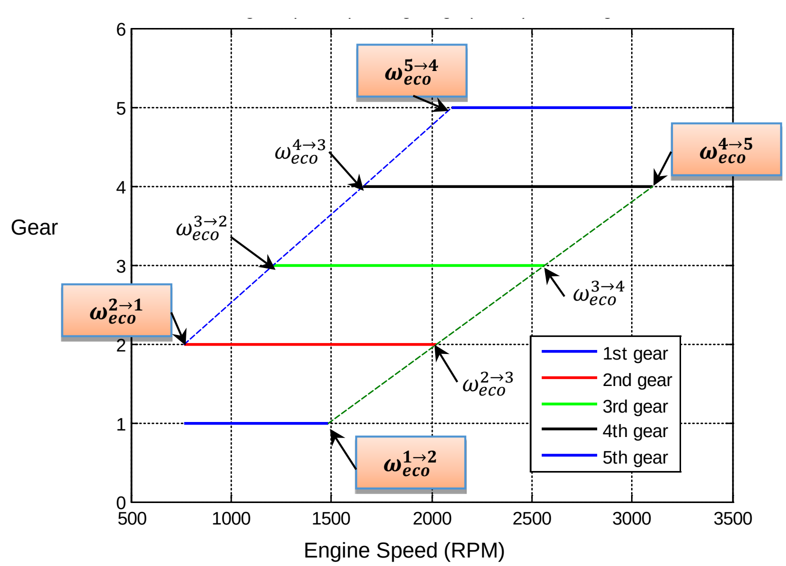


Figure 27 – Example of Engine Speed Range in Economical Driving, and Economical Shift

The initializing algorithm for the shifting controller computes the up- and downshifting speeds at zero pedal position based on the four "extreme" shift points: upshifting from lowest gear ($\omega_{eco}^{1\to2}$), upshifting into highest gear ($\omega_{eco}^{N-1\to N}$), downshifting into lowest gear ($\omega_{eco}^{2\to1}$), and downshifting from highest gear ($\omega_{eco}^{N\to N-1}$). N is the number of gears. The speeds can be set by the user or left at their default values. Below is a description of their default values in Autonomie:

- $\omega_{eco}^{2\to1}$=$\omega_{idle} + \omega_{margin}$ [ω_{idle}: engine idle speed; ω_{margin}: speed margin, ≈50–100 rpm]
- $\omega_{eco}^{1\to2} = \omega_{idle}\frac{k_1}{k_2}(1+\epsilon_{ud})$ [k_1,k_2: gear ratios for gears 1,2; ϵ_{ud}: margin to avoid overlap, ≈ 0.05–0.1]
- $\omega_{eco}^{N-1\to N}$: Engine speed at which best efficiency can be achieved
- $\omega_{eco}^{N\to N-1} = \omega_{eco}^{N-1\to N} - \omega_{\Delta}$ [$\omega_{\Delta} \approx 1{,}000 \text{ rpm}$]

Once those four speeds are computed, the remaining ones are computed by linear interpolation to allow consistent shifting patterns that are acceptable to the drivers. For example, any upshifting speed is given by Equation 1:

$$\omega_{eco}^{i\to i+1} = \frac{\omega_{eco}^{N-1\to N} - \omega_{eco}^{1\to2}}{N-2}\cdot(i-1) + \ \omega_{eco}^{1\to2}\,, \qquad 1 \le i \le N-1$$

In a shifting map, the vehicle upshifting speed from gear *i* to *i*+1 shall be strictly higher than the downshifting speed from gear *i*+1 to *i*. Otherwise, the downshifting speed will always request gear *i* while gear *i*+1 is engaged and vice-versa, resulting in oscillations between gears that would be unacceptable to the driver. For this study, the algorithm in the initialization file prevents that by making sure the following relation is true:

$$\omega_{eco}^{i\to i+1} > \omega_{eco}^{i+1\to i}\cdot\frac{k_1}{k_2}(1+\epsilon_{ud}), \qquad 1 \le i \le N-1$$

The values of the engine economical shifting speeds at lowest and highest gears are automatically defined on the basis of the engine and transmission characteristics.

Finally, the vehicle economical up- and downshifting speeds can be computed using the engine up- and downshifting speeds, the gear ratio, the final drive ratio and the wheel radius:

$$V_{eco}^{i\to i+1} = \frac{\omega_{eco}^{i\to i+1}}{k_i k_{FD}}\cdot R_{wh}\,,$$

where k_{FD} is the final drive ratio and R_{wh} is the wheel radius.

Performance Shifting

During performance, the gears are automatically selected to maximize the torque at the wheel. Figure 28 illustrates that gear selection, which consists of finding the point where the engine peak torque (reported at the wheels) curve at gear *k* falls under the one at gear *k*+1.

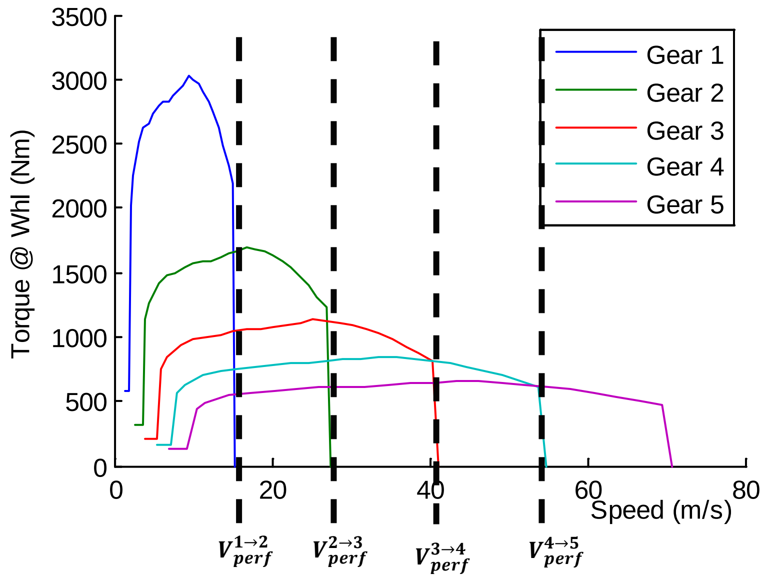


Figure 28 – Maximum Engine Torque at Wheels and Performance Upshift Speeds

The performance downshifting speed is given by the performance upshifting speed and the difference between the economical shifting speeds:

$$\Delta V_{perf}^{i} = \alpha_{pf,ec} \cdot \Delta V_{eco}^{i} \;\Leftrightarrow\; V_{perf}^{i\to i+1} - V_{perf}^{i+1\to i} = \alpha_{pf,ec} \cdot (V_{perf}^{i\to i+1} - V_{perf}^{i+1\to i})$$

Final Shifting Curves

The definition of the final shifting curves is critical to properly evaluating the benefits of transmission technologies while maintaining acceptable performance. Figure 29 shows how a set of upshifting and downshifting curves for two adjacent gears is built, based on selected vehicle speeds and accelerator pedal positions. At low pedal positions (i.e., below a_{eco}^{up}), the upshifting speed is the economical upshifting speed. Similarly, below a_{eco}^{dn}, the downshifting speed is the economical downshifting speed. This approach ensures optimal engine operating conditions under gentle driving conditions. At high pedal positions (i.e., above a_{perf}), the shifting speed is the performance shifting speed, ensuring maximum torque at the wheels under aggressive driving conditions.

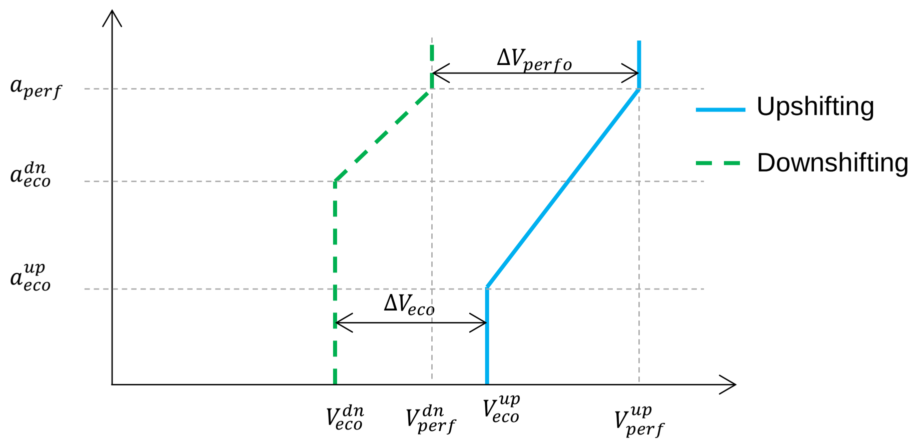


Figure 29 – Design of Upshifting and Downshifting Speed Curves for Two Adjacent Gears

6.3.1.3. Torque Control during Shifting Events

Figure 30 shows the transmission clutch pressure, output torque, and engine speed curves during a change from 1st to 2nd gear. The output torque experienced both a trough period (lower than the torque in the original gear) and a crest period (higher than the torque in the original gear). The trough period is called a torque hole, while the crest period is called a torque overshoot. The torque hole is defined by depth and width, where the depth is the difference between minimum torque and the torque in previous gear, and the width is the half value of the maximum width of the torque hole.

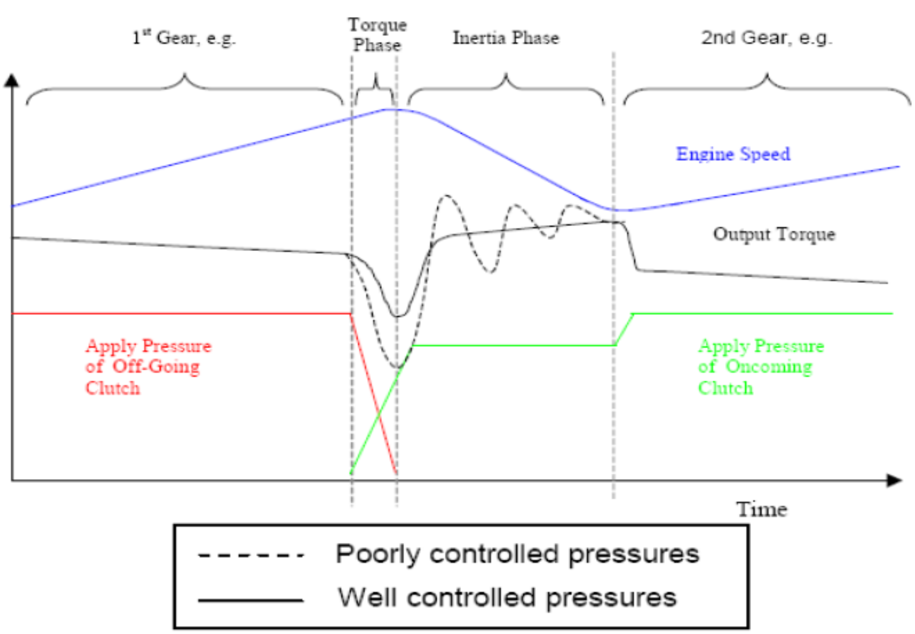


Figure 30 – Generic Shift Process for Automatic Transmission

The bigger the torque hole, the larger the decrease of torque in torque phase, which results in a more significant reduction in acceleration. Because the decrease in acceleration causes discomfort for both the driver and passengers, the torque hole should be as shallow and narrow as possible. Torque reduction behavior is a well-known phenomenon, observed during vehicle testing and referenced in several papers and presentations.

Autonomie integrates a low-level control algorithm that reproduces the torque hole phenomenon. Figure 31 illustrates, in detail, the behavior of the vehicle model for a short period of time [205 sec to 205.8 sec]. The area highlighted by the grey circle indicated the torque hole during a shifting event.

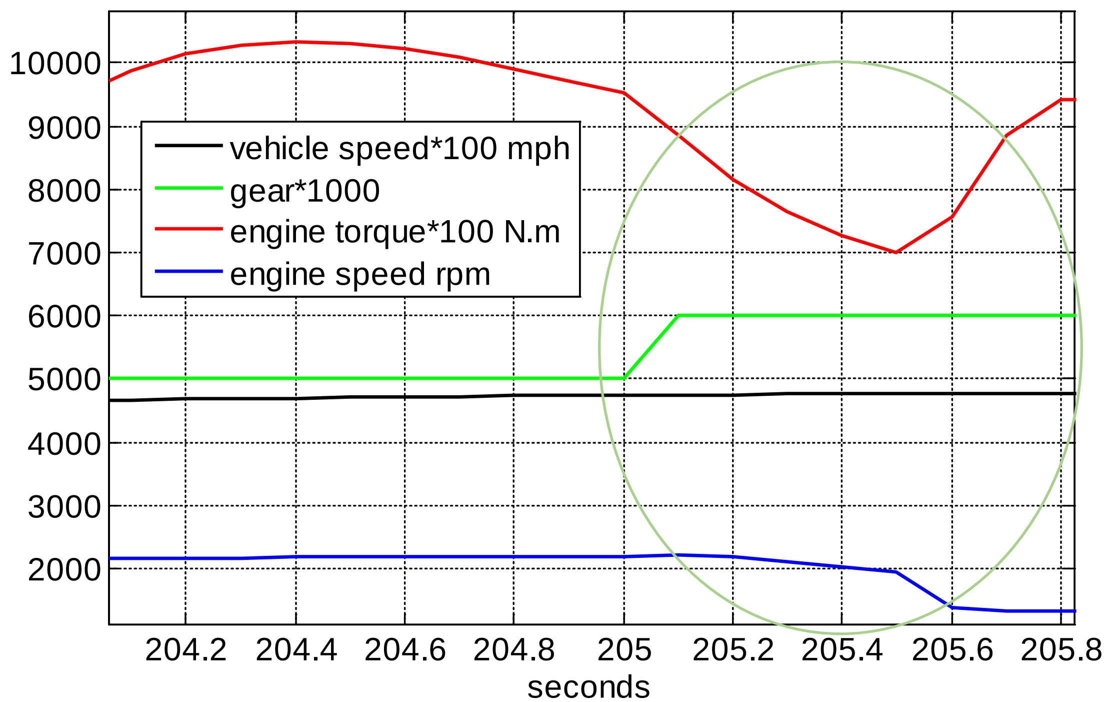


Figure 31 – Torque Hole in Autonomie during Shifting Event

6.3.1.4. Shifting Maps

All shifting maps used for the simulations are presented below. The shifting maps have been developed to ensure minimum fuel consumption across all transmissions while maintaining an acceptable drivability. While plant models with higher degree of fidelity would be necessary to accurately model the impact of each technology on the drivability, using such models was not appropriate for the current study. As a result, the work related to the drive quality was focused on number of shifting events, time in between shifting events, engine time response and engine torque reserve.

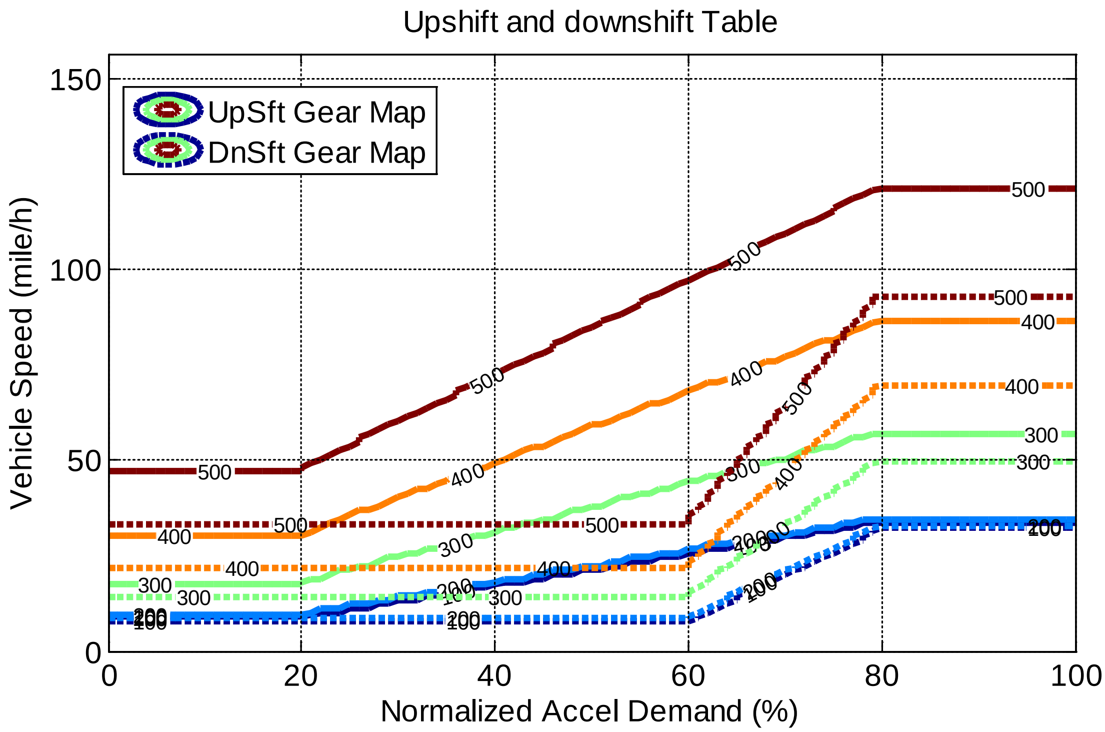


Figure 32 – 5-speed automatic up (plain lines) and down (dotted lines) shifting map

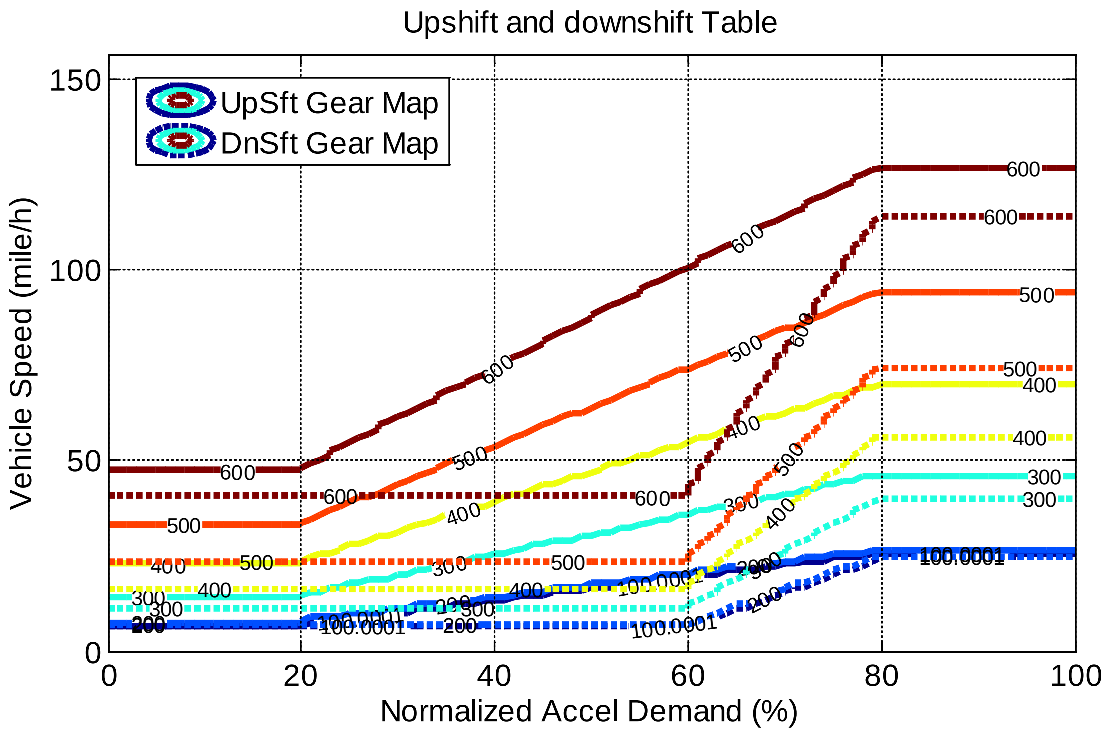


Figure 33 – 6-speed automatic up (plain lines) and down (dotted lines) shifting map

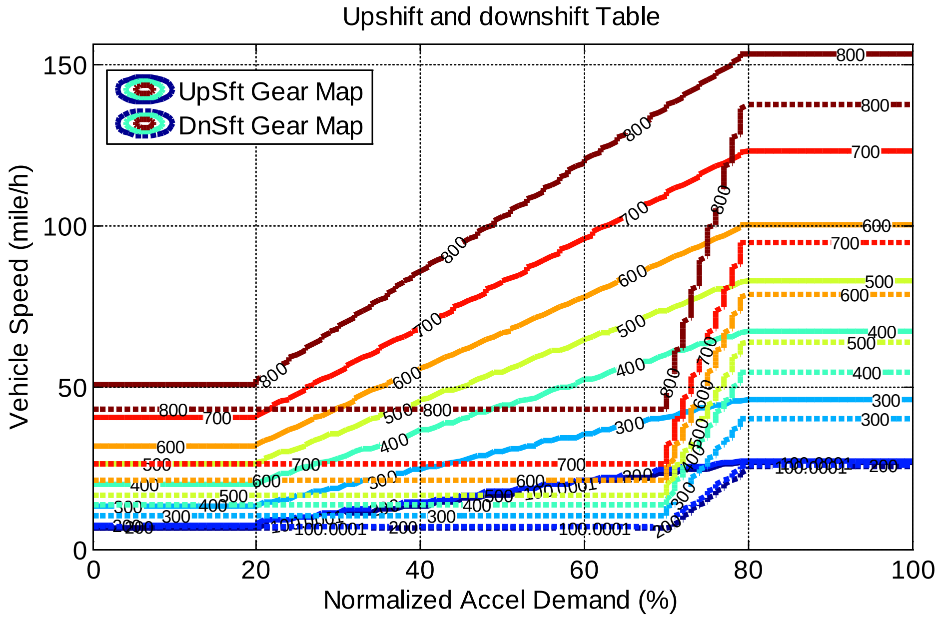


Figure 34 – 8-speed automatic up (plain lines) and down (dotted lines) shifting map

6.3.2. Torque Converter

A torque converter is a hydrodynamic fluid coupling used to transfer rotating power from a prime mover, such as an internal combustion engine, to a rotating driven load. It is composed of an impeller (drive element); a turbine (driven component); and a stator, which assist the torque converter function. The torque converter is filled with oil and transmits the engine torque by means of the flowing force of the oil. The device compensates for speed differences between the engine and the other drivetrain components and is therefore ideally suited for start-up function.

