U.S. Department of Transportation
National Highway Traffic Safety Administration

www.nhtsa.gov

DOT HS 811 667 August 2012

Impact of Transmission Technologies on Fuel Efficiency – Final Report

Suggested APA Format Reference:

Moawad, A. and Rousseau, A. (2012, August). *Effect of Transmission Technologies on Fuel Efficiency – Final Report*. (Report No. DOT HS 811 667). Argonne, IL: Argonne National Laboratory.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 811 667		

4. Title and Subtitle	5. Report Date
Effect of Transmission Technologies on Fuel Efficiency – Final Report	August 2012
	6. Performing Organization Code
7. Author(s) Ayman Moawad, Aymeric Rousseau	8. Performing Organization Report No.
9. Performing Organization Name and Address Energy Systems Division Argonne National Laboratory Argonne, IL 60439	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590	13. Type of Report and Period Covered External Technical Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In developing Corporate Average Fuel Economy (CAFE) standards, DOT/NHTSA makes use of the CAFE Compliance and Effects Modeling System (the "CAFE model"), which was developed by DOT's Volpe National Transportation Systems Center. The Volpe model uses numerous engineering and economic inputs in its analysis of potential CAFE standards. Some of the most significant engineering inputs are the incremental fuel-savings estimates and synergy factors associated with new technology applications.

Vehicle simulation results are used by the Volpe Center to update the model's technology effectiveness estimates found in the model's decision trees. The decision trees are designed and configured to allow the Volpe model to apply technologies in a cost-effective, logical order that also considers ease of implementation. The decision trees are created such that each technology step is represented by an incremental effectiveness, the actual fuel consumption improvement in moving from one step to another, as well as an absolute value of effectiveness, which signifies the overall improvement starting from the reference baseline vehicle.

The objectives of the present study were to: (1) Update the current decision tree structure based on the latest transmission technologies, and (2) Quantify the impact of each technology option as both an incremental improvement from the previous technology and absolute improvement over the baseline vehicle in each of the vehicle classes. ANL used its vehicle simulation tool, Autonomie, to provide DOT/NHTSA with fuel-efficiency improvement results for different technologies within the decision trees. The technologies considered included the following: Automatic transmissions (up to 8 speeds), Dual clutch transmissions (DCTs) up to 8 speeds, High-efficiency transmissions, and early torque converter lockup.

The results from each are summarized for the various vehicle classes, including the incremental effectiveness values used by the CAFE model decision trees.

17. Key Words	18. Distribution Statement
	Document is available to the public from the National Technical Information Service www.ntis.gov

19 Security Classif. (of this report)	20. Security Classif. (of this page)	21 No. of Pages	22. Price
Unclassified	Unclassified	129	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ANL/ESD/12-6

Impact of Transmission Technologies on Fuel Efficiency

Energy Systems Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

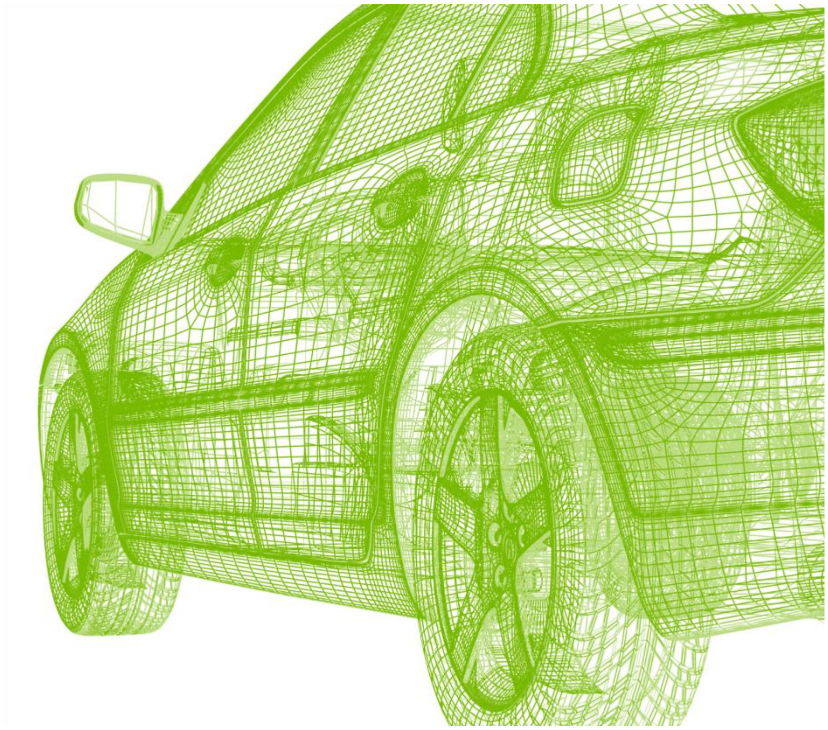
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

ANL/ESD/12-6

Impact of Transmission Technologies on Fuel Efficiency

by
Ayman Moawad and Aymeric Rousseau
Energy Systems Division, Argonne National Laboratory
August 2012

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815
www.anl.gov



Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Contents

Tables

Figures

Acronyms

Acronyms and Abbreviations

2-d	two-dimensional
6SPD	6-speed transmission
8SPD	8-speed transmission
APRF	Advanced Powertrain Research Facility
AU	Automatic transmission
CAFE	Corporate Average Fuel Economy
CVT	continuously variable transmission
DCT	dual clutch transmission
DOT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EVS	International Electric Vehicle Symposium
FTP	Federal Test Procedure
HETRANS	high-efficiency 8-speed automatic
HEV	hybrid electric vehicle
HFET	Highway Fuel Economy Test
HIL	hardware-in-the-loop
I/O	input/output
IATC	aggressive torque converter lockup
INC	incremental
MY	model year
NAUTO	5- to 6-speed automatic
NHTSA	Highway Traffic Safety Administration
PHEV	plug-in hybrid electric vehicle
PSAT	Powertrain System Analysis Toolkit
RCP	rapid-control prototyping
SAE	Society of Automotive Engineers
SHIFTOP	shifting optimizer algorithm
SIDI	spark-ignition direct-injection
SIL	software-in-the-loop
SUV	sport utility vehicle

Volpe model	CAFE Compliance and Effects Modeling System
VPA	vehicle powertrain architecture
XML	extendible markup language

Units of Measure

gal	gallon(s)
kg	kilogram(s)
kW	kilowatt(s)
L	liter(s)
m^2	square meter(s)
mm	millimeter(s)
mpg	mile(s) per gallon
mph	mile(s) per hour
N m	Newton meter(s)
rpm	rotation(s) per minutes
sec	second(s)

Acknowledgments

We would like to express special thanks to Argonne System Modeling and Control Group and especially Dominik Karbowski for his contributions to this report.

Thanks are also extended to those who have patiently reviewed the report, including Ann Schlenker, Ryan Harrington, John Whitefoot, Lixin Zhao and Rebecca Yoon.

1. Introduction

The U.S. Department of Transportation (DOT's) National Highway Traffic Safety Administration (DOT/NHTSA), in coordination with the U.S. Environmental Protection Agency (EPA), recently issued a final rulemaking to establish Corporate Average Fuel Economy (CAFE) standards for model year (MY) 2012–2016 passenger cars and light trucks. The standards were established pursuant to the amendments made by the Energy Independence and Security Act of 2007 to the Energy Policy and Conservation Act.

In developing the standards, DOT/NHTSA made use of the CAFE Compliance and Effects Modeling System (the "Volpe model"), which was developed by DOT's Volpe National Transportation Systems Center. The Volpe model uses numerous engineering and economic inputs in its analysis of potential CAFE standards. Some of the most significant engineering inputs are the incremental fuel-savings estimates and synergy factors associated with new technology applications, which have come under increased scrutiny over the past several rulemakings. The automotive industry, other government agencies, and non-governmental organizations have been comparing the effectiveness estimates, synergy factors, and CAFE model outputs with estimates and results obtained from physics-based full vehicle simulation tools (software programs). In addition, in a report [1] to DOT/NHTSA, the National Academies of Sciences recommended that DOT/NHTSA use full vehicle simulations tools to develop effectiveness estimates and synergy factors for rulemaking analyses. DOT/NHTSA, in coordination with EPA, has recently issued a Notice of Proposed Rulemaking (NPRM) for CAFE standards to cover MYs 2017 and beyond and is currently working on the final rule. The analysis requires numerous updates to the Volpe model and to a number of the inputs listed above.

Manufacturers have been considering various technology options for improving vehicle fuel economy; DOT/NHTSA has typically categorized these technology options into several groups, including engine technologies, transmission technologies, hybrid and electrification technologies, and what the agency calls "vehicle" technologies (e.g., weight reduction, aerodynamic drag improvement). 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 (DCT).

Since the MY 2005-2007 CAFE rulemaking, DOT/NHTSA has relied on the Volpe model to evaluate potential CAFE standards. In fact, the model is the primary tool used by the agency to evaluate potential CAFE stringency levels by applying technologies incrementally until the desired stringency is met. The Volpe 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”. Vehicle simulation results are used by the Volpe Center to update the model’s technology effectiveness estimates found in the model’s decision trees. The decision trees are designed and configured to allow the Volpe model to apply technologies in a cost-effective, logical order that also considers ease of implementation. 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 Volpe model can be found in NHTSA’s upcoming Final Regulatory Impact Analysis for the MYs 2017 and beyond CAFE standards, which will be available with the model itself and its inputs at http://www.nhtsa.gov/fuel-economy [2].