The torque converter is modeled as two separate rigid bodies when the coupling is unlocked and as one rigid body when the coupling is locked. The downstream portion of the torque converter unit is treated as being rigidly connected to the drivetrain. Therefore, there is only one degree of dynamic freedom, and the model has only one integrator. This integrator is reset when the coupling is locked, which corresponds to the loss of the degree of dynamic freedom. Figure 35 shows the efficiency of the torque converter used for the study.

The effective inertias are propagated downstream until the point where actual integration takes place. When the coupling is unlocked, the engine inertia is propagated up to the coupling input, where it is used for calculating the rate of change of the input speed of the coupling. When the coupling is locked, the engine inertia is propagated all the way to the wheels.

The torque converter model is based on a lookup table, which determines the output torque depending on the lockup command. The upstream acceleration during slip and the downstream acceleration are taken into account in calculating the output speed.

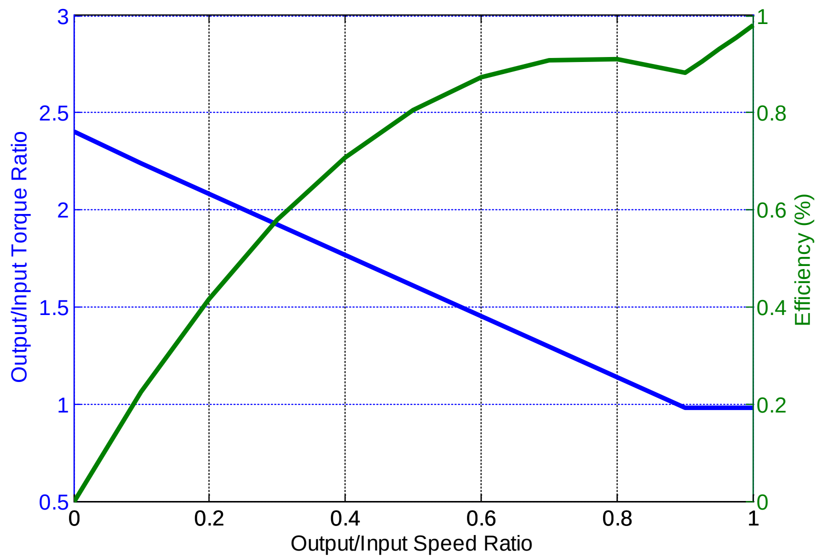


Figure 35 – Torque Converter efficiency

Figure 36 describes the conditions under which the torque converter will be locked. The same algorithm is used to represent current torque converter lockup logic, as well as future aggressive lockup logic. In today's vehicles, the torque converter locks at vehicle speeds between 30 and 40 mph under most driving conditions. In the future, it is expected that it can be locked as soon as the second gear is engaged. Different sets of parameters were developed in the algorithm to represent both current and future lock-up conditions.

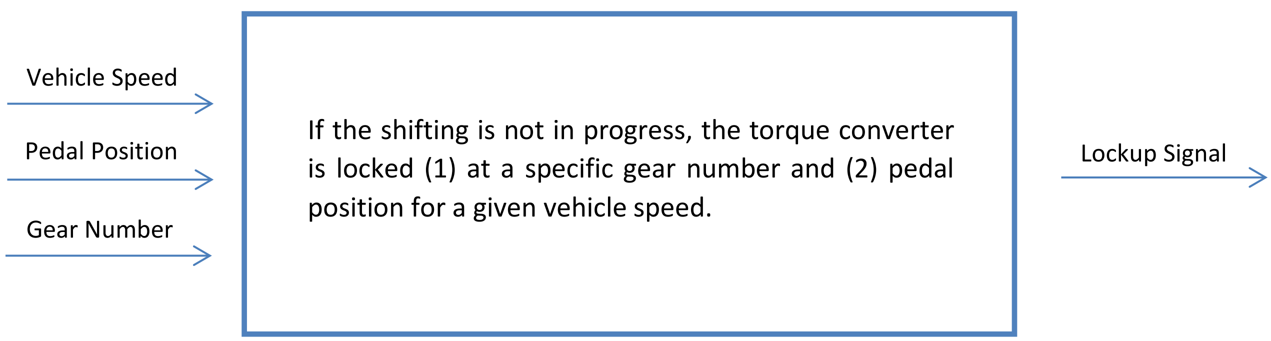


Figure 36 – Torque Converter Lockup Control Algorithm

6.4. Electric Machine

Electric machine performance data were provided by Oak Ridge National Laboratory and represent a synchronous permanent-magnet technology. Figure 37 is the electric machine efficiency map used for the micro-HEV, BISG, and CISG; and Figure 38 is the map for the HEV and PHEVs. The maps were developed assuming normal temperature operating conditions. Electric machine inverter losses are included in the maps.

Figures 10 and 11 represent peak torque curves. A constant ratio was assumed between the continuous and peak torque curves, as follows:

- 2 for the micro-HEV, BISG, and CISG
- 2 for the motor 1 and 1.5 for the motor 2 of the power-split HEV and blended PHEV
- 1 for EREV, BEVs, and fuel cell HEV

The electric machine specific weight is 1,080 W/kg and its controller 12,000 W/kg. The peak efficiency is set to 90%.

The main focus of BISG hybrid vehicles is to capture regenerative braking energy as well as provide minimal assist to the engine during high-transient operating modes. Because the electric machine is linked to the engine through a belt, its power is usually limited. A value of 7 kW is assigned to the BISG for this project.

CISG hybrid vehicles focus on the same areas of improvement as BISG vehicles. However, owing to its position, the electric machine can be larger; consequently, more benefits can be obtained from regenerative braking and assist in a CISG vehicle than in a BISG vehicle. An electric machine size of 15 kW was selected for the midsize car.

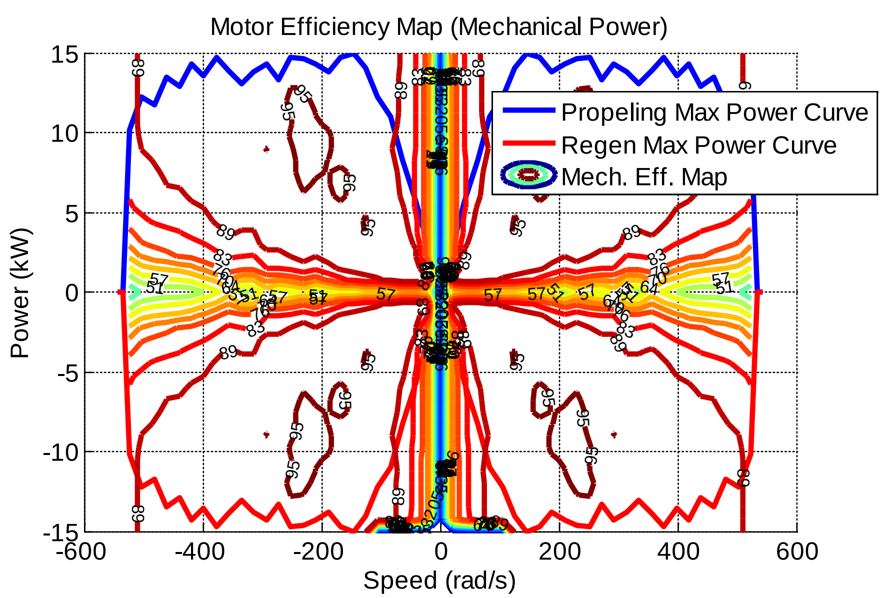


Figure 37 – Electric Machine Map for Micro- and Mild HEV

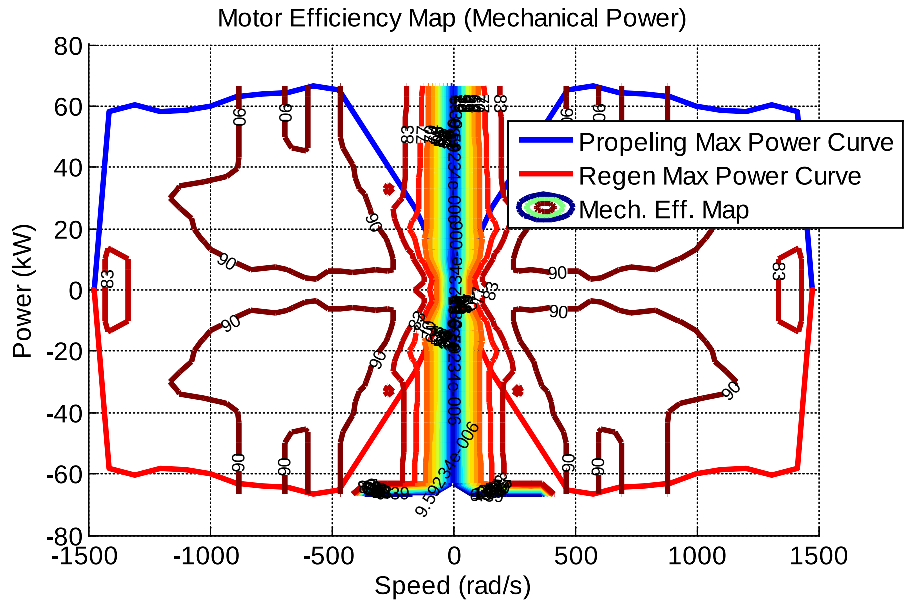


Figure 38 – Electric Machine Map for Full HEV

6.5. Fuel Cell System

The fuel cell system is modeled to represent the hydrogen consumption as a function of the produced power. The system's peak efficiency is 59%, including the balance of plant, and represents normal temperature operating conditions. The data set cannot be provided here because it is proprietary. The system's specific power is 659 W/kg.

The hydrogen storage technology selected is a high-pressure tank with a specific weight of 0.04 kg H_2/kg, sized to provide a 320-mile range on the FTP drive cycle.

6.6. Energy Storage System

The battery used for the BISG and CISG HEVs and the PHEVs is lithium-ion. Table 5 provides a summary of the battery characteristics and technologies used by each powertrain.

Table 5 – Reference Battery Characteristics

Powertrain Types	Technology	Reference Cell Capacity (Ah)
Micro-HEV	Lead acid	66
BISG	Li-ion	6
CISG	Li-ion	6
HEV	Li-ion	6
PHEVs	Li-ion	41

The battery capacity selected for each option to allow a global pack voltage between 200 V (full HEV case) and 350 V (BEV case). The energy storage cell weights for the PHEVs are based on 92 Wh/kg for PHEVs 30 and 50 AER; and 90 Wh/kg for the BEVs based on battery total energy. The energy storage cell weights for micro-HEV, BISG, CISG, and full HEVs are based on 2000 W/kg.

Different useable state-of-charge (SOC) ranges have also been selected depending on the powertrain configuration:

- 10% SOC range for micro, mild, and full HEVs.
- 60% SOC range for PHEVs and 95% for BEVs.

Over time, batteries lose some of their power and energy capacity. To be able to maintain the same performance at the end of life (EOL) compared with the beginning of life (BOL), an oversize factor is applied while sizing the batteries for power (HEVs) and energy (PHEV). These factors are supposed to represent the percentage of power and energy that will not be provided by the battery at the EOL compared with the initial power and energy given by the manufacturer. The performance data used to model the other components are based on normal temperature operating conditions. The vehicles are sized with a 20% power oversize factor for all hybrid vehicles and energy oversize factors of 30% for PHEVs. BEVs 200 AER are not oversized.

Vehicle test data have shown that, for the drive cycles and test conditions considered, battery cooling does not draw a significant amount of energy, if any at all, for most of the vehicle powertrain architectures. The exception is high energy PHEVs and BEVs, for which an additional constant power draw is used to account for battery cooling.

The energy storage system block models the battery pack as a charge reservoir and an equivalent circuit. The equivalent circuit accounts for the circuit parameters of the battery pack as if it were a perfect open-circuit voltage source in series with an internal resistance and 2 RC circuits which represent the polarization time constants. The amount of charge that the energy storage system can hold is taken as constant, and the battery is subject to a minimum voltage limit. The amount of charge required to replenish the battery after discharge is affected by coulombic efficiency. A simple single-node thermal model of the battery is implemented with parallel-flow air cooling.

The voltage is calculated at t=0 as $V_{out} = V_{oc} - R_{int} * I$, with V_{oc} = open-circuit voltage, R_{int} = internal resistance (two separate sets of values for charge and discharge), and I = internal battery current (accounts for coulombic efficiencies).

6.7. Accessory Loads

Electrical and mechanical accessory base loads are assumed constant over the drive cycles, with a value of 220 W. Derived from data from Argonne's Advanced Powertrain Research Facility, this value is used to represent the average accessory load consumed during the standard urban FTP and EPA's Highway Fuel Economy Test (HFET) drive-cycle testing on a dynamometer. Only the base load accessories are assumed during the simulations, similarly to the dynamometer test procedure.

6.8. Driver

The driver model is based on a look-ahead controller. No anticipation is imposed (0 sec anticipated time) during sizing for acceleration testing, in order to provide realistic vehicle performances.

6.9. Vehicle-Level Control Algorithms

All the vehicle-level control algorithms used in the study have been developed on the basis of vehicle test data collected at Argonne's Advanced Powertrain Research Facility. It is important to note that while the logic for the vehicle-level control algorithms were developed on the basis of test data, only the logic has been used for the present study, since the calibration parameters have been adapted for each vehicle to ensure fuel consumption minimization with acceptable drive quality (i.e., acceptable number of engine on/off conditions).

6.9.1. Micro- and Mild HEV

The vehicle-level control strategies of the micro- and mild (i.e., BISG and CISG) micro-HEVs is similar in many aspects due to the low peak power and energy available from the energy storage system.

For the micro HEV case, the engine is turned off as soon as the vehicle is fully stopped and restarted as soon as the brake pedal is released. No regenerative braking is considered for that powertrain.

For the mild HEV cases, the engine is turned off as soon as the vehicle is fully stopped. However, since some regenerative braking energy is recovered, the vehicle is propelled by the electric machine during vehicle launch, allowing the engine to be restarted later.

6.9.2. Single-Mode Power-Split HEV

The vehicle-level control strategy of a single-mode power split HEV was based on the Toyota Prius analysis. The control implemented can be divided into three areas: engine-on condition, battery SOC control, and engine operating condition. Each algorithm is described below.

Engine-On Condition

The operation of the engine determines the mode, such as pure electric vehicle (PEV) mode or HEV mode. The engine is simply turned on when the driver's power demand exceeds a predefined threshold. As shown in Figure 39, the engine is turned on early if the SOC is low, which means that the system is changed from PEV mode to HEV mode to manage the battery SOC.

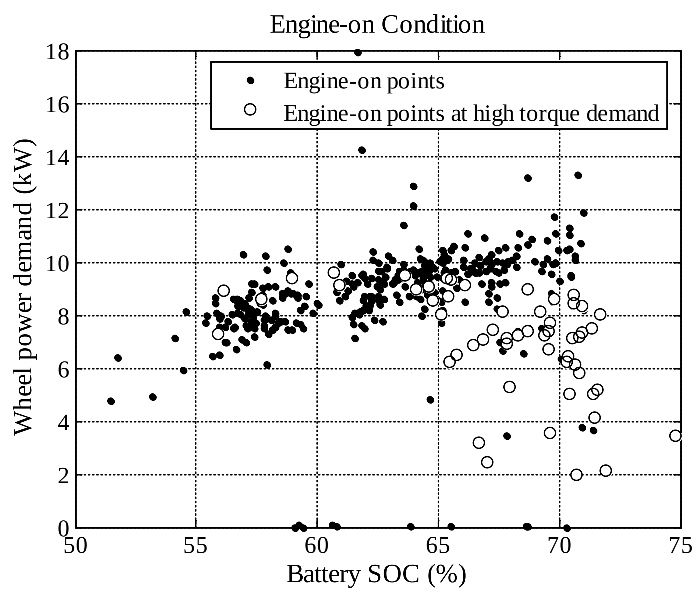


Figure 39 – Engine-On Condition – 2010 Prius Example Based on 25 Test Cycles

The engine is turned off when the vehicle decelerates and is below a certain vehicle speed.

SOC Control

The desired output power of the battery is highly related to the energy management strategy. When the vehicle is in HEV mode, the battery power is determined by the current SOC, as shown in Figure 40. The overall trend shows that the energy management strategy tries to bring the SOC back to a regular value of 60%. Both the engine on/off control and the battery power control are robust approaches to manage the SOC in the appropriate range for an input-split hybrid. If the SOC is low, the engine is turned on early, and the power split ratio is determined to restore the SOC to 60% so that the SOC can be safely managed without charge depletion. In summary, the battery SOC is controlled by raising (low SOC) or lowering (high SOC) the engine power demand required to meet the vehicle speed trace.

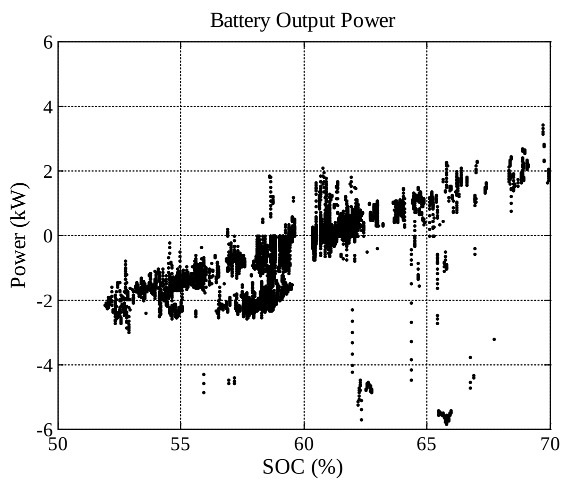


Figure 40 – SOC Regulation Algorithm – 2010 Prius Example Based on 25 Test Cycles

Engine Operation

The two previously described control concepts determine the power split ratio. The concepts do not, however, generate the target speed or torque of the engine because the power split system could have infinite control targets that produce the same power. Therefore, an additional algorithm is needed to determine the engine speed operating points according to the engine power, as shown in Figure 41. An engine operating line is defined on the basis of the best efficiency curve to select the optimum engine speed for a specific engine power demand.

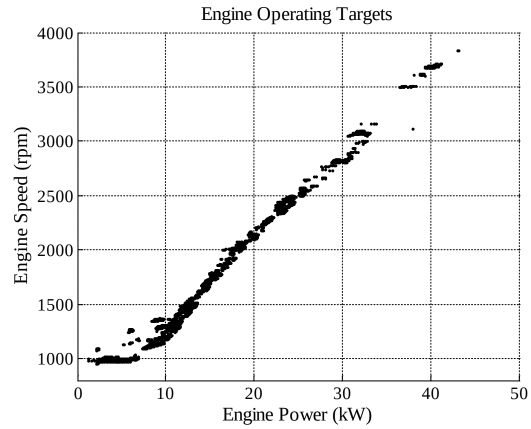


Figure 41 – Example of Engine Operating Target – 2010 Prius Example Based on 25 Test Cycles

In summary, the engine is turned on based on the power demand at the wheel along with the battery SOC. If the engine is turned on, the desired output power of the battery is determined on the basis of the current SOC and the engine should provide appropriate power to drive the vehicle. The engine operating targets are determined by a predefined line, so the controller can produce required torque values for the motor and the generator on the basis of the engine speed and torque target.

6.9.3. Voltec PHEV

The Voltec system has four different operating modes, as shown in Figure 42.