Figure 1 shows an original transmission decision tree provided by DOT/NHTSA. This original tree, for a midsize conventional vehicle, was used in the NPRM analysis. Starting from a 5-speed-automatic-transmission as the baseline, step-by-step improvements are made incrementally. For each technology step, the incremental effectiveness estimate represents the actual fuel consumption improvement of moving from one step from the previous step, whereas the absolute value signifies the overall fuel consumption improvement starting from the reference baseline transmission/vehicle. The original incremental improvement values used in the Volpe model’s decision tree for the transmission technologies estimated a maximum absolute fuel consumption reduction of 18.8% once the final technology (Shift Optimizer) was reached. These values were based upon simulation results generated by Ricardo and then incorporated into EPA’s lumped parameter model (LPM). A detailed description of the Ricardo simulation work and how it was incorporated into the LPM can be found in the Draft Technical Support Document found at http://www.nhtsa.gov/fuel-economy [2].

ORIGINAL TREE

			Auto Trans					
START	2012-2016	INC	%	3.0%	$	$ 54.85	$ 54.17	
4/5-spd		ABS	%	3.0%	$	$ 55	L	
Auto			Imp. Auto Trans Cnrt./ Externals (IATC) - TBL					IATC
	2017+	INC	%	3.0%	$	$ 55	$ 54.17	
Start assumed to be 5 AU for midsize		ABS	%	3.0%	$	$ 55	L	
	2012-2016	INC	%	2.0%	$	$ (37.59)	$ 100.55	
		ABS	%	5.0%	$	$ 17	L	
			6-spd Auto Trans w/Imp Internals (NAUTO) - TBL					NAUTO
	2017+	INC	%	2.0%	$	$ (38)	$ 10.00	
		ABS	%	5.0%	$	$ 17	L	
	2012-2016	INC	%	4.1%	$	$ (78.51)	$ (10.47)	
		ABS	%	8.8%	$	$ (61)	L	
			6-spd Dual Clutch Trans (DCT) - TBL					DCT
	2017+	INC	%	4.1%	$	$ (79)	$ (10.47)	
		ABS	%	8.8%	$	$ (61)	L	
	2012-2016	INC	%	4.6%	$	$ 221.43	$ -	
		ABS	%	13.0%	$	$ 160	M	
			8-spd Trans (Auto or DCT) (8SPD) - TBL					8SPD
	2017+	INC	%	4.6%	$	$ 221	$ 10.00	
		ABS	%	13.0%	$	$ 160	L	
	2012-2016	INC	%	0.0%	$	$ -	$ 10.00	
		ABS	%	13.0%	$	$ 160	L	
			High Eff. Gearbox (Auto or DCT) - (HETRANS) - TBL					HETRANS
	2017+	INC	%	2.7%	$	$ 225.17	$ 10.00	
		ABS	%	15.3%	$	$ 385	L	
	2012-2016	INC	%	0.0%	$	$ -	$ 10.00	
		ABS	%	13.0%	$	$ 160	L	
			Shift Optimizer (SHFTOPT) - TBL					SHFTOPT
	2017+	INC	%	4.1%	$	$ 30.29	$ 10.00	
		ABS	%	18.8%	$	$ 416	L	

Figure 1 – Original Decision Tree (June 24, 2011; VOLPE)

The objectives of this study were to:

- Update the current decision tree structure to reflect the latest transmission technologies; and
- Quantify the impact of each technology option as both an incremental improvement from the previous technology and absolute improvement over the baseline.

Argonne used its vehicle simulation tool, Autonomie, to provide DOT/NHTSA with fuel-efficiency improvement results for different technologies within the decision trees. The following technologies were evaluated:

- Automatic transmissions (up to 8 speeds),
- DCTs (up to 8 speeds),
- High-efficiency transmissions, and
- Early torque converter lockup.

This report and the analysis herein was peer-reviewed by independent experts in the field. The comments from the peer reviewers were used to modify and improve the analysis and this report. These peer-reviewer comments and the responses to them are summarized in Appendix 1.

2. Autonomie

2.1. Overview

Autonomie [3, 4] 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. Autonomie has been validated for several powertrain configurations and vehicle classes using vehicle test data from Argonne's Advanced Powertrain Research Facility (APRF) [5, 6, 7, 8].