During EV operation:

1. One-motor EV: The single-speed EV drive power-flow, which provides more tractive effort at lower driving speeds
2. Two-motor EV: The output power split EV drive power flow, which has greater efficiency than one-motor EV at higher speeds and lower loads

During extended-range (ER) operation:

3. One-motor ER (series): The series ER power flow, which provides more tractive effort at lower driving speeds
4. Combined two-motor ER (split): The output power split ER power-flow, which has greater efficiency than series at higher speeds and lighter loads

A vehicle-level control strategy was developed on the basis of vehicle test data to properly select each of the operating modes. The logic developed for the power split mode is similar to the one for the input split configuration discussed previously.

For the two-level EV mode, an algorithm has been developed to minimize the losses of both electric machines at every sample time on the basis of each component's efficiency map. For the series mode, the combination of the engine and electric machine losses is also minimized at every sample time. It is important to note that the engine is not operated at its best efficiency point, but rather along its best efficiency line for drive quality and efficiency reasons.

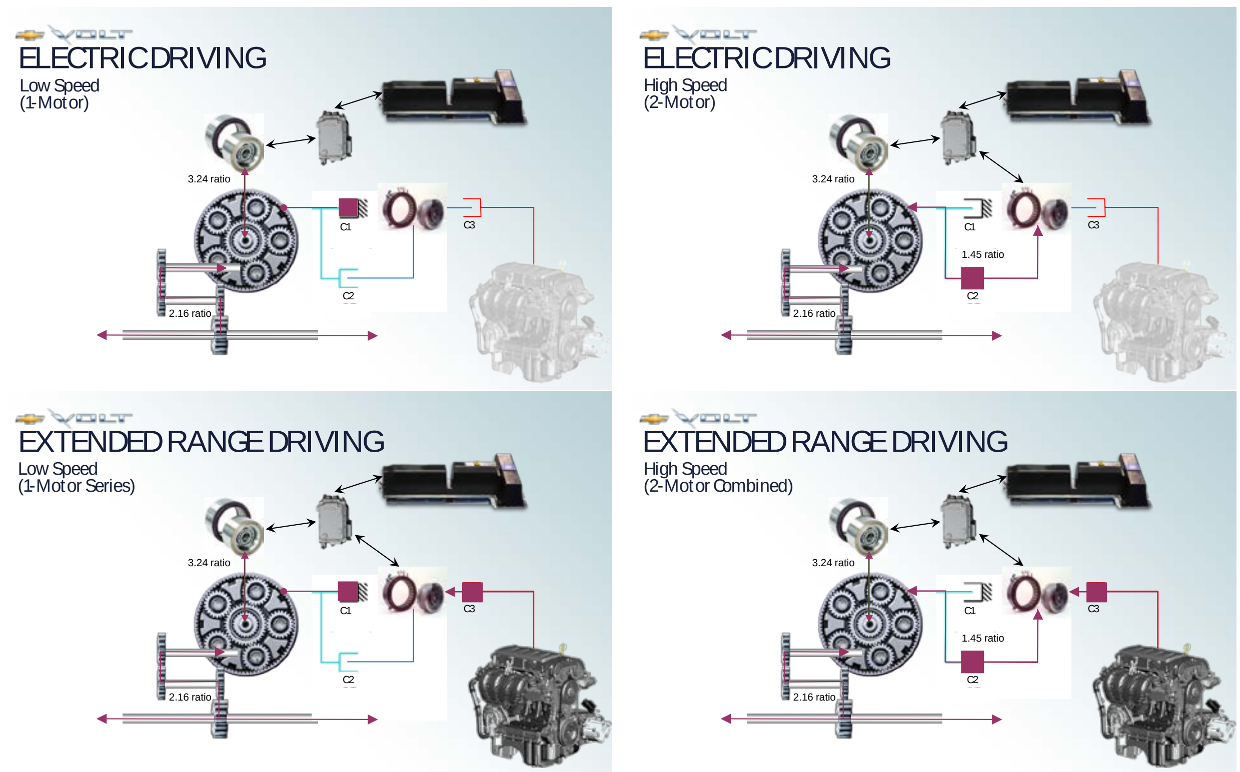


Figure 42 – Voltec Operating Modes [www.gm.com]

6.9.4. Fuel Cell HEV

Unlike the other vehicle-level controls previously discussed, the algorithm for the fuel cell HEVs is not derived from test data, due to the lack of test vehicles. Instead, dynamic programming is used to define the optimum vehicle-level control algorithms for a fuel cell vehicle. A rule-based control is then implemented to represent the rules issued from the dynamic programming. Overall, owing to the high efficiency of the fuel cell system, energy storage only recuperates energy during deceleration and propels the vehicle under low-load operations — the fuel cell system does not recharge the battery. Unlike electric drive powertrains with an engine, the battery does not smooth the transient demands. An example of fuel cell hybrid operations is shown in Figure 43.

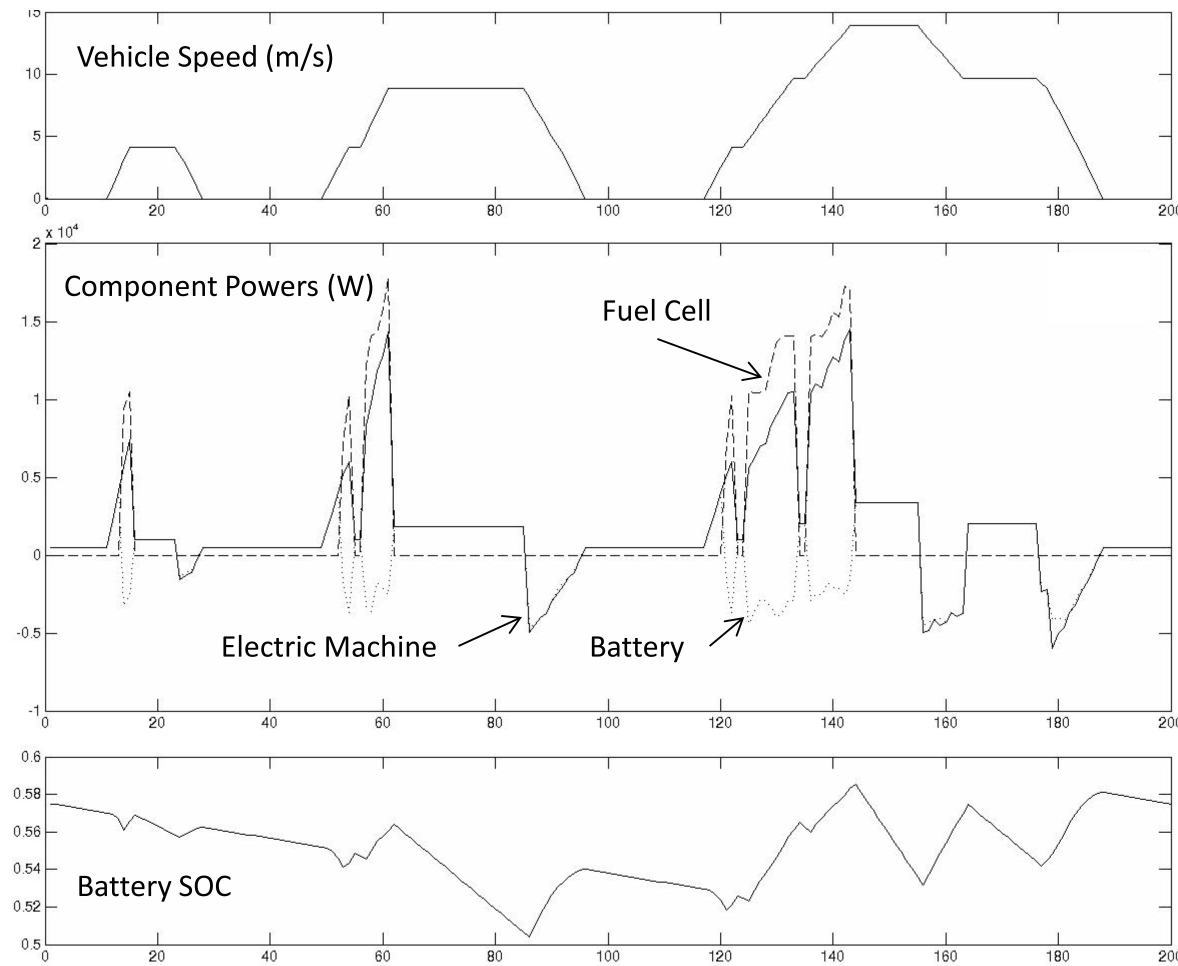


Figure 43 – Component Operating Conditions of a Fuel Cell Vehicle on the Urban European Drive Cycle using Dynamic Programming

6.10. Test Procedure and Consumption Calculations

All the simulations were performed under hot conditions. The cold-start penalties were assessed after the simulations, on the basis of test data collected at Argonne's APRF and a literature search. A two-cycle test procedure, based on the UDDS and HWFET drive cycles, was used.

6.10.1. Conventional Vehicles

The conventional vehicle test procedure follows the current EPA two-cycle test procedure (EPA n.d.).

The urban cycle for a non-hybrid vehicle (Figure 68) is composed of four parts:

1. Bag 1: cold start
2. Bag 2: stop and go
3. Idling
4. Bag 3: hot start

The highway cycle for a non-hybrid vehicle is composed of only one part, the HWFET (Figure 69).

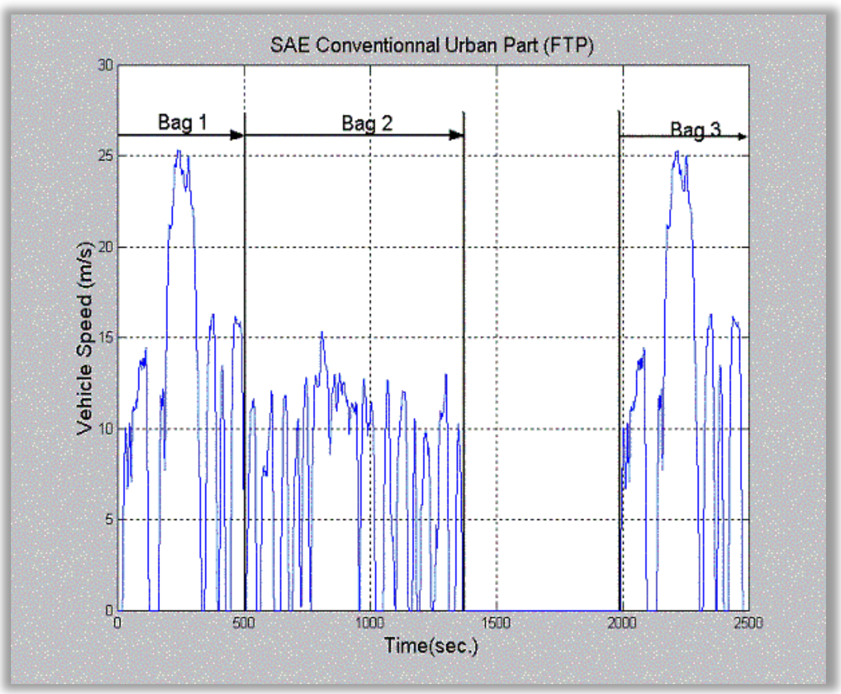


Figure 44 - The urban cycle for a non-hybrid vehicle

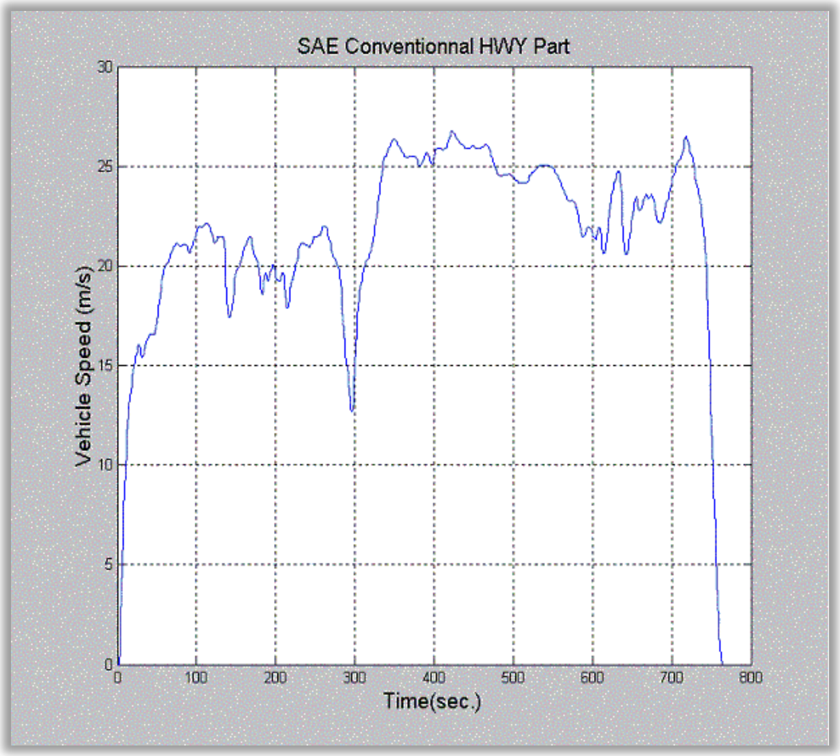


Figure 45 - The highway cycle for a non-hybrid vehicle

6.10.2. Hybrid Electric Vehicles

The HEV procedure is similar to the conventional-vehicle procedure except that the drive cycles are repeated until the initial and final battery SOCs are within a tolerance of 0.5% (see Figures 70 and 71.)

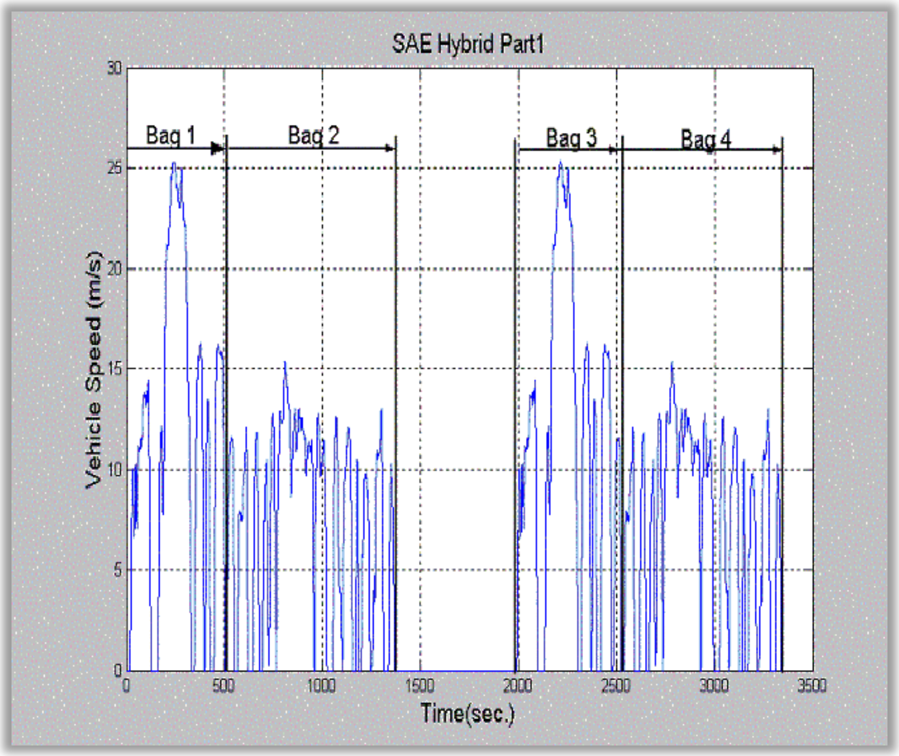


Figure 46 - The urban cycle for a hybrid vehicle

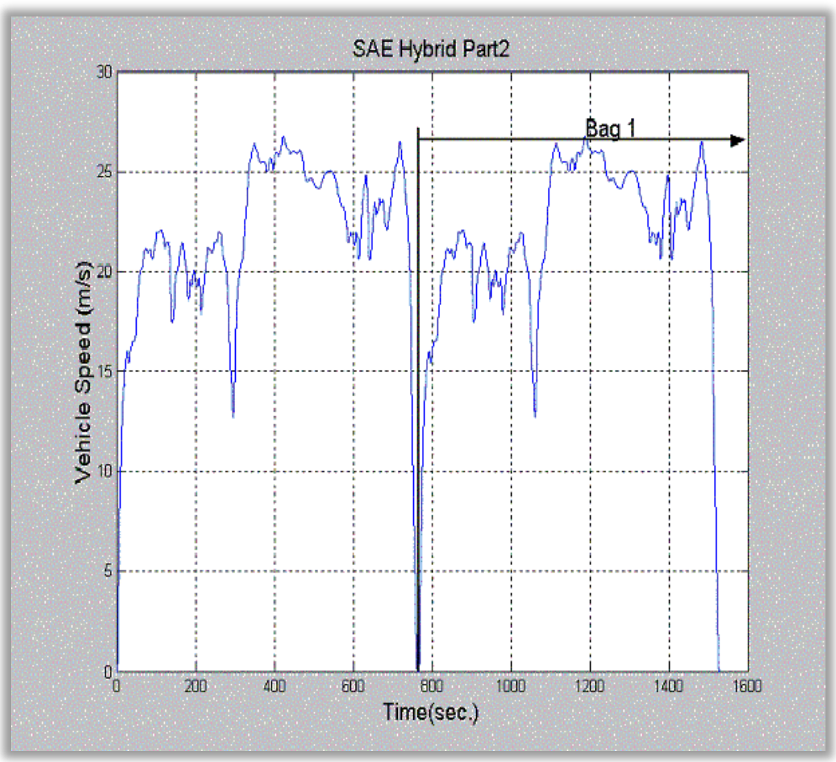


Figure 47 - The highway cycle for a hybrid vehicle (Only the results from the second cycle were used)

6.10.2.1. Two-Cycle Procedure Calculations for Conventional and Hybrid vehicles

Fuel Consumption

For the urban procedure, the fuel consumption was computed via Equation (1):

$$(1) \quad FC = 0.43\frac{V_{Fuel}^{1} + V_{Fuel}^{2}}{Dist_1 + Dist_2} + 0.57\frac{V_{Fuel}^{3} + V_{Fuel}^{Z}}{Dist_3 + Dist_Z}$$

Where

- V_{Fuel}^{y} = volume of fuel from Bag y,
- $Dist_y$ = distance driven by the vehicle for the Bag y part of the cycle, and
- Z = Bag 2 for a non-hybrid vehicle and Bag 4 for a hybrid.

The same equation was used to compute the gas-equivalent fuel consumption as well as the SOC-adjusted fuel consumption by replacing V_{Fuel} with the corresponding physical quantity.

The highway procedure results were the same as for a simple cycle, except for the hybrid case, where only the results from Bag 1 were used to compute the values:

$$(2) \quad FC = \frac{V_{Fuel}^{2}}{Dist}$$

Combined Fuel Consumption

The combined fuel consumption is a weighted value lying between the urban and highway cycles:

$$(3) \quad FC^{combined} = 0.55 \times FC^{urban} + 0.45 \times FC^{highway}$$

6.10.3. Plug-in Hybrid Electric Vehicles

This section describes the methodology currently implemented in Autonomie to support the Government Performance and Results Act (GPRA). The implementation is based on the J1711 procedure. The procedure is divided into several phases, as described below.

6.10.3.1. Charge-Sustaining on the UDDS Cycle

1. Set battery SOC to charge-sustaining (CS) value.

2. Run UDDS.

3. 10-minute soak with the key off.

4. Run UDDS.

5. Assume the cycle charge is balanced. Display warning if it does not meet 1%.

Weightings and cold factor correction:

The following equations demonstrate the cold compensation:

$$(4) \quad M^*_{0-505} = \frac{M_{0-505}}{1 - CF_{75F}}$$

Where

M_{0-505} = fuel mass consumed during the time window between 0 and 505 sec,

CF_{75F} = cold-factor correction at 75°F, and

M^*_{0-505} = cold-corrected mass of fuel.

$$(5) \quad Vol^*_{0-505} = \frac{M^*_{0-505}}{\delta_{gasoline}}$$

Where

Vol^*_{0-505} = volume of fuel consumed during the time window between 0 and 505 sec, and

$\delta_{gasoline}$ = density of gasoline.

One can then calculate FC^{UDDS}, the fuel consumed on the UDDS cycle:

$$(6) \quad FC^{UDDS} = 0.43 \times \left(\frac{Vol^*_{0-505} + Vol_{506-1372}}{D_{0-505} + D_{506-1372}}\right) + 0.57 \times \left(\frac{Vol_{1972-2477} + Vol_{2478-3340}}{D_{1972-2477} + D_{2478-3340}}\right)$$

6.10.3.2. Charge-Sustaining on the HWFET Cycle

1. Set battery SOC to CS value.

2. Run HWFET.

3. Wait 4 sec.

4. Run HWFET.

5. Assume the cycle is charge balanced.

6. Perform calculations on the second HWFET cycle.

$$(7)\quad FC^{HWFET} = \frac{Vol_{765-1529}}{D_{765-1529}}$$

Where

$Vol_{765-1529}$ = volume of fuel consumed during the time window between 765 and 1,529 sec,

$D_{765-1529}$ = distance traveled during the time window between 765 and 1,529 sec, and

FC^{HWFET} = highway fuel consumption.