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 [9, 10], as well as to define the component requirements (e.g., power, energy) to maximize fuel displacement for a specific application [11, 12]. 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 [13, 14, 15, 16], cost-benefit analysis, or greenhouse gases [17, 18].

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

2.2. 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 2).

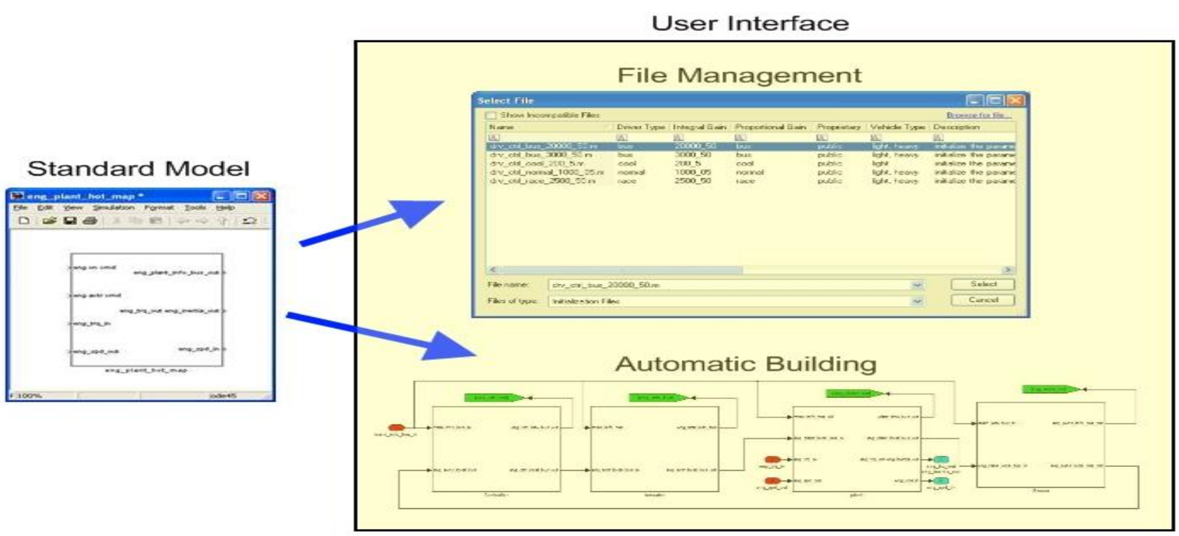


Figure 2 – Simulation Management Concepts

All systems in the vehicle architecture can be logically categorized as either a "containing system" or a "terminating system" (Figure 3). 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.

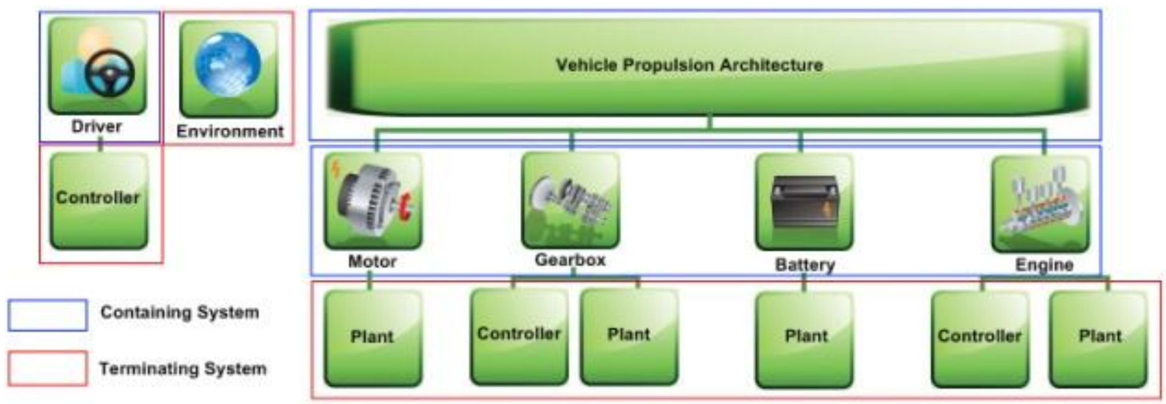


Figure 3 – Class Diagram of Container and Terminating Systems

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 4). The VPA system will contain the powertrain components that are required to simulate the vehicle, such as engine, battery, and wheels.

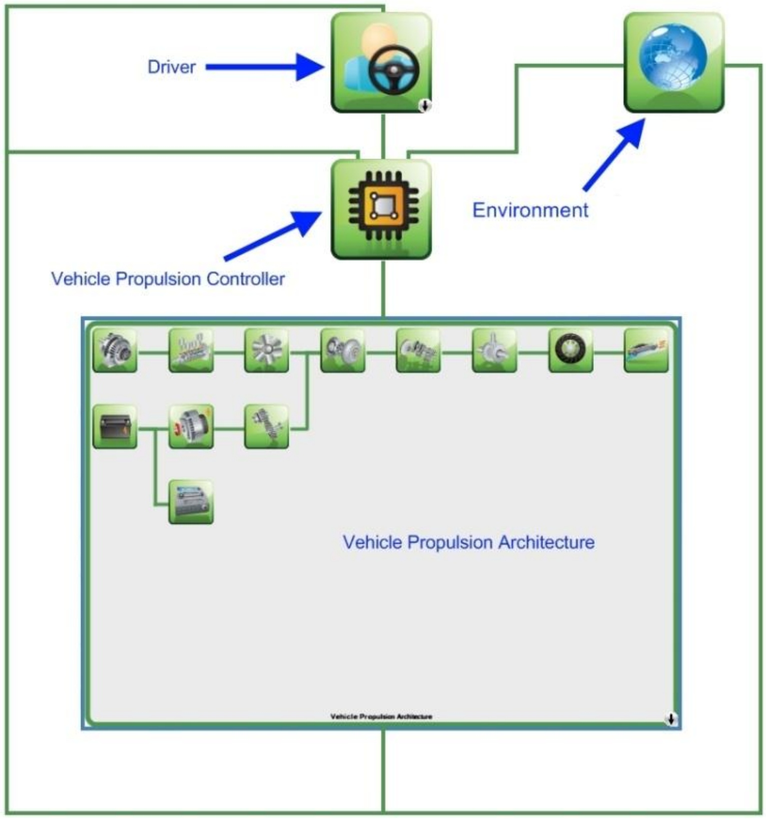


Figure 4 – Top-Level Vehicle Layout

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 5.

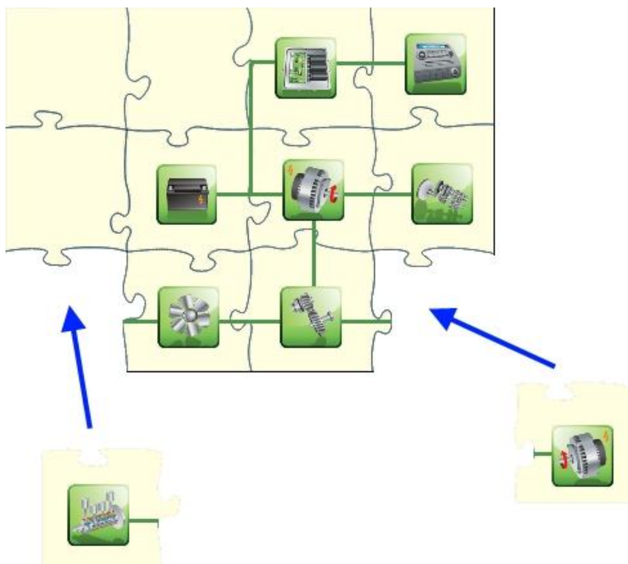


Figure 5 – Models are Automatically Built

3. Study Assumptions

The transmission decision tree, as described in section 1, is linear. However in reality, there are technically two paths. The first path is for vehicle classes where the assumed transmission of choice is the dual clutch transmission (DCT). The second path is for vehicle classes where the assumed transmission of choice is an automatic transmission because of launch and/or towing requirements that could benefit from the torque converter's torque multiplication. For this second path, the DCT step is disabled and the transmission progresses from a 6-spd automatic to an 8-spd automatic. In essence, there are two paths in one and the path taken is determined by the class of vehicle being evaluated. For purposes of this study and to make it easier to follow progressions down the decision tree, the two paths are shown explicitly as shown in Figure 6.