6.10.3.3. Charge-Depleting on the UDDS and HWFET Cycles

1. The calculations are identical for the UDDS and HWFET cycles.

2. Set battery SOC to full charge test initial SOC.

3. Run UDDS (HWFET).

4. 10-minute soak with the key off (15-sec pause with key on).

5. Run UDDS (HWFET).

6. 10-minute soak with the key off (15-sec pause with key on).

7. Repeat until SOC reaches the CD/CS crossover point and the last cycle is completed.

8. Round down the number of cycles unless the CD range is less than one cycle. In that case, round up the number of cycles. At least 1 CD cycle is required to run the analysis.

Cold weighting calculation:

The user specifies the number of cycles over which to apply the cold correction factor:

$$(8)\quad N_{cold} = \min(\mathrm{N_{cold}^{user}}, \mathrm{N_{cd}})$$

$$(9)\quad N_{hot} = N_{cd} - N_{cold}$$

Where

N_{cold} = number of cold cycles,

N_{hot} = number of hot cycles,

$\mathrm{N}_{\mathrm{cold}}^{\mathrm{user}}$ = number of user-specified cold cycles, and

N_{cd} = total number of CD cycles.

$$(10) \quad M_{cd} = \left[\frac{\alpha_{cold} M_{cd-cold}^{1}}{1 - CF_{75F}}, \cdots, \frac{\alpha_{cold} M_{cd-cold}^{N_{cold}}}{1 - CF_{75F}}, \alpha_{hot} M_{cd-hot}^{1}, \cdots, \alpha_{hot} \mathrm{M}_{cd-hot}^{N_{hot}}\right]^{T}$$

Where

$M_{cd-cold}^{1}$ = mass of fuel consumed during the first cold CD cycle,

$M_{cd-cold}^{N_{cold}}$ = mass of fuel consumed during the last cold CD cycle,

CF_{75F} = cold-start fuel economy penalty at 75°F,

M_{cd-hot}^{1} = mass of fuel consumed during the first hot CD cycle,

$\mathrm{M}_{cd-hot}^{N_{hot}}$ = mass of fuel consumed during the last hot CD cycle,

α_{cold} = user-specified cold weighting factor (default value = 0.43),

α_{hot} = user-specified hot weighting factor (default value = 0.57), and

M_{cd} = column vector of cold-corrected fuel mass.

$$(11) \quad Vol_{cd} = \frac{M_{cd}}{\delta_{gasoline}}$$

Where

Vol_{cd} = column vector of cold-corrected fuel volumes.

Note that each element in the Vol_{cd} vector is divided by its respective distance:

$$(12) \quad FC_{cd} = \frac{Vol_{cd}}{D_{udds}}$$

Where

FC_{cd} = column vector of cold-corrected fuel consumptions.

The net battery energy used was calculated for each cycle using the open-circuit voltage and the current.

$$(13) \quad for\ i = 1, \cdots, N_{cd}\ ;\ E_{cd}^{i} = \int_{(i-1)T_{udds}}^{(i)T_{udds}+t} V_{oc}(\tau) * I(\tau) d\tau$$

Where

E_{cd}^{i} = net battery energy used during the i^{th} CD cycle,

T_{udds} = duration of the UDDS cycle + soak time or (HWFET + 15 sec),

i = index of the CD cycle,

N_{cd} = total number of CD cycles,

V_{oc} = open-circuit voltage as a function of time during the cycle, and

I = battery current as a function of time during the cycle.

$$(14) \quad E_{cd} = \left[E_{cd}^{1}, \cdots, E_{cd}^{N_{cd}}\right]^{T}$$

Where

E_{cd} = column vector of net battery energy used on each cycle.

Note that each element in the E_{cd} vector is divided by its respective distance.

$$(15) \quad EC_{cd} = \frac{E_{cd}}{D_{udds} * \eta_{chg}^{ess} * \eta_{charger}}$$

Where

EC_{cd} = column vector of electrical-energy consumption in AC-Joules (wall outlet),

D_{udds} = distance traveled on a UDDS (or $HWFET - D_{HWFET}$) cycle,

η_{chg}^{ess} = user-definable efficiency of the battery during charging (default value = 0.99), and

$\eta_{charger}$ = user-definable efficiency of the charger (wall or in-vehicle) (default value = 0.88).

$$(16) \quad for\ i = 1, \cdots, N_{cd}\ ;\ \mu_i = \mu\left(i * D_{udds}^{i}\right) - \mu(i-1) * D_{udds}^{i}$$

$$\mu_{cd} = \left[\mu_1, \cdots, \mu_{N_{cd}}\right]$$

Where

μ_{cd} = row vector of utility factors,

μ_1 = utility factor on the first CD cycle,

μ_i = utility factor on the i^{th} CD cycle,

$\mu_{N_{cd}}$ = utility factor on the last CD cycle, and

μ = fleet Mileage Fraction Utility Factor as a function of distance.

$$(17) \quad FC = \mu_{cd} FC_{cd} + \left(1 - \sum_{i}^{N_{cd}} \mu_i\right) FC_{cs}$$

Where

FC= fuel consumed on the city or highway portion of the PHEV procedure.

$$(18) \quad EC = \mu_{cd} EC_{cd}$$

Where

EC = electrical energy consumed during the city or highway portion of the PHEV procedure.

Consumption adjustment factors:

Although *only unadjusted values were used to support NEMS (National Energy Modeling System), MARKAL, and SEDS (State Energy Data System)*, this section describes the adjusted fuel-consumption values provided.

$$(19) \quad FE_{adj}^{udds} = 0.003259 + 1.1805 * FE^{udds}$$

$$(20) \quad FE_{adj}^{hwfet} = 0.001376 + 1.3466 * FE^{hwfet}$$

$$(21) \quad FC_{adj}^{combined} = 0.55 * FC_{adj}^{udds} + 0.45 * FC_{adj}^{hwfet}$$

Electrical consumption (corrected) = 0.7 * electrical consumption, per communication with EPA.

6.10.4. Electric Vehicles

Start the battery at full SOC and run until minimum SOC is reached:

$$(22) \quad C = \frac{\int V_{oc} * I_{ess}}{\eta_{ess}\eta_{charger}}$$

Where

η_{ess} = efficiency of the battery while charging,

$\eta_{charger}$ = average efficiency of the charger while charging,

V_{oc} = open-circuit voltage as a function of time over the cycle, and

I_{ess} = current as a function of time over the cycle.

6.10.5. Cold-Start Penalty

A cold start penalty of 12% was applied for the fuel consumption of the FTP for conventional vehicles, HEVs, and PHEVs; 0% for BEVs.

7. Individual Vehicle Setup Process

The Large-Scale Simulation Process was developed by Argonne to run a very large number of vehicles/simulations in a fast and flexible way. It allows Argonne to quickly respond to Volpe and DOT/NHTSA requests to be able to simulate any technology combination in any vehicle class. The following subsections describes the different steps of the process.

7.1. Vehicle Spreadsheet Definition

A template spreadsheet contains the basic information of a vehicle such as vehicle name, vehicle class, and vehicle technology, as well as components information such as battery technology, engine technology, and transmission type.

The template spreadsheet contains seven tabs: Vehicle, Parameter, Control, Sizing, Run, Translation, and Assumptions. In each tab, columns outline vehicle configurations. Four columns refer to the four low-electrification-level vehicles and 11 columns refer to the high-electrification-level vehicles.

7.1.1. Vehicle Tab

The Vehicle tab, shown in Figure 48, defines the initialization files, the component models required for each vehicle, and the vehicle configuration selected. The initialization files selected will depend on the tree selection and the technological combination nominated for that vehicle.

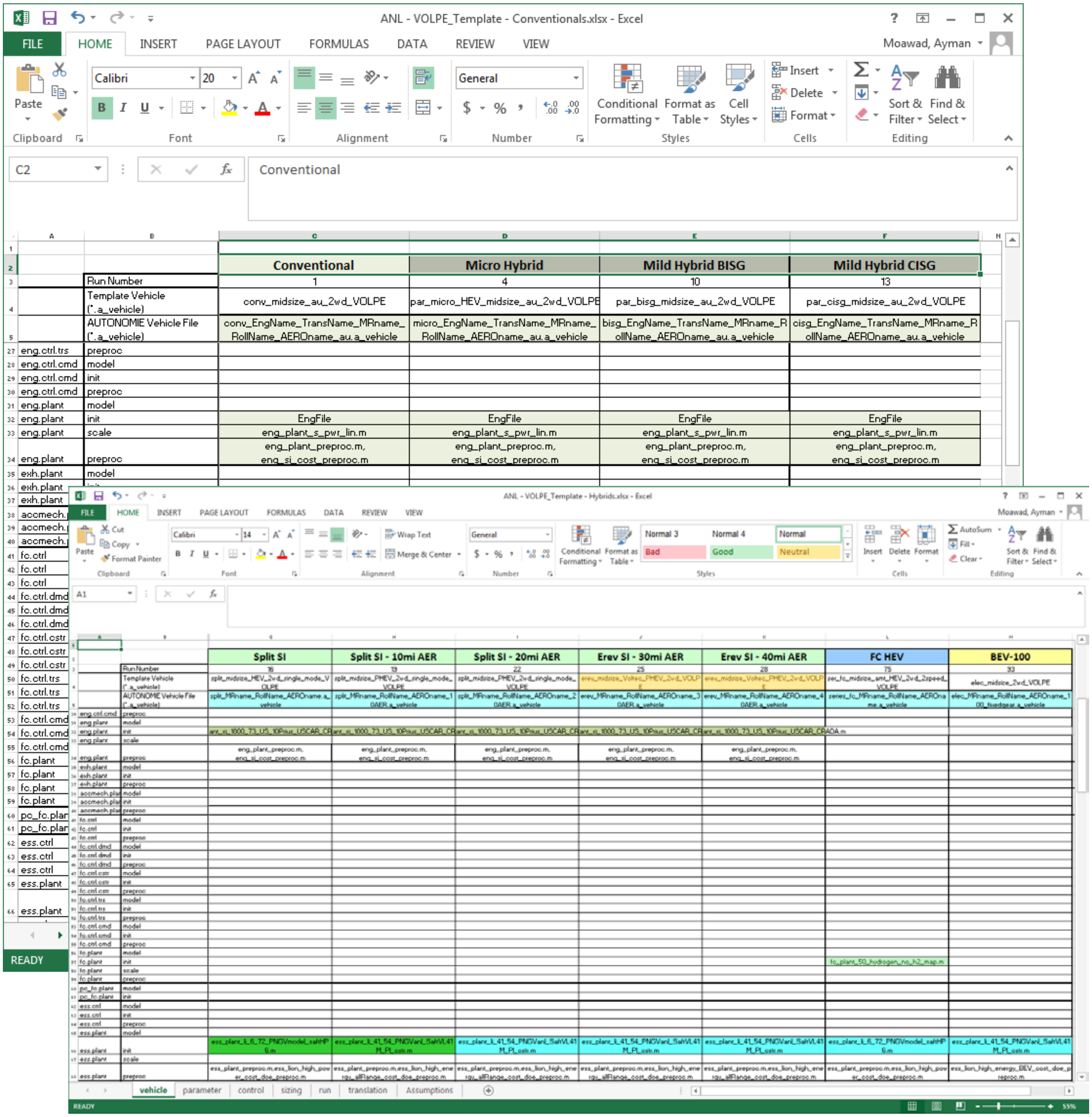


Figure 48 – Vehicle Setup – Vehicle Tab

7.1.2. Parameter Tab

The Parameter tab, shown in Figure 49, defines the values of the components specific to the vehicle designated (e.g., powers, masses, performance constraints).

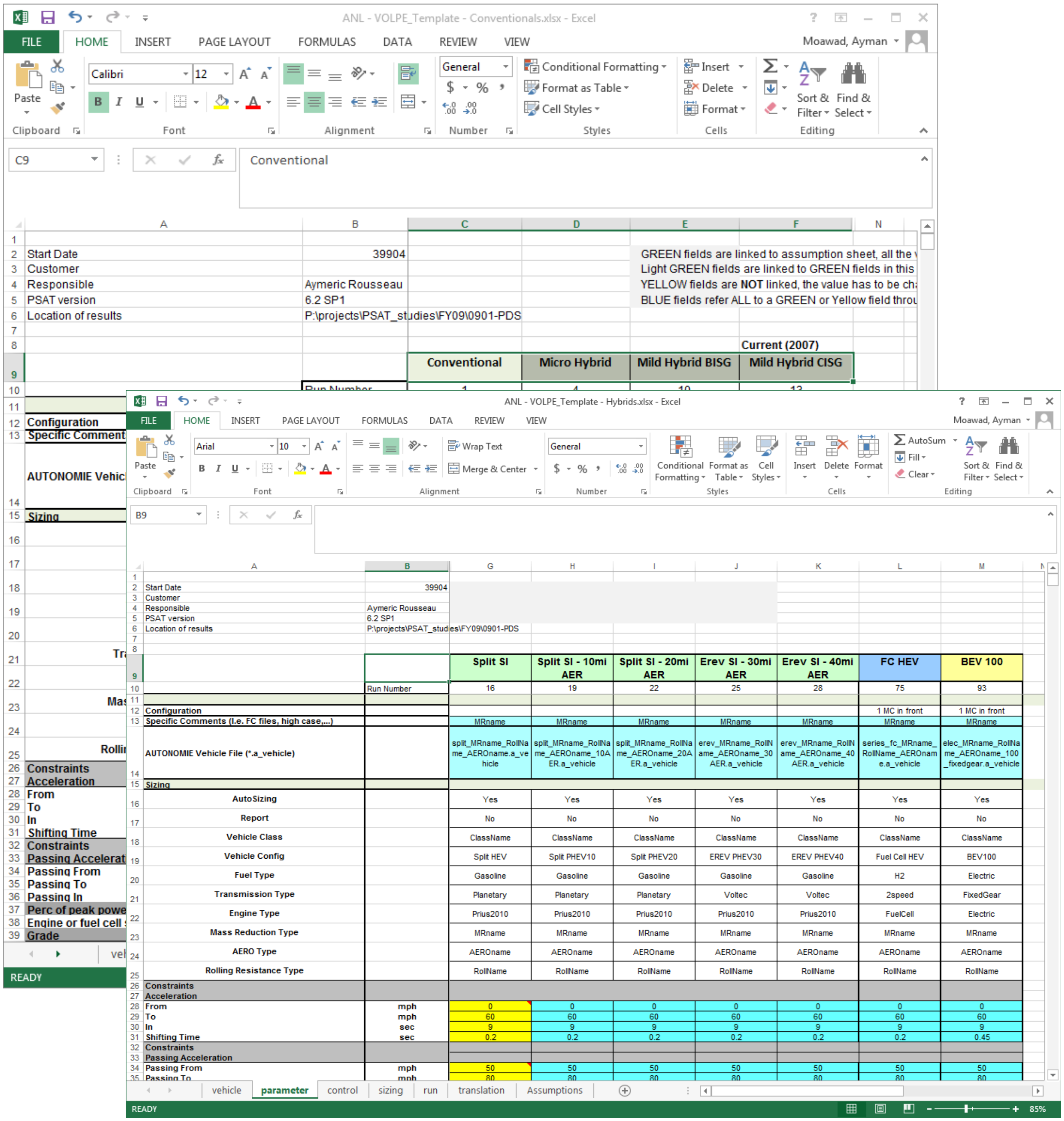


Figure 49 – Vehicle Setup – Parameter Tab

7.1.3. Control Tab

The Control tab, shown in Figure 50, selects the appropriate controller for the designated vehicle.

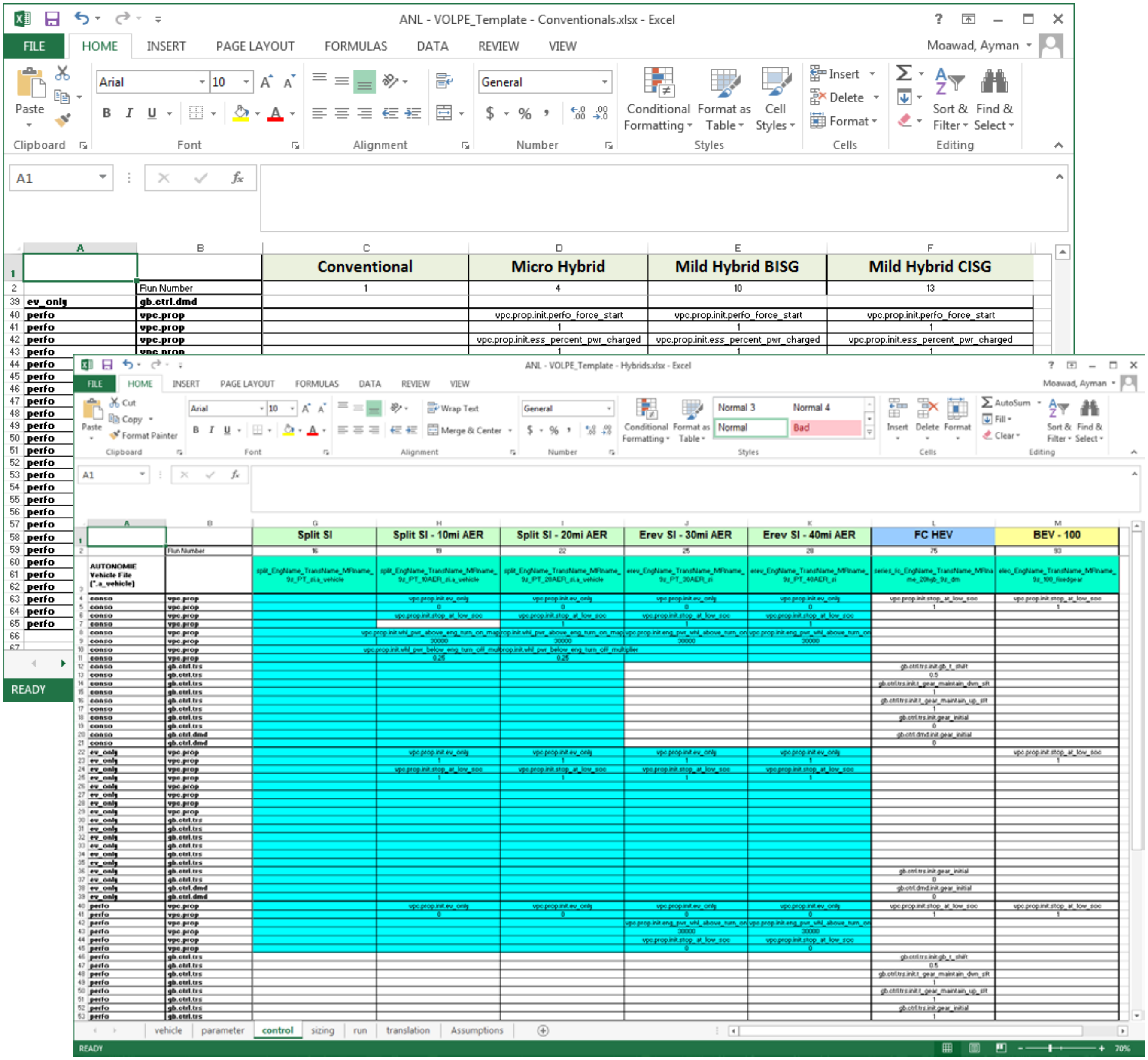


Figure 50 – Vehicle Setup – Control Tab

7.1.4. Sizing Tab

The Sizing tab selects the appropriate sizing rule and algorithms with which to run the vehicle performance test (Figure 51).

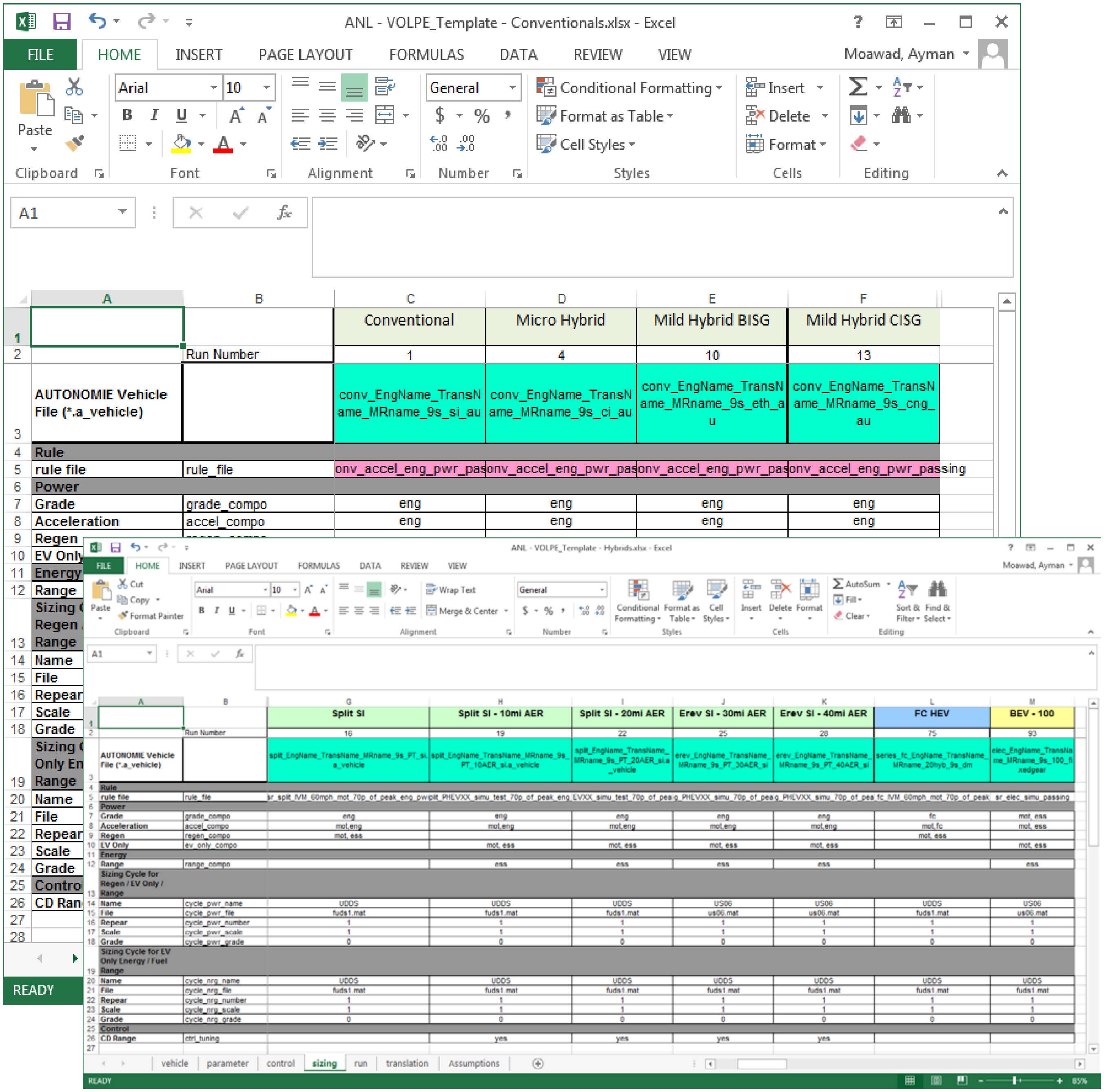


Figure 51 – Vehicle Setup – Sizing Tab

7.1.5. Run Tab

The Run tab selects the drive cycle/procedure that needs to be run (Figure 52).

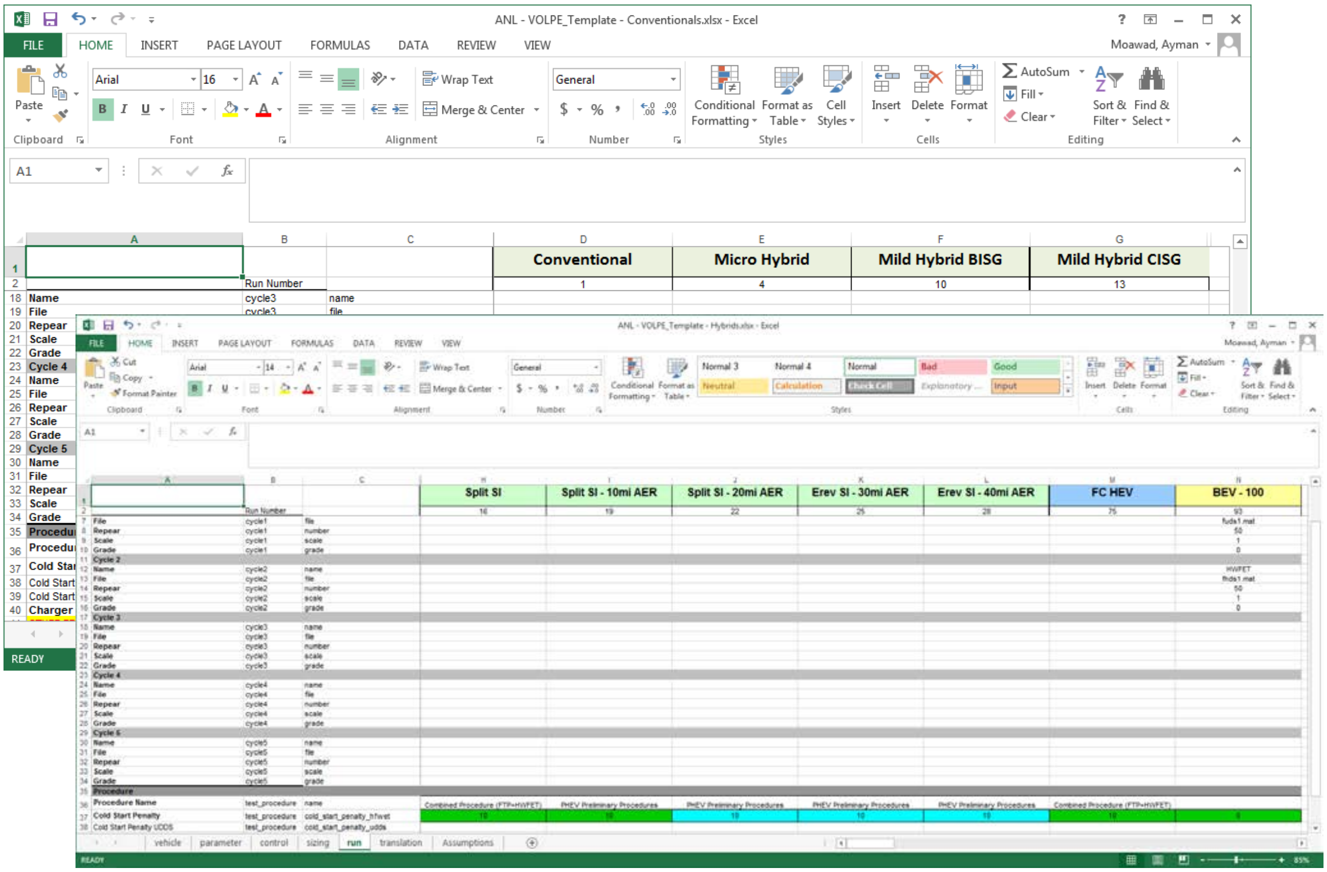
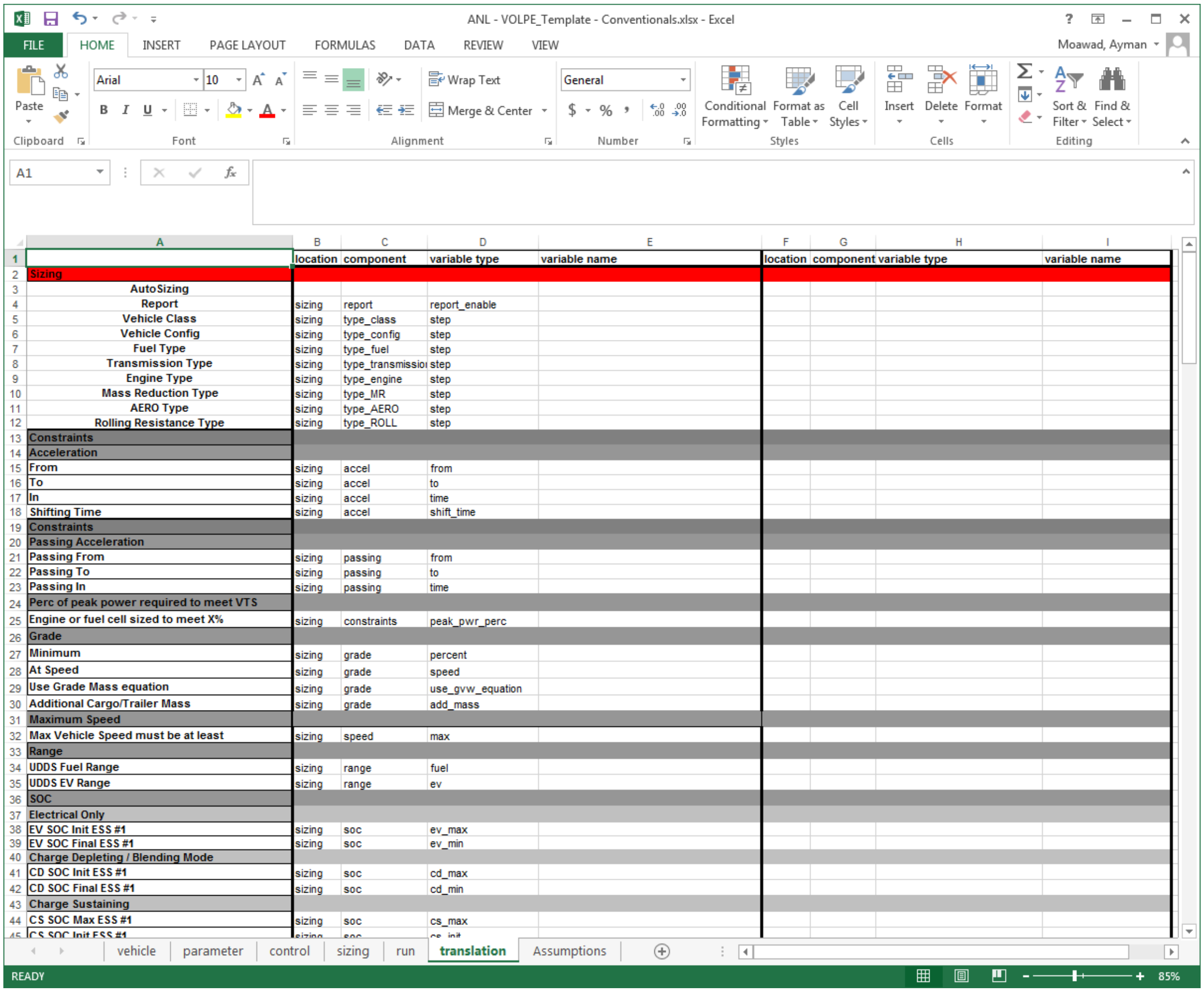


Figure 52 – Vehicle Setup – Run Tab

7.1.6. Translation Tab

The Translation tab, shown in Figure 53, translates and transfers every input into Autonomie to build the vehicle model.



	location	component	variable type	variable name	location	component	variable type	variable name
Sizing								
AutoSizing								
Report	sizing	report	report_enable					
Vehicle Class	sizing	type_class	step					
Vehicle Config	sizing	type_config	step					
Fuel Type	sizing	type_fuel	step					
Transmission Type	sizing	type_transmissio	step					
Engine Type	sizing	type_engine	step					
Mass Reduction Type	sizing	type_MR	step					
AERO Type	sizing	type_AERO	step					
Rolling Resistance Type	sizing	type_ROLL	step					
Constraints								
Acceleration								
From	sizing	accel	from					
To	sizing	accel	to					
In	sizing	accel	time					
Shifting Time	sizing	accel	shift_time					
Constraints								
Passing Acceleration								
Passing From	sizing	passing	from					
Passing To	sizing	passing	to					
Passing In	sizing	passing	time					
Perc of peak power required to meet VTS								
Engine or fuel cell sized to meet X%	sizing	constraints	peak_pwr_perc					
Grade								
Minimum	sizing	grade	percent					
At Speed	sizing	grade	speed					
Use Grade Mass equation	sizing	grade	use_gvw_equation					
Additional Cargo/Trailer Mass	sizing	grade	add_mass					
Maximum Speed								
Max Vehicle Speed must be at least	sizing	speed	max					
Range								
UDDS Fuel Range	sizing	range	fuel					
UDDS EV Range	sizing	range	ev					
SOC								
Electrical Only								
EV SOC Init ESS #1	sizing	soc	ev_max					
EV SOC Final ESS #1	sizing	soc	ev_min					
Charge Depleting / Blending Mode								
CD SOC Init ESS #1	sizing	soc	cd_max					
CD SOC Final ESS #1	sizing	soc	cd_min					
Charge Sustaining								
CS SOC Max ESS #1	sizing	soc	cs_max					
CS SOC Init ESS #1	sizing	soc	cs_init					

Figure 53 – Vehicle Setup – Translation Tab

7.1.7. Assumption Tab

The Assumption tab describes the vehicle and component assumptions used to define the Vehicle tab (Figure 54).

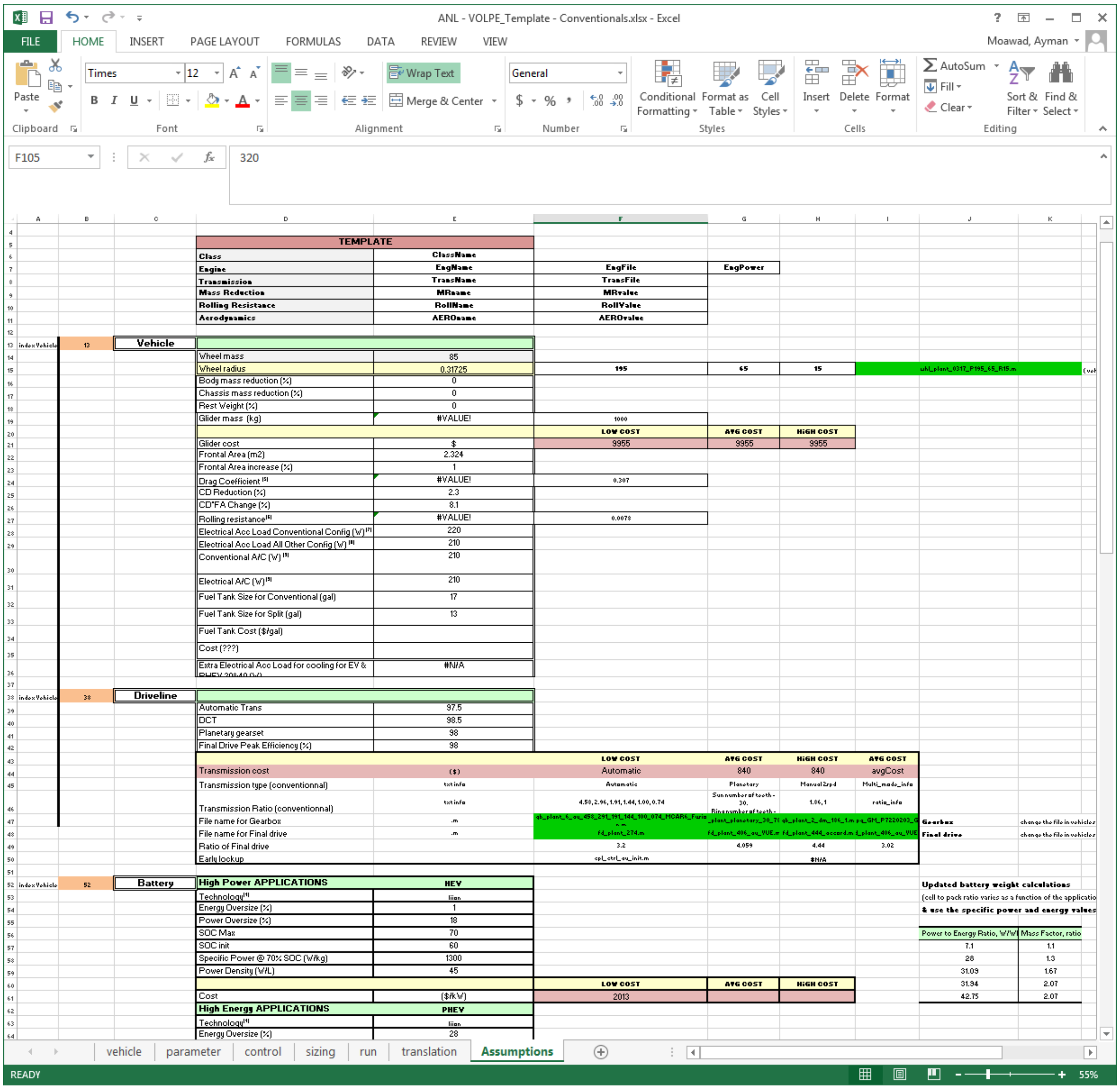


Figure 54 – Vehicle Setup – Assumption Tab

7.2. Multi-Spreadsheet Expansion/Duplication

After the Large-Scale Simulation Process defines the spreadsheet with all the component and vehicle inputs, a multiplier code, shown in Figure 55, expands the reference/template spreadsheet into as many spreadsheets as needed to define the vehicle's technological combinations based on the decision trees' input.

The template spreadsheet is duplicated, multiplied, and expanded to define the complete combination tree equivalent to a total of 27,600 vehicles created.

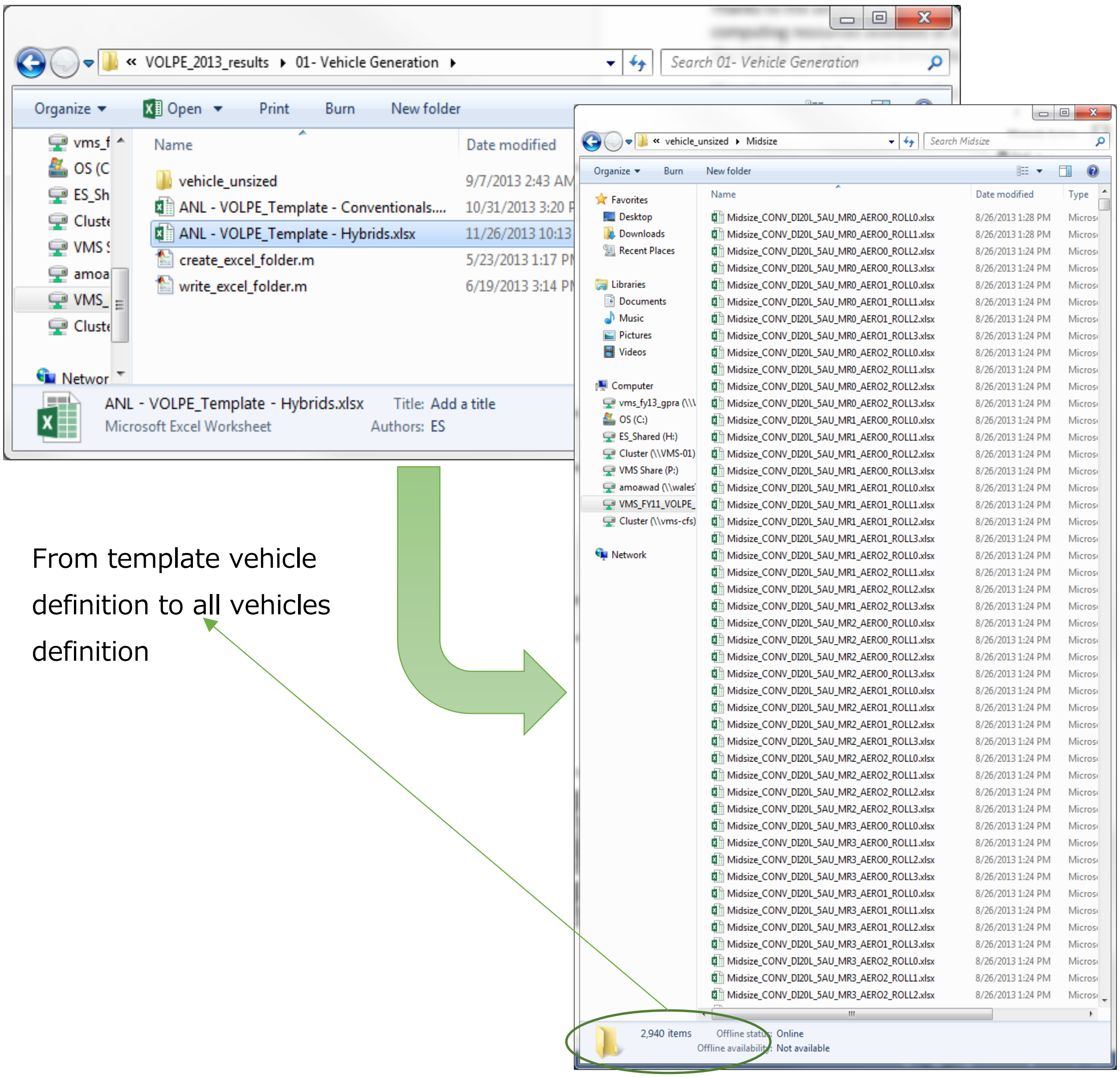


Figure 55 – Multi Spreadsheet Expansion/Duplication

8. Distributed Computing Process

At that stage of the large scale simulation process, all the vehicles are created and ready to be sized and simulated in Autonomie. Running 27,600 vehicles requires more than 250,000 simulations, from sizing algorithms — imposing recurrence and iteration/looping — to vehicle simulation on cycles and combined or PHEV procedures.