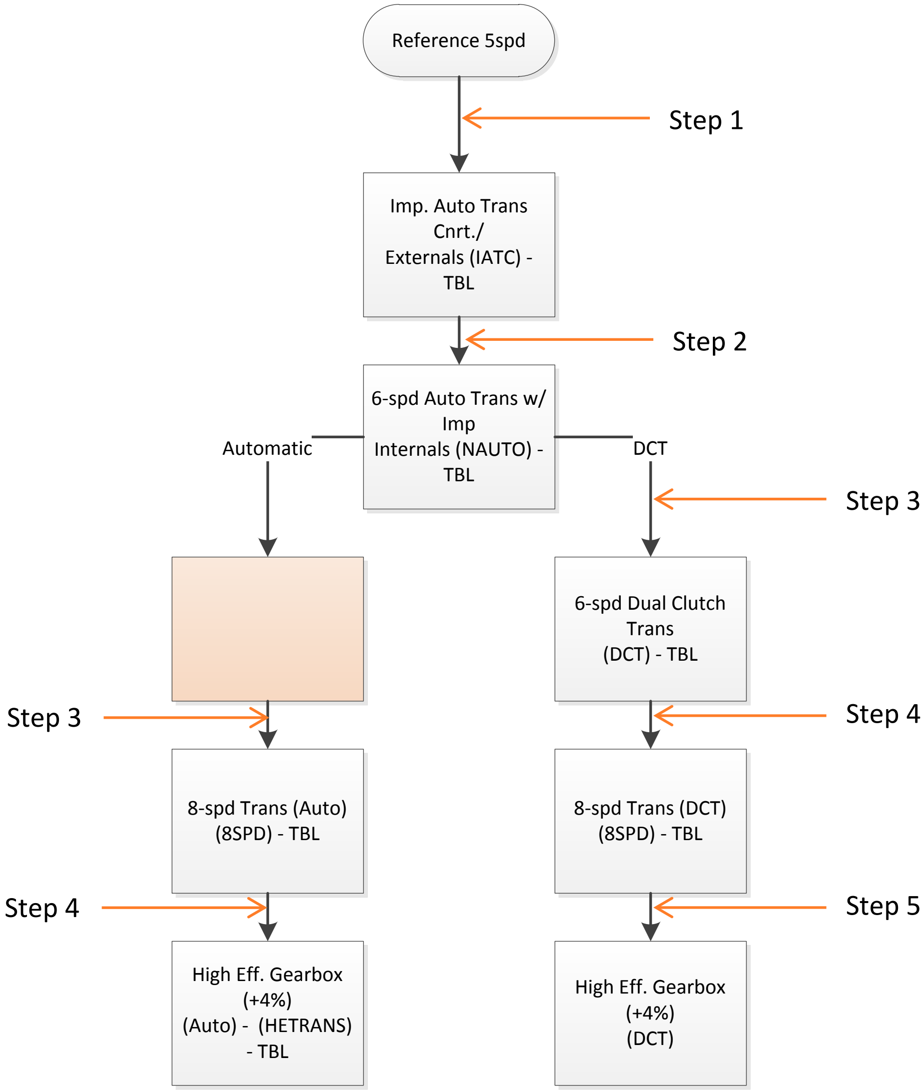


Figure 6 – Modified Decision Tree

The reference vehicle used is a midsize conventional vehicle with a 5-speed automatic transmission and current (non-aggressive) lockup strategy. All of the following transmission steps have an early lockup strategy, meaning the torque converter will be locked once it is in second gear.

The transmission decision tree steps are as follow:

Step 1: Using aggressive torque converter lockup strategy for 5 speed transmission

Step 2: Going from 5-speed improved transmission with early lockup, with 92% constant efficiency, to 6-speed transmission with 92% constant efficiency.

Step 3: Going from 6-speed automatic transmission with 92% constant efficiency to either:

- 6-speed DCT with 92% constant efficiency; or
- 8-speed (8SPD) automatic transmission with 92% constant efficiency.

Step 4:

- Going from 6-speed DCT with 92% constant efficiency to 8-speed DCT with 92% constant efficiency.
- Going from 8-speed (8SPD) automatic transmission with 92% constant efficiency to 8-speed automatic transmission with 96% constant efficiency (HETRANS).

Step 5: Going from 8-speed automatic transmission with 92% constant efficiency to 8-speed DCT with 96% constant efficiency.

It should be noted that the shift optimizer (SHFTOPT) technology, the last step in the original decision tree, was not included in this study. In an attempt to replicate the shift optimizer technology, we removed all drivability constraints from the shifting control algorithm (i.e., number of shifting events, torque reserve…). However, even when the algorithm allowed for more frequent shifts, we could find any significant fuel consumption reductions for a shift optimizer type technology once all the other preceding technologies had been added. For this reason, the shift optimizer technology was not included in this study.

Constant efficiency values were used in the study to facilitate comparison among transmission technologies. The reference value was selected to match the average efficiency of the current gearbox, which was derived from proprietary information.

4. Baseline Assumptions

4.1. Reference Vehicle

The reference vehicle selected is a conventional midsize vehicle, characterized in Table 1

Table 1 – Main Vehicle Specifications

Component	Value
Engine power (kW)	115
Transmission ratios	[2.56 1.55 1.02 0.72 0.52]
Final drive ratio	4.7
Test weight (kg)	1,580
Drag coefficient	0.3
Frontal area (m²)	2.25
Rolling-resistance coefficient 1	0.008
Rolling-resistance coefficient 2 (speed term)	0.00012

Figure 7 shows a schematic of the different component models of the conventional vehicle in Autonomie.