With the multitude of technology combinations to simulate, the usual computing resources are no longer practical. Running all of the simulations on one computer would take several months or years before any analysis could be completed. Thanks to advances in distributed computing, simulation time can be greatly reduced. Among the computing resources available at Argonne National Laboratory is a cluster of 160 worker nodes dedicated to the System Modeling and Control Group. A larger computing facility could be used in the future to further accelerate the simulations.

8.1. Setup

The researchers of the System Modeling and Control Group use Autonomie as the simulation framework, synchronized by a cluster head node computer. The head computer extracts the data from the Excel files describing the different technology pathways and distributes it to the researchers, as diagrammed in Figure 56. An algorithm optimizes the distribution of jobs for vehicle simulations and parametric studies. The total simulation time for the 27,600 vehicles is about 115 hours (~5 days).

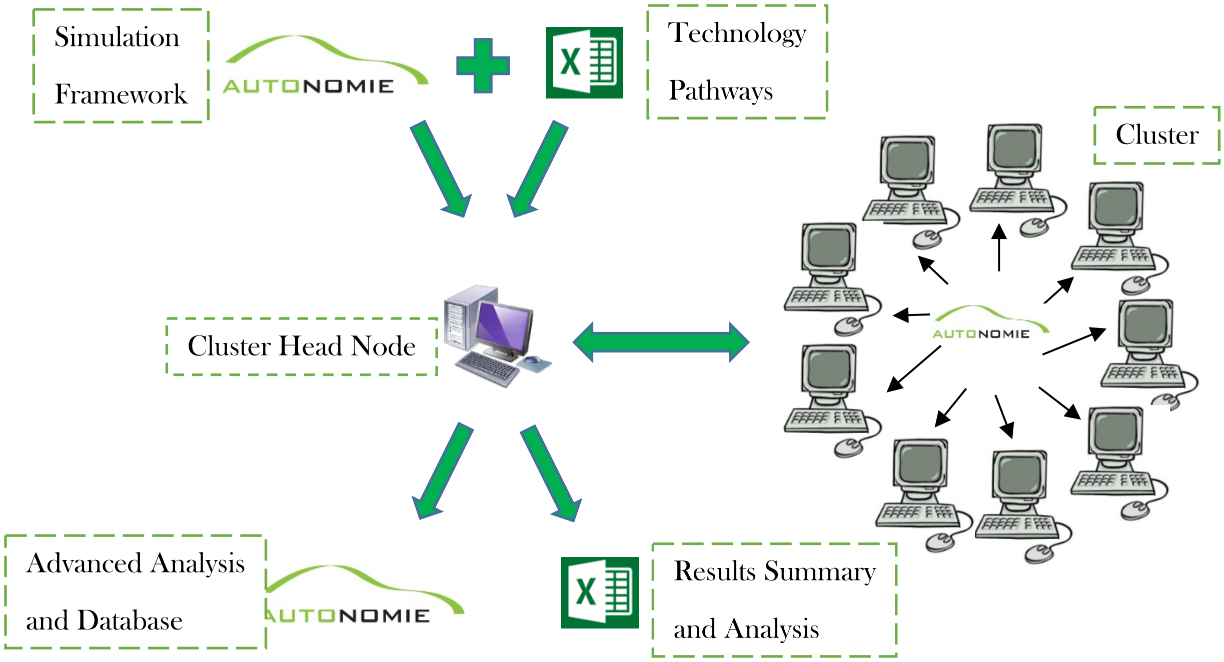


Figure 56 – Diagram of Distributed Computing Process

8.2. Distributed Computing Flexibility

One of the biggest advantages of the distributed computing is that it facilitates the quick rerun of simulations, which occurred many times during this study. This experience allowed Argonne to develop a new process: an ultimate Large-Scale Simulation Process (LSSP) that is functional, smooth, and flexible, with the ability to easily and quickly add and rerun as many vehicles and new technologies as needed. The generic process will be able to automatically handle the additional technologies without any code modification. As a result, the CAFE model's future technological needs will be easily and quickly integrated at any time and proceed to new runs in order to feed the model for CAFE rulemaking analyses.

9. Vehicle Sizing Process

9.1. Vehicle Technical Specifications

To compare different vehicle technology-configuration-powertrain combinations, all selected vehicles to be sized are designed to meet the same requirements. Note that not all vehicles are sized as explained in 5.3 – 5.4 – 5.5.

- Initial vehicle movement to 60 mph in 9 sec ± 0.1 sec
- Maximum grade (gradability) of 6% at 65 mph at GVW
- Maximum vehicle speed >100 mph

These requirements are a good representation of the current American automotive market and of American drivers' expectations. The relationship between curb weight and GVW for current technology-configuration-powertrain combinations was modeled and forms the basis for estimating the GVWs of future vehicle scenarios.

9.2. Component Sizing Algorithms

Owing to the impact of the component maximum torque shapes, maintaining a constant power-to-weight ratio for all configurations leads to an erroneous comparison between technologies because of different vehicle performances (I.e. 0-60mph). Each vehicle should be sized independently to meet the vehicle technical specifications.

Improperly sizing the components will lead to differences in fuel consumption and will influence the results. On this basis, we developed several automated sizing algorithms to provide a fair comparison between technologies. Algorithms have been defined depending on the powertrain (e.g., conventional, power split, series, electric) and the application (e.g., HEV, PHEV).

All algorithms are based on the same concept: the vehicle is built from the bottom up, meaning each component assumption (e.g., specific power, efficiency) is taken into account to define the entire set of vehicle attributes (e.g., weight). This process is always iterative in the sense that the main component characteristics (e.g., maximum power, vehicle weight) are changed until all vehicle technical specifications are met. The transmission gear span or ratios are currently not modified to be matched with specific engine technologies. On average, the algorithm takes between five and 10 iterations to converge. Figure 57 shows an example of the iterative process for a conventional vehicle.

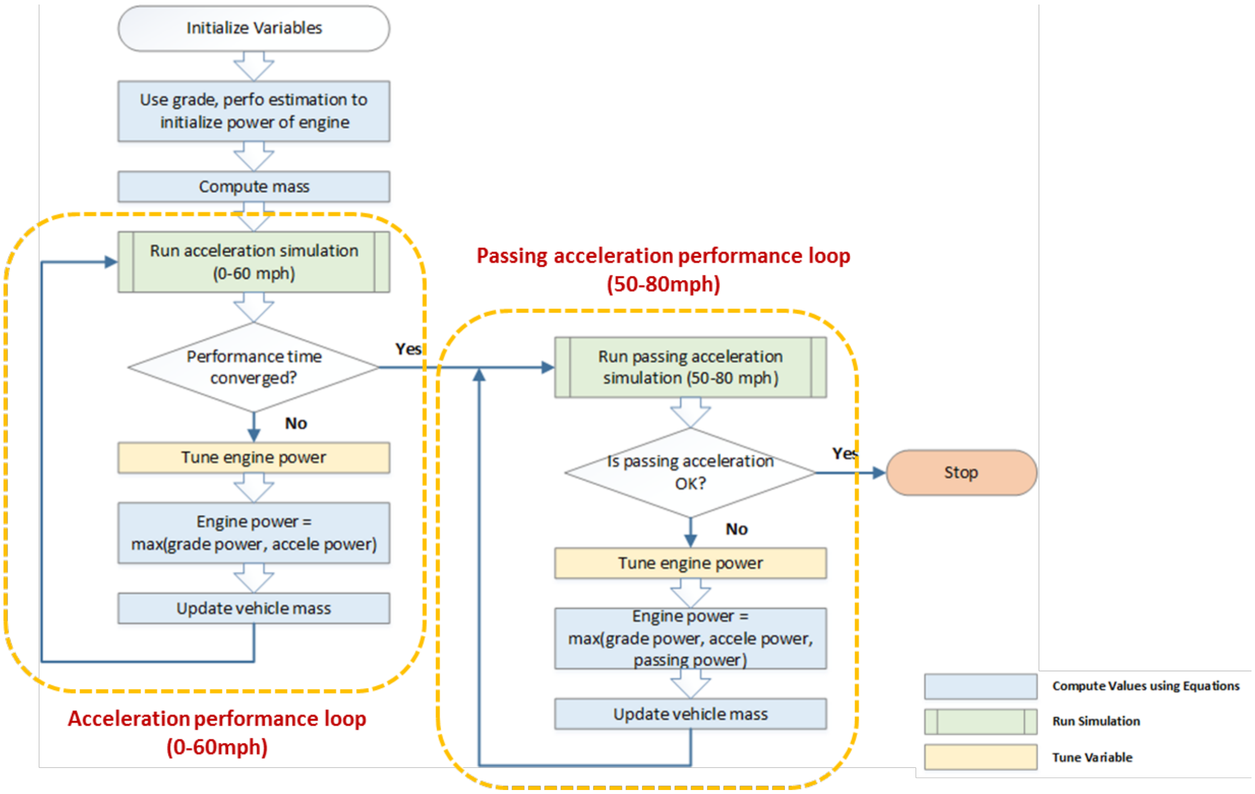


Figure 57 – Conventional Powertrain Sizing Algorithm

Since each powertrain and application is different, the rules are specific:

- For HEVs, the electric-machine and battery powers are determined in order to capture all of the regenerative energy from an FTP cycle. The engine and the generator are then sized to meet the gradeability and performance (initial vehicle movement to 60 mph) requirements.
- For PHEV20s, the electric machine and battery powers are sized to follow the FTP cycle in electric-only mode (this control is only used for the sizing; a blended approach is used to evaluate consumptions). The battery's usable energy is defined to follow the FTP drive cycle for 20 miles, depending on the requirements. The engine is then sized to meet both performance and gradeability requirements (usually, gradeability is the determining factor for PHEVs).
- For PHEV40s, the main electric-machine and battery powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode. The battery's usable energy is defined to follow the FTP drive cycle for 40 miles, depending on the

requirements. The genset (engine + generator) or the fuel cell systems are sized to meet the gradeability requirements.

- For BEVs, the electric machine and energy storage systems are sized to meet all of the vehicle technical specifications.

The micro-HEV, BISG, and CISG have sizing results very similar to their conventional counterparts because they all use the same sizing rule.

10. Vehicle Simulation Process

Once the vehicles are sized to meet the same vehicle technical specifications, they are simulated following the appropriate standard driving cycles (27,600 vehicles or >250,000 runs for this example). It is important to properly store individual results as structured data because they will be reused to support database generation (see Section 11).

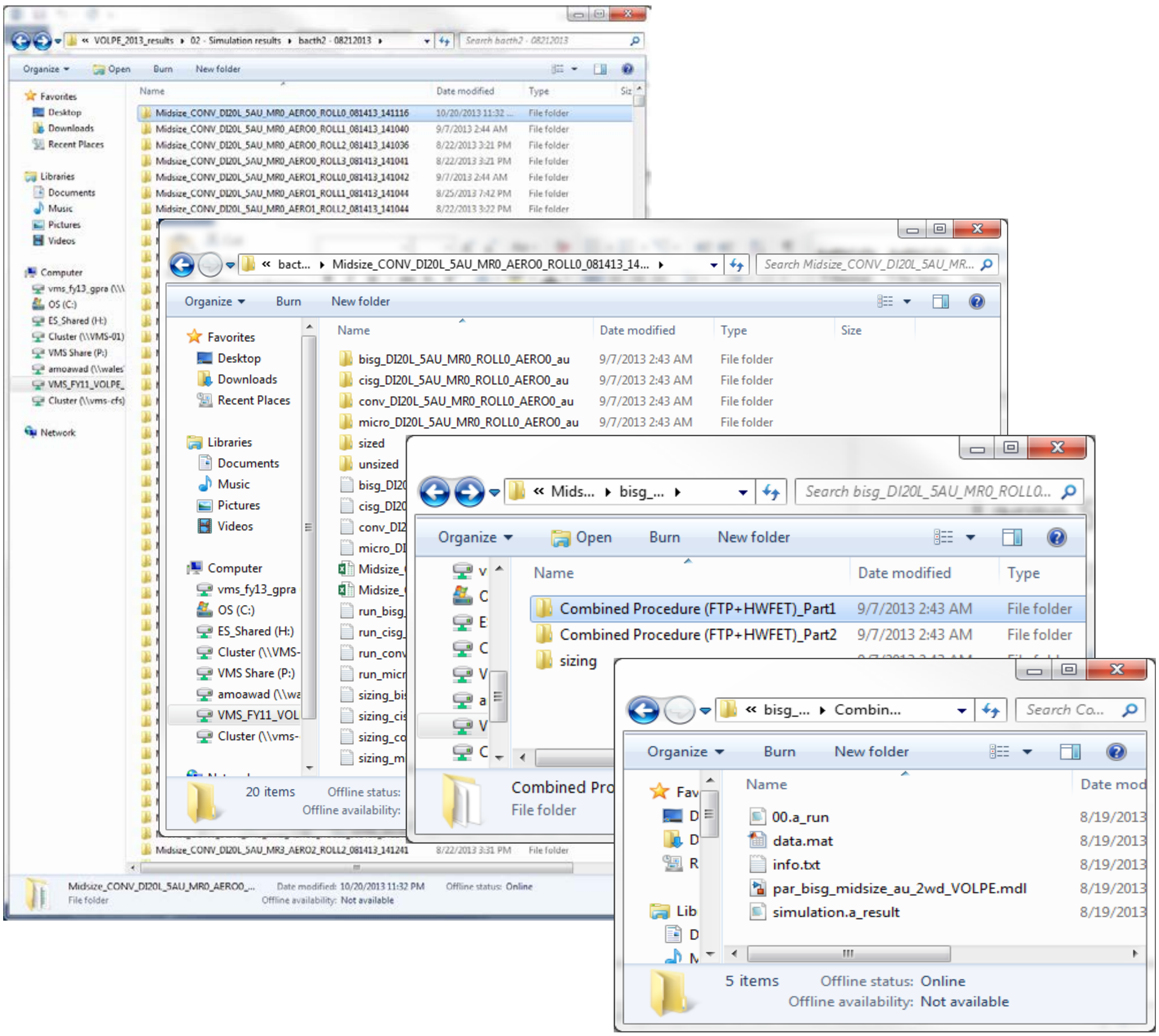


Figure 58 – Results Folder Organization for Individual Simulations

Figure 58 shows the folder organization for each individual simulation. Each folder contains the results for one combination and characterizes one branch/path of the tree. Folders can contain up to five directories, depending on the vehicle technology and the type of run performed. Results are divided into directories representing the cycle or procedure simulated. For example, the combined procedure for conventional vehicles has two parts separating the FTP and HFET run, and the PHEV procedure has four parts separating the FTP and HFET runs as well as the charge-sustaining and charge-depleting modes. The last directory is the sizing structure (performance test).

10.1. Run File

"xx.a_run" includes all the information of the vehicle as well as a cycle/procedure as shown in Figure 59. This file allows us to reproduce the simulation in the future if modifications or changes are to occur.

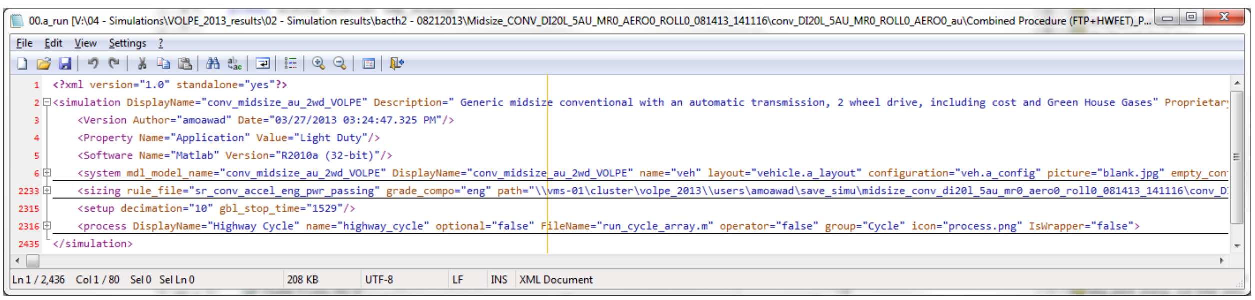
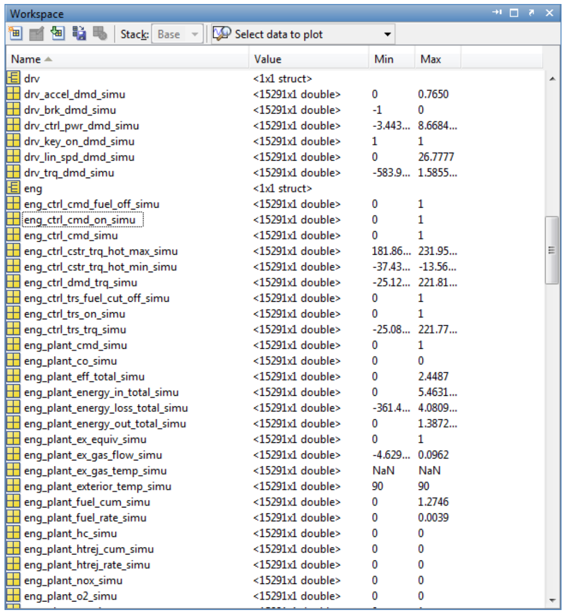


Figure 59 – Autonomie Run File

10.2. Data.mat File

"data.mat" is the results file containing all of the vehicle parameters and all of the time-based signals. A sample of signals and parameters included in data.mat is shown in Figure 60.



Name	Value	Min	Max
drv	<1x1 struct>		
drv_accel_dmd_simu	<15291x1 double>	0	0.7650
drv_brk_dmd_simu	<15291x1 double>	-1	0
drv_ctrl_pwr_dmd_simu	<15291x1 double>	-3.443...	8.6684...
drv_key_on_dmd_simu	<15291x1 double>	1	1
drv_lin_spd_dmd_simu	<15291x1 double>	0	26.7777
drv_trq_dmd_simu	<15291x1 double>	-583.9...	1.5855...
eng	<1x1 struct>		
eng_ctrl_cmd_fuel_off_simu	<15291x1 double>	0	1
eng_ctrl_cmd_on_simu	<15291x1 double>	0	1
eng_ctrl_cmd_simu	<15291x1 double>	0	1
eng_ctrl_cstr_trq_hot_max_simu	<15291x1 double>	181.86...	231.95...
eng_ctrl_cstr_trq_hot_min_simu	<15291x1 double>	-37.43...	-13.56...
eng_ctrl_dmd_trq_simu	<15291x1 double>	-25.12...	221.81...
eng_ctrl_trs_fuel_cut_off_simu	<15291x1 double>	0	1
eng_ctrl_trs_on_simu	<15291x1 double>	0	1
eng_ctrl_trs_trq_simu	<15291x1 double>	-25.08...	221.77...
eng_plant_cmd_simu	<15291x1 double>	0	1
eng_plant_co_simu	<15291x1 double>	0	0
eng_plant_eff_total_simu	<15291x1 double>	0	2.4487
eng_plant_energy_in_total_simu	<15291x1 double>	0	5.4631...
eng_plant_energy_loss_total_simu	<15291x1 double>	-361.4...	4.0809...
eng_plant_energy_out_total_simu	<15291x1 double>	0	1.3872...
eng_plant_ex_equiv_simu	<15291x1 double>	0	1
eng_plant_ex_gas_flow_simu	<15291x1 double>	-4.629...	0.0962
eng_plant_ex_gas_temp_simu	<15291x1 double>	NaN	NaN
eng_plant_exterior_temp_simu	<15291x1 double>	90	90
eng_plant_fuel_cum_simu	<15291x1 double>	0	1.2746
eng_plant_fuel_rate_simu	<15291x1 double>	0	0.0039
eng_plant_hc_simu	<15291x1 double>	0	0
eng_plant_htrej_cum_simu	<15291x1 double>	0	0
eng_plant_htrej_rate_simu	<15291x1 double>	0	0
eng_plant_nox_simu	<15291x1 double>	0	0
eng_plant_o2_simu	<15291x1 double>	0	0

Figure 60 – Autonomie data.mat File

10.3. Vehicle Model

"*.mdl" represents the complete vehicle model as shown in Figure 61. Saving each vehicle model ensures that any simulation can be replicated at any time.

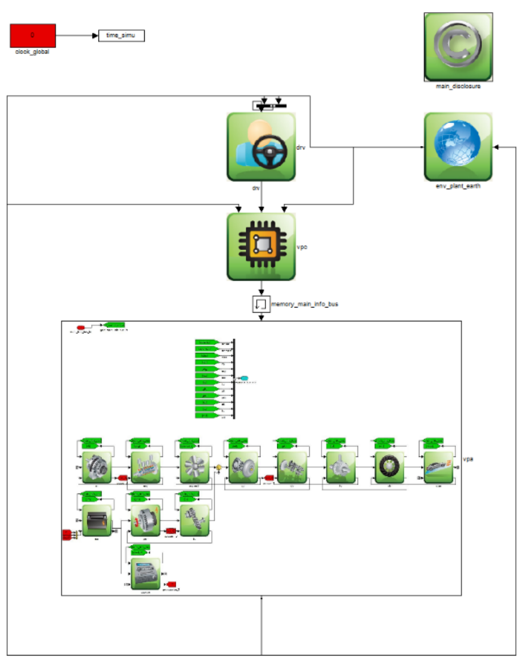


Figure 61 – Autonomie Conventional Vehicle

10.4. Results XML File

As shown in Figure 62, “simulation.a_result” is an XML version of the results file that includes the main simulation inputs and outputs. This file is later used to generate the complete MySQL database.

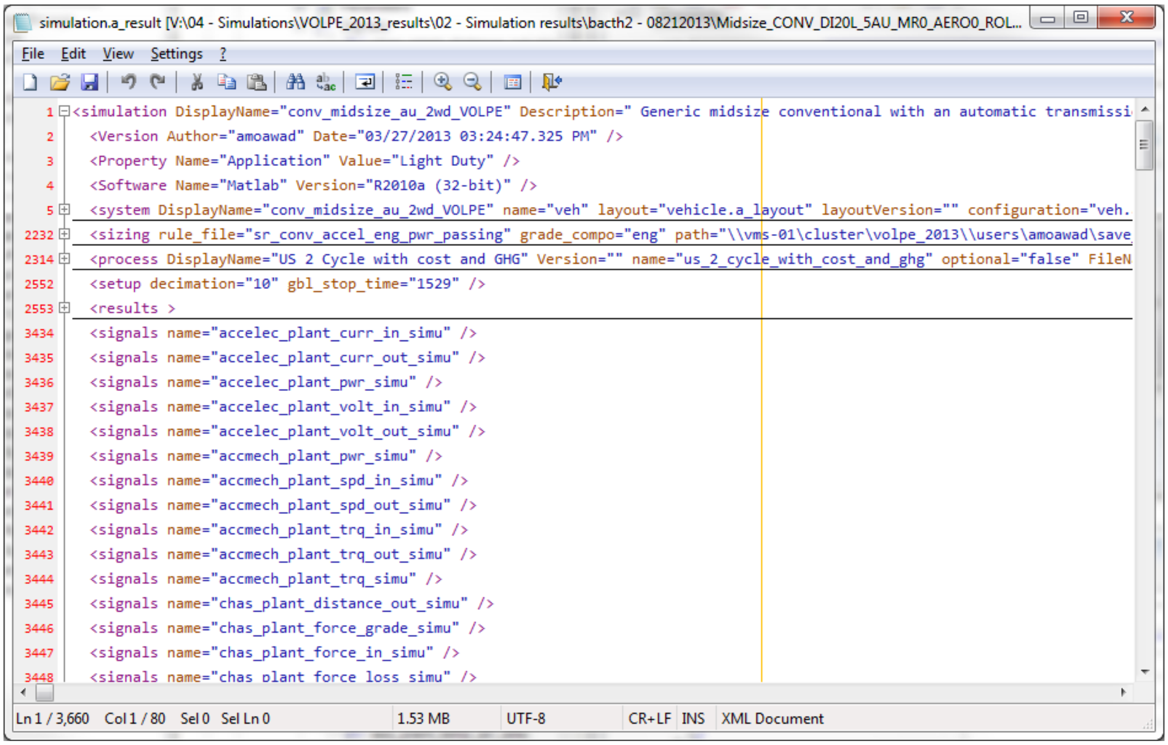


Figure 62 – Autonomie Results XML File

10.5. Folder Nomenclature

The MySQL database created and used by the CAFE model required a searchable list of parameters from which to retrieve information about a particular vehicle. Because some of these parameters did not come from Autonomie, a folder nomenclature was adopted as shown in Figure 63.

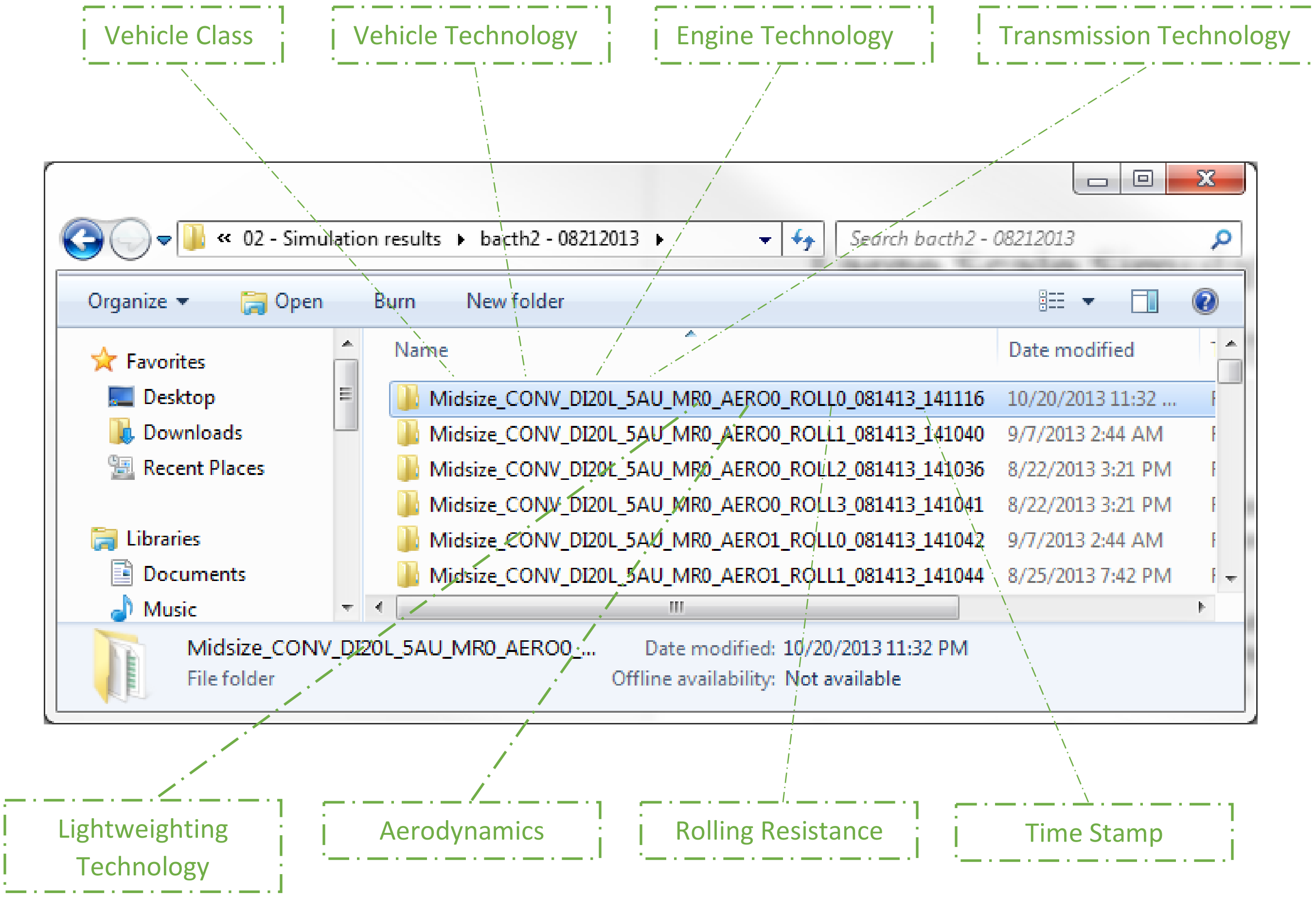


Figure 63 – Folder Nomenclature

The naming conventions are similar to the preliminary acronyms that may be used in the decision trees by the CAFE model. For example, the transmission technology acronyms are:

- 5AU — 5-speed automatic transmission
- 6AU — 6-speed automatic transmission
- 8AU — 8-speed automatic transmission
- 6DCT — 6-speed dual-clutch transmission
- 8DCT — 8-speed dual-clutch transmission
- 5DM — 5-speed manual transmission
- 6DM — 6-speed manual transmission
- 7DM — 7-speed manual transmission

The lightweighting acronyms are:

- MR0 — glider mass reduction of 0%
- MR1 — glider mass reduction of 1.5%
- MR2 — glider mass reduction of 7.5%
- MR3 — glider mass reduction of 10%
- MR4 — glider mass reduction of 20%

The aerodynamics acronyms are:

- AERO0 — aerodynamics reduction of 0%
- AERO1 — aerodynamics reduction of 10%
- AERO2 — aerodynamics reduction of 20%

The rolling resistance acronyms are:

- ROLL0 — rolling resistance reduction of 0%
- ROLL1 — rolling resistance reduction of 5%
- ROLL2 — rolling resistance reduction of 10%
- ROLL3 — rolling resistance reduction of 20%

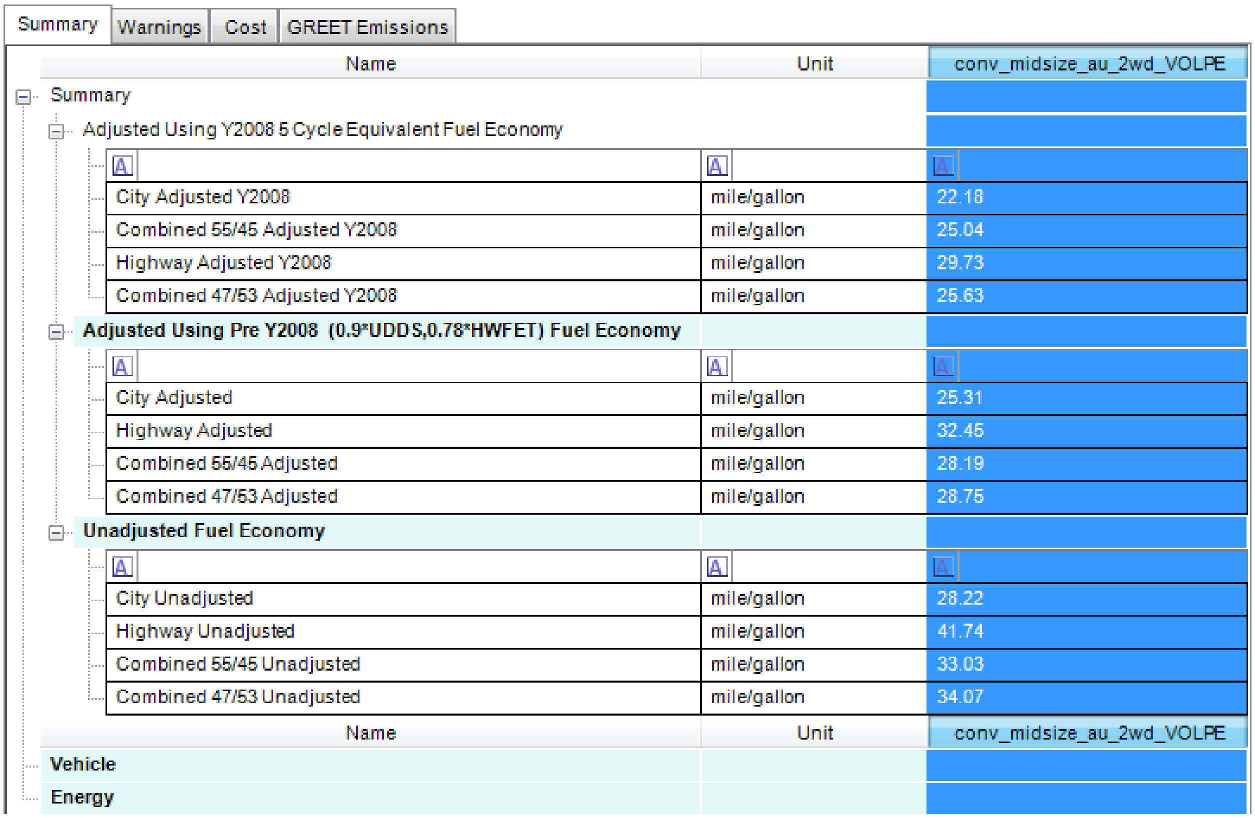
Since the engine technologies were not all represented to demonstrate the process, the following acronyms were selected:

- PFI20L – 2.0-liter naturally aspirated engine, port fuel injection, variable valve timing
- DI20L — 2.0-liter naturally aspirated engine, variable valve timing, direct injection
- DIVVL20L — 2.0-liter naturally aspirated engine, variable valve timing, variable valve lift, direct injection
- TDI16L — 1.6-liter turbo charged engine, direct fuel injection, variable valve timing
- TDIVVL16L — 1.6-liter turbo charged engine, direct fuel injection, variable valve timing and lift
- TDIVVL12L — 1.2-liter turbo charged engine, direct fuel injection, variable valve timing

10.6. Individual Vehicle Validation

Once the individual simulations are completed, Autonomie provides the ability to analyze them at both a high level (i.e., fuel economy) and a low level (i.e., time-based engine power) through its graphical user interface. An algorithm is also used to automatically flag any potential issues within a simulation (i.e., too many shifting events on a specific cycle).

Figure 64 shows a sample of parameter outputs from Autonomie provided for every vehicle among the 27,600 vehicles simulated. The list of output parameters generated for the CAFE model is detailed in Section 11.



Summary | Warnings | Cost | GREET Emissions

Name	Unit	conv_midsize_au_2wd_VOLPE
Summary		
Adjusted Using Y2008 5 Cycle Equivalent Fuel Economy		
City Adjusted Y2008	mile/gallon	22.18
Combined 55/45 Adjusted Y2008	mile/gallon	25.04
Highway Adjusted Y2008	mile/gallon	29.73
Combined 47/53 Adjusted Y2008	mile/gallon	25.63
Adjusted Using Pre Y2008 (0.9*UDDS,0.78*HWFET) Fuel Economy		
City Adjusted	mile/gallon	25.31
Highway Adjusted	mile/gallon	32.45
Combined 55/45 Adjusted	mile/gallon	28.19
Combined 47/53 Adjusted	mile/gallon	28.75
Unadjusted Fuel Economy		
City Unadjusted	mile/gallon	28.22
Highway Unadjusted	mile/gallon	41.74
Combined 55/45 Unadjusted	mile/gallon	33.03
Combined 47/53 Unadjusted	mile/gallon	34.07
Name	Unit	conv_midsize_au_2wd_VOLPE
Vehicle		
Energy		

Figure 64 – Example Baseline Conventional Vehicle Outputs

Numerous predefined plots are also available to analyze any time-based parameter from the simulation. Figure 65 shows an example of engine speed, vehicle speed, and gear number for a conventional vehicle.

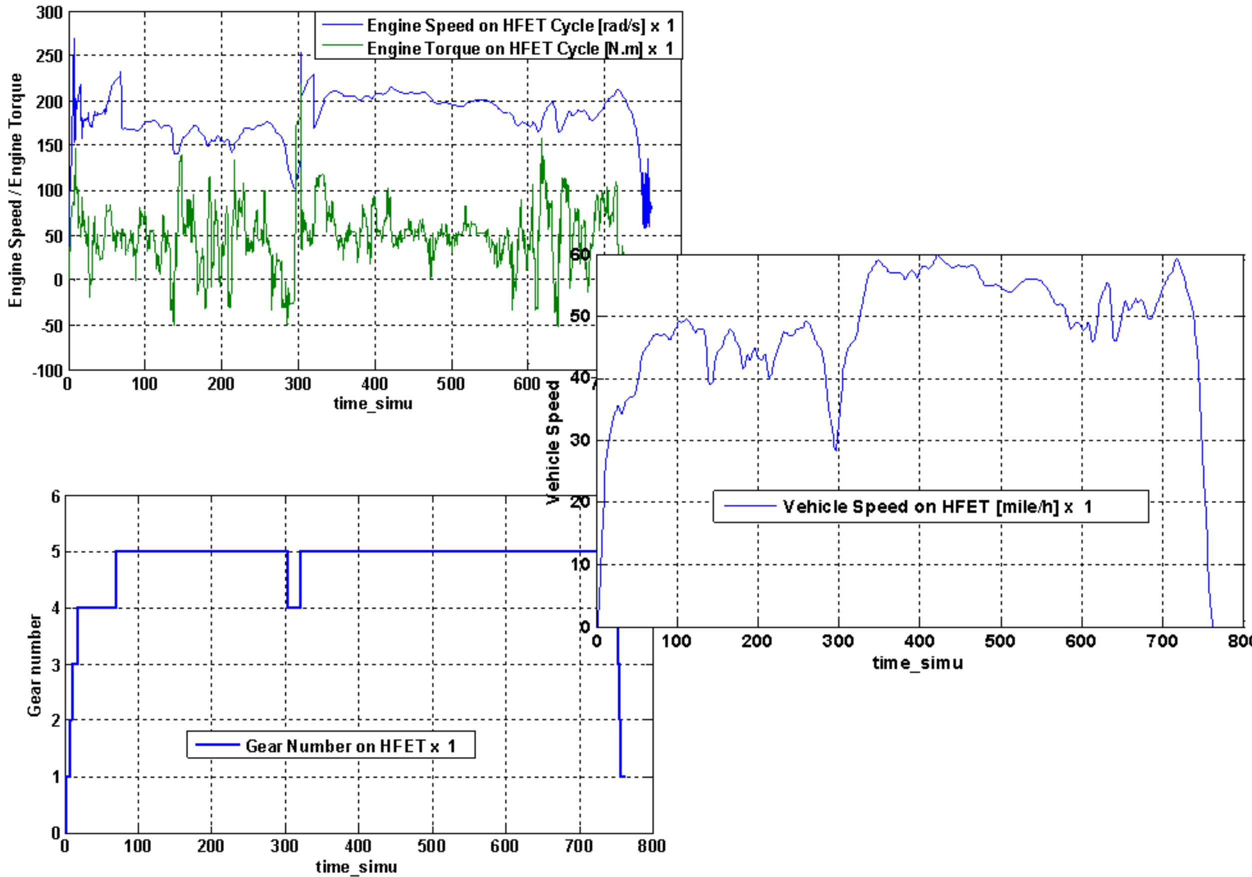


Figure 65 – Engine Speed, Engine Torque, Gear Number, and Vehicle Speed Time-Based Signals on HFET Cycle.

11. Vehicle Database

CAFE model requirements require the user to tackle two complicated problems simultaneously:

1. A vehicle simulation tool must be used to quickly and properly estimate energy consumption of extremely large numbers of specific vehicle, powertrain, and component technologies.
2. The user must easily access and analyze information across large amounts of data.

As discussed in Section 10, a process for performing large-scale simulation with Autonomie is now in place. With it, a simulation can be quickly validated, or any discrepancies in the results can be examined in detail. Additionally, Autonomie is fully integrated with distributed computing, making extremely large numbers of simulations, such as the quantity required for full CAFE analysis, feasible.

However, Autonomie was not originally designed to analyze such large sets of data. Such analyses impose data management concerns (numbers of files, disk sizes, access times); require the ability to run post-processing calculations without the time cost of rerunning all of the simulations; and involve plots, calculations, and other analytical tools for looking at high-level indicators and spotting overall trends. In response, Argonne's new process allows the detailed simulation results provided by Autonomie to either be distilled into a format that can be easily distributed and analyzed horizontally across many simulations, or examined via a deep, vertical dive into one simulation. Both aspects are critical for the full-scale vehicle analysis that Volpe requires.

The output of the simulations includes everything necessary for Autonomie to analyze or recreate an individual simulation, including the Simulink model representing the vehicle, a metadata file containing simulation results *.a_result file, and a data.mat file containing all of the time-based signal data. These results can be archived for full traceability and reproducibility of all simulations. However, it is currently not feasible to share or analyze these data. For example, 27,600 simulation results resulted in 2 TB of disk space usage. It's simply not scalable to pass this much information around, much less the number of simulations required for Volpe. Additionally, each simulation has individual files storing the results, so just managing or indexing the sheer number of files becomes an issue. Most of the information contained in those results files, however, is not necessary for the Volpe analysis (i.e., second-by-second fuel or electrical consumption values). Therefore, a subset of the data is collected into a portable, user-friendly database.

11.1. Database Creation

Argonne's database creation process works from an input sheet that specifies which input and output parameters should be included in the database. The process scans all of the simulation results files, extracts the specified parameters, and stores them in a single, specialized database file. This allows us to exclude irrelevant information not needed for cross-cutting analyses, while leaving the full results archived, just in case. Figure 66 lists the input and output parameters currently included in the database.