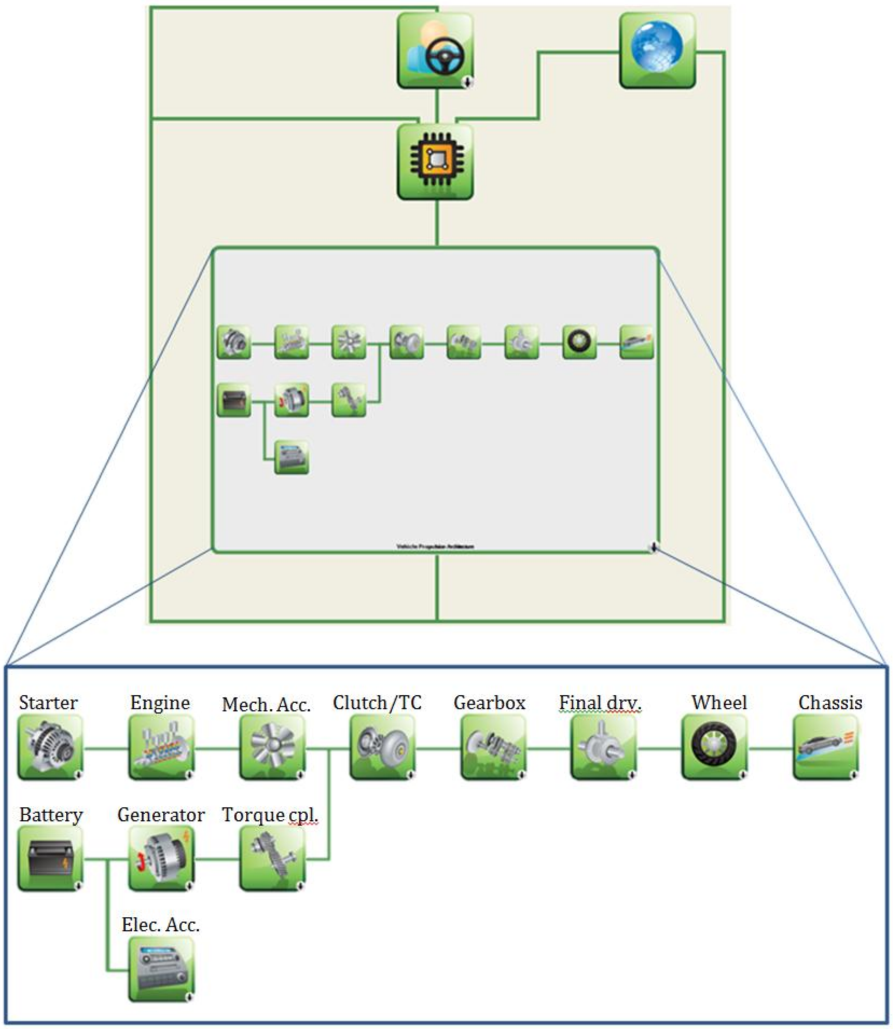


Figure 7 – Conventional Vehicle Model

4.2. Engine

The engine is one of the main components affecting the fuel economy of conventional vehicles. The benefits of advanced transmissions are expected to be lower for advanced engines, which have higher peak efficiencies and larger constant efficiencies islands— meaning that additional gears would offer lower benefits than on lower-efficiency engines. The engine model used in this study is based on steady-state data collected at Argonne. The main data set, also known as an engine map, comprises fueling rate, as a function of engine torque, and rotational speed. The engine characteristics, as well as the other assumptions (except those for transmissions), are kept constant throughout the study to focus solely on the transmission benefits. The interactions among component technologies (i.e., synergies), as well as the impact of the reference technologies (i.e., engine technologies), will be addressed at a later date.

The engine selected is a dual-overhead-camshaft, four-cylinder engine equipped with direct fuel injection and exhaust gas recirculation; Table 2 lists the major specifications.

Table 2 – Main Engine Specifications

Engine Type	2.2-L Ecotec Direct
Cylinders	4
Displacement (L)	2.198
Bore (mm)	86
Stroke (mm)	94.6
Connecting rod length (mm)	145.5
Compression ratio	12:1
Maximum power (kW)	114 at 5,600 rpm
Maximum torque (N m)	220 at 3,800 rpm

The engine map (Figure 8) used to generate the results is based on experimental data collected at Argonne Advanced Powertrain Research Facility.