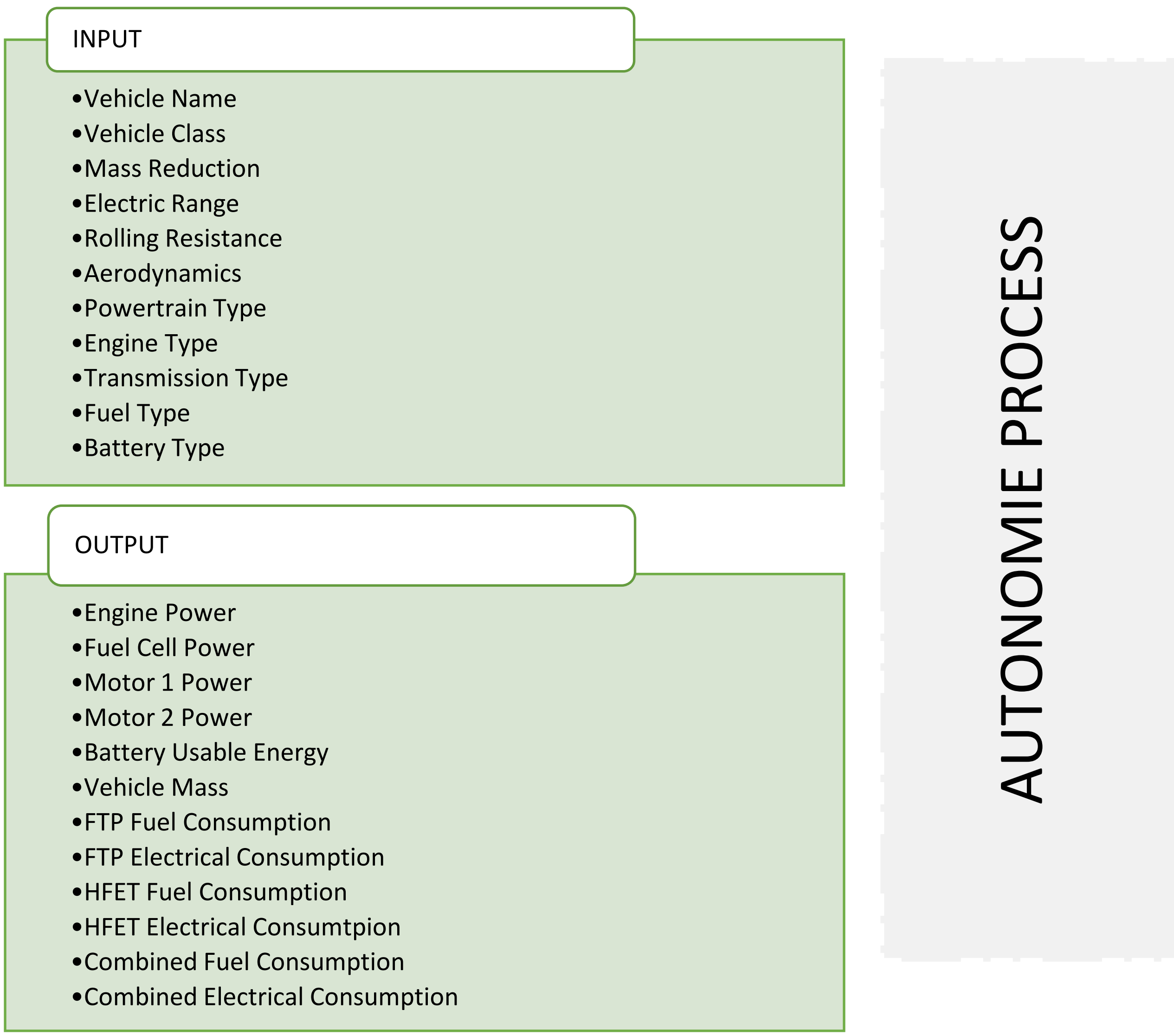


Figure 66 – Inputs and Outputs from Simulation Can Be Saved to the Database

A single database file is easy to redistribute. The aforementioned 2 TB of data was compressed into 180 MB of data, and took 7 hours to generate from the original simulation results. Additionally, the database is developed using the MS SQL Express 2012 format, which is free and easily accessed by standard structured query language tools.

11.2. Database Structure

As shown in Figure 67, the database is structured to be generic, so that any simulation input parameter, result, or descriptive property can be stored. This allows maximum flexibility in the type of data that can be stored. The tables are structured to allow logical grouping of data, maximize retrieval speed, and minimize disk space.

Vehicles and the references to their parameters are stored separately from parameters specific to the type of simulation, because the same vehicle can be run on multiple procedures or cycles. For example, one vehicle may be run on an acceleration test and a fuel consumption test, such as a combined cycle procedure. Each simulation may produce a fuel consumption, which would then be linked to that simulation record. However, parameters common across both simulation runs, such as the coefficient of drag of the vehicle, would be linked to the vehicle record. Not all vehicles and simulations have the same parameters; for example, motor parameters are only available for a vehicle with an electric power path (e.g., EVs, HEVs, PHEVs), and fuel consumption is only available for simulations with an engine or fuel cell, which excludes EVs.

Each parameter stores name, description, data type (i.e., string, double, integer, Boolean), and unit. The values themselves are organized into tables by data type for disk size optimization.

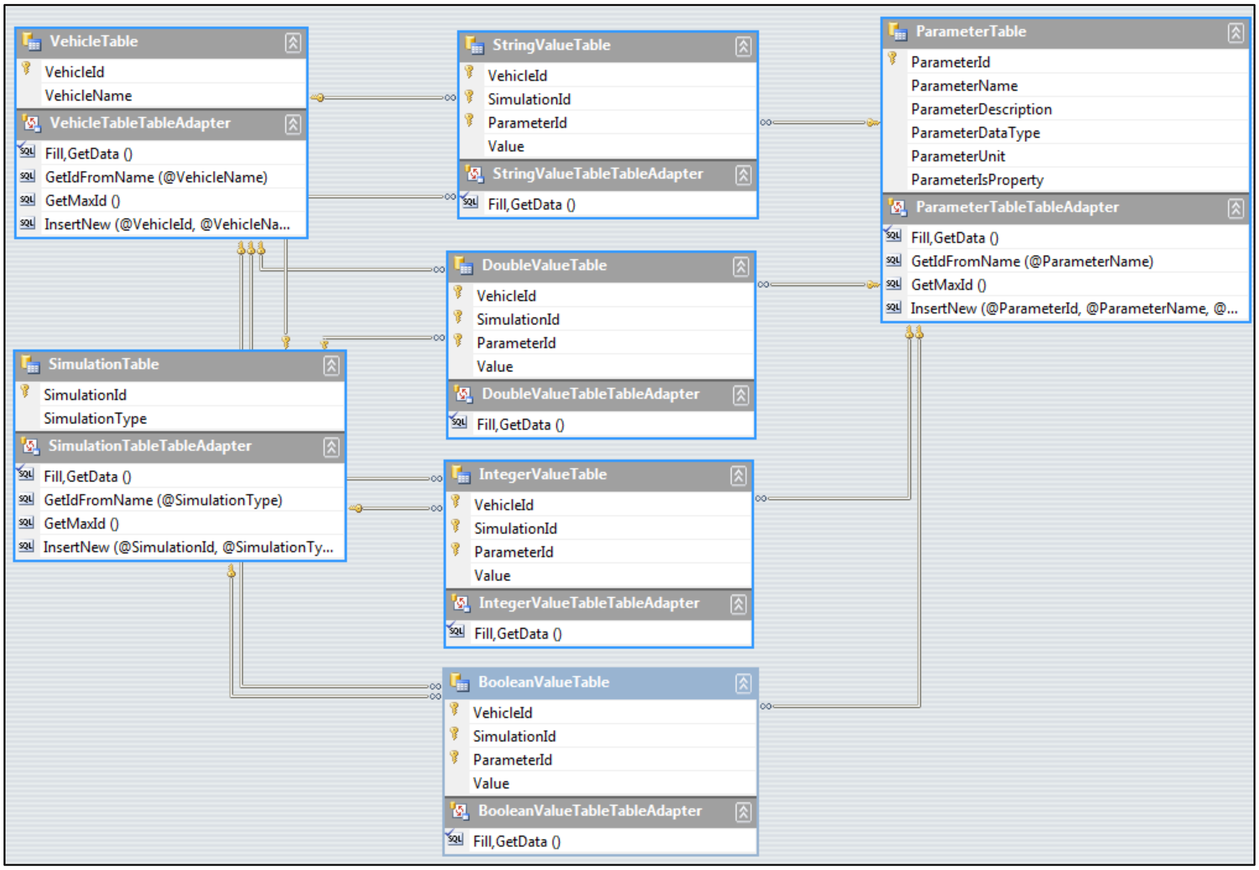


Figure 67 – Database Structure

11.3. User Interface

Although the database is accessible by any tool or programming language that can interact with databases, Argonne has also developed a tool to easily visualize and analyze the data (Figure 68). This tool provides a quick and intuitive way for users to quickly select subsets of simulation results of interest, select which parameters to view, modify assumptions, perform additional post-processing calculations on the data retrieved from the database, and view plots to better visualize the data.

Additionally, the user interface provides some advanced features that allow users to import their own plots and analysis functions; save “projects” of filters, parameters, and overridden assumptions; or export subsets of the data to Excel for additional data analysis or redistribution.

This tool allows users who are not familiar or comfortable with direct database access to perform the analysis necessary for Volpe.

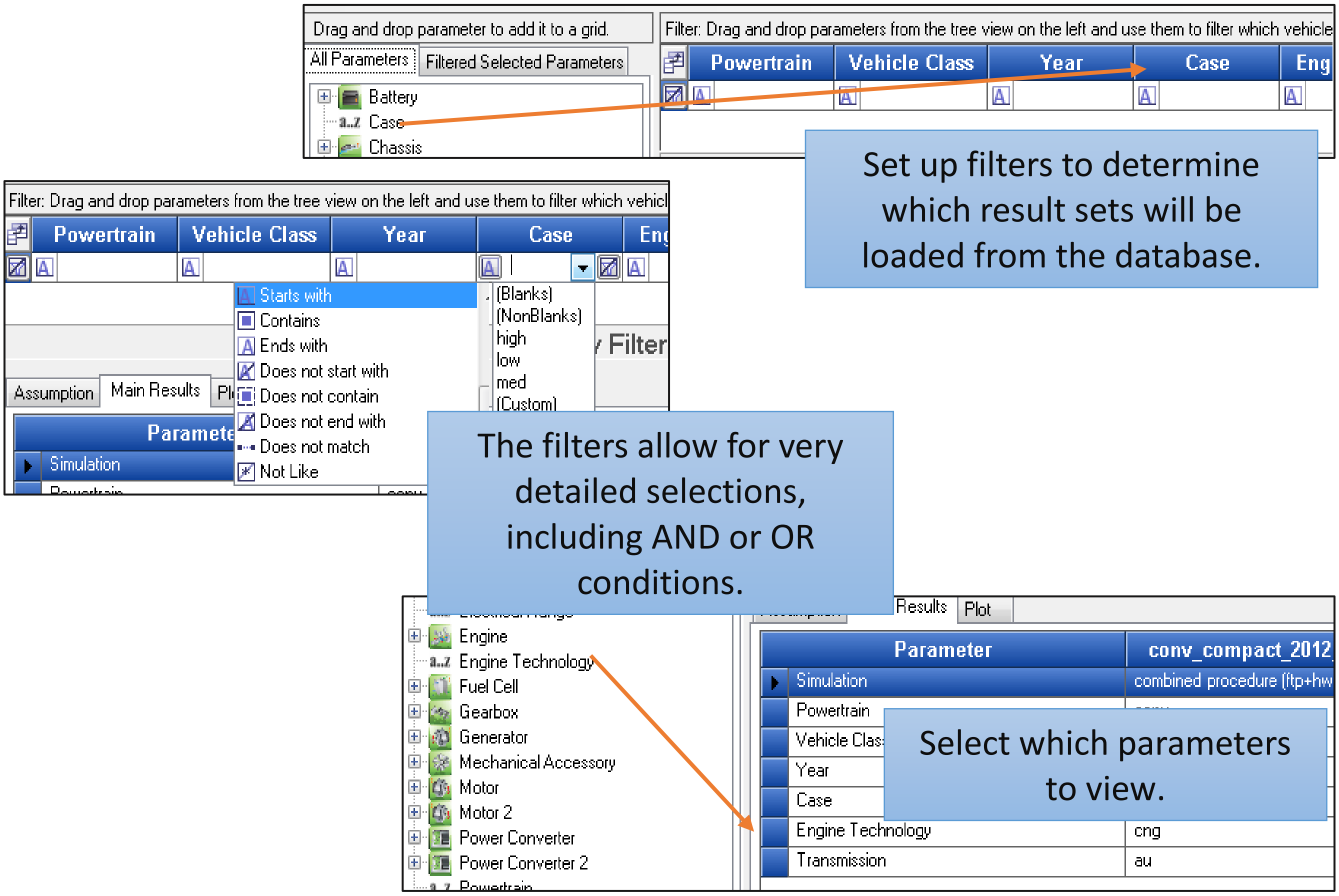


Figure 68– Database Analysis Tool

11.4. CAFE Model Access to the Database

A critical part of the process validation was to ensure that the CAFE model can access any information from the database. That step was successfully validated by the Volpe developers using a complete MySQL database provided by Argonne.

12. QA/QC Process

The large number of results could lead to an increase in number of iterations, in erroneous results propagating to further steps of the study and could introduce delays in generating results.

In order to improve accuracy and reduce iterations a QA/QC (Quality Assurance/Quality Check) process has been developed at ANL to perform checks on simulation results. This automated checking process can greatly reduce simulation iterations and improve quality of results.

Fields of interest are extracted from simulation results and imported into the database where an interactive report is generated listing the results that need to be examined. Statistical procedures are applied to flag erroneous results, also current methods are developed to have the ability to trace invalid results to cause of error (Figure 69).

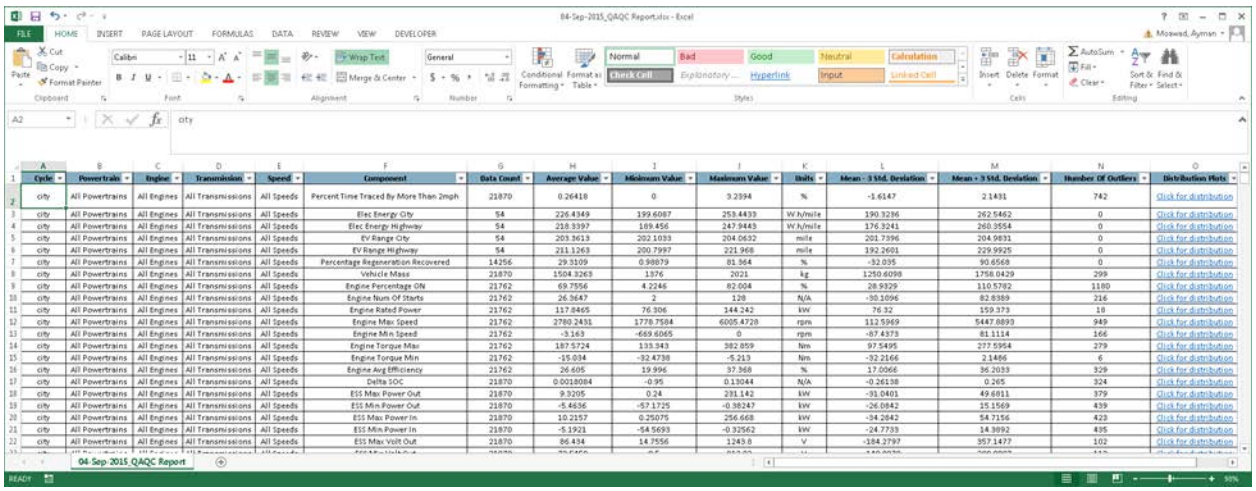


Figure 69 – Example of QA/QC report

An exhaustive list of parameters are extracted and checked for each vehicle simulation:

- Trace
- Vehicle Mass
- 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 Economy ratios
- :
- :

Distribution plots are generated as part of the report for visual perspectives (Figure 69)

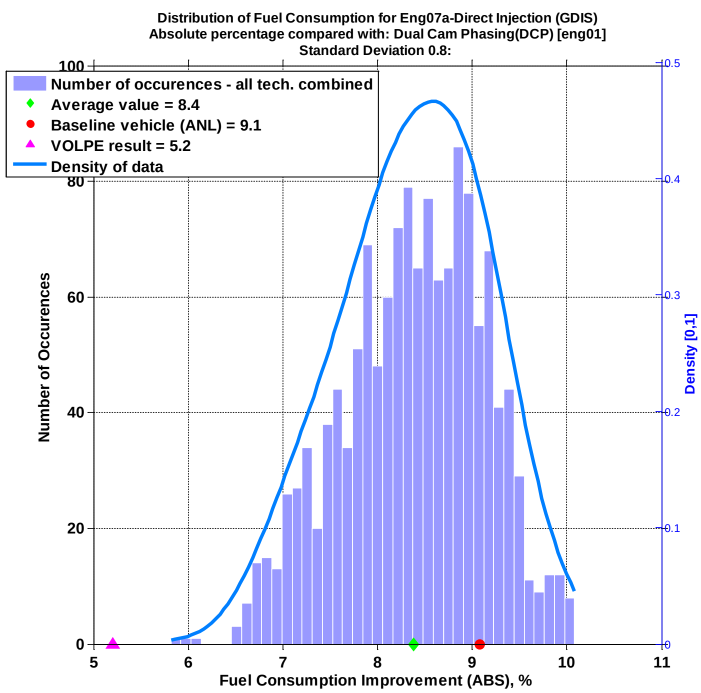


Figure 69 – Example of QA/QC distribution plot

13. Summary

The objective of the project was to develop and demonstrate a process to replace the current decision trees and synergies by individual results generated from detailed vehicle simulations.

This report described the process developed, including the generation of the MySQL database that will be accessible by the CAFE model. The process was validated by running numerous simulations representing most of the vehicle, powertrain, and component technologies currently included in the decision trees. The process efficiently simulates hundreds of thousands of vehicles to model anticipated future vehicle technologies and more than a million simulations including sizing iterative algorithms and standard procedure runs. A statistical model has been established in ordered to find relationships and reduce the necessary number of runs. Also a QA/QC process was thoroughly developed in order to assure the accuracy and validity of the results. Figure 70 shows a visual summary of the entire process.

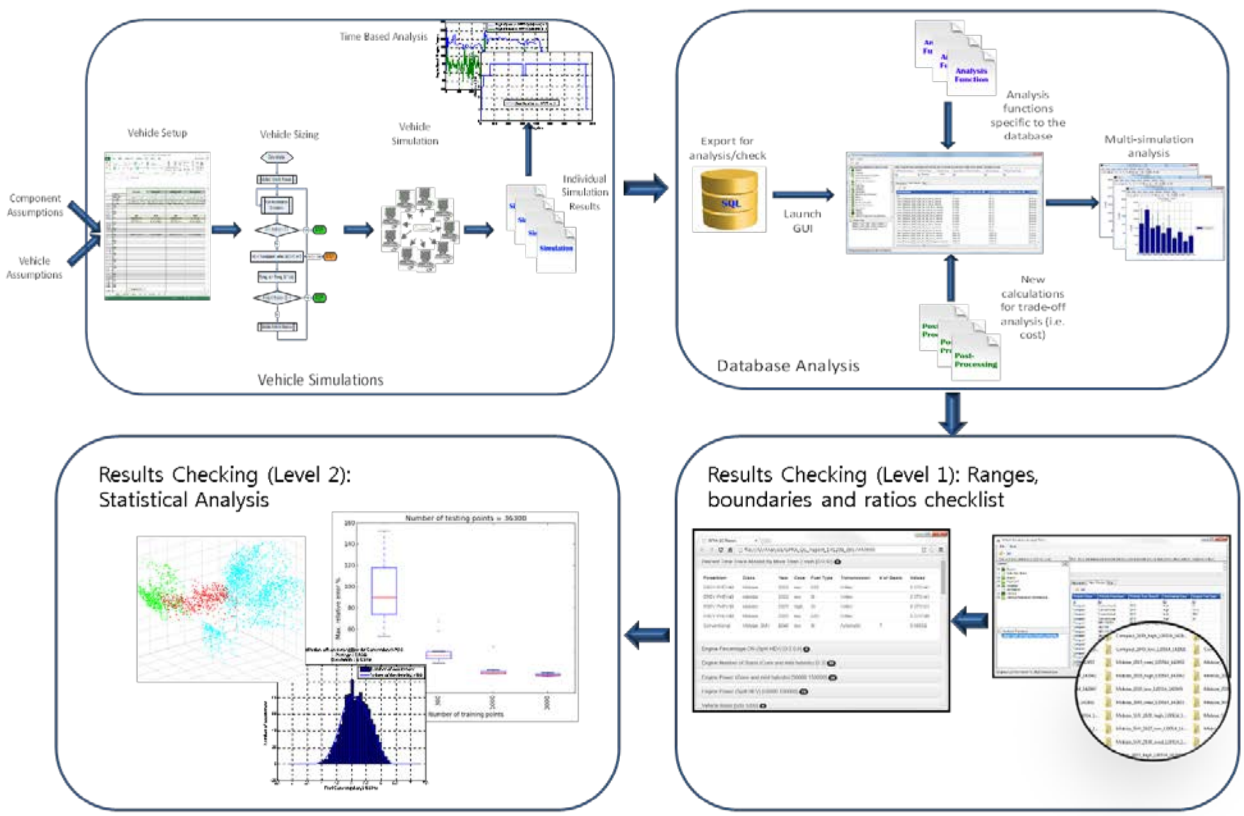


Figure 70 – Large Scale Simulation Process Summary