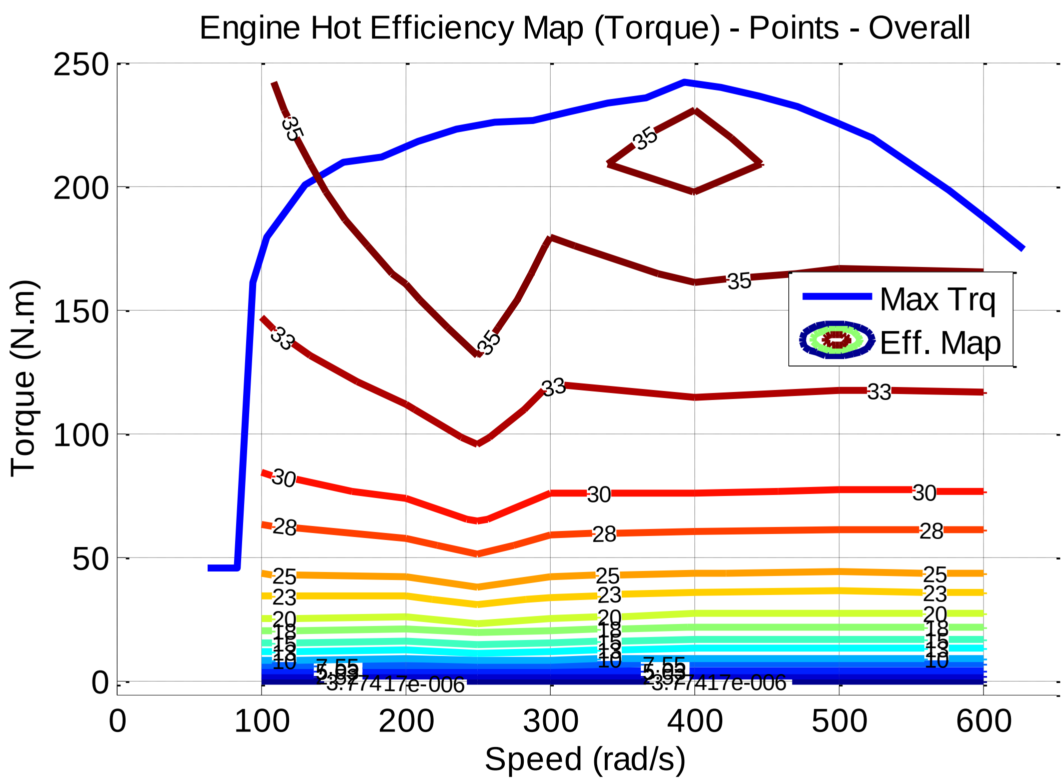


Figure 8 – Spark-Ignition Direct-Injection (SIDI) 2.2-L Engine Map (Argonne Test Data)

4.3. Transmission

On the basis of the reference 5-speed automatic transmission, the following technology options were selected:

- DCT technology,
- Increased gear number (6 and 8 gears), and
- Lower transmission losses (4% efficiency percentage point increase).

As a result, six transmissions were selected, in addition to the reference transmission:

1. 6-speed automatic transmission, base efficiency of 92% for the gearbox;
2. 8-speed automatic transmission, base efficiency;
3. 8-speed automatic transmission, improved efficiency;
4. 6-speed DCT, base efficiency;
5. 8-speed DCT, base efficiency; and
6. 8-speed DCT, improved efficiency.

An efficiency for the gearbox (i.e., not including the torque converter) of 92% was selected for the study. This value was selected after running simulations using several proprietary detailed transmission data (i.e., losses as a function of rotational speed and torque for each gear) to provide transparent results. As for all the other models, the study assumed that all components are fully warmed-up. As a result, the potential difference in warm-up between all the different transmission technologies is not considered.

For each technology, numerous transmission ratios could be selected. For this study, we did not consider optimizing the gear ratios for each case. Rather, the gear span (ratio between minimum and maximum gear) was increased for transmissions with a higher number of gears. For consistency within the study, both the automatic transmission and DCT have the same gear ratios. The gear ratios were selected based on transmissions currently in the market. Table 3 lists the gear ratio for each technology.

Table 3 – Transmission Ratios

	1	2	3	4	5	6	7	8
Reference 5-speed automatic	2.56	1.55	1.02	0.72	0.52			
6-speed transmissions	4.15	2.37	1.56	1.16	0.86	0.52		
8-speed transmissions	4.6	2.72	1.86	1.46	1.23	1	0.82	0.52

Figure 9 shows the average gear span and total top gear ratios (final drive ratio included) of selected 5, 6, and 8 speed transmissions currently on the market. One notices that the gear span increases with the higher number of gears in a transmission while the top gear ratio decreases with higher transmission gear number. The transmissions were selected from similar vehicles (class, engine power, etc…) using same technology but different gear number; for example the V6 charger 2011 has a 5 speed transmission whereas the V6 charger 2012 has an 8 speed transmission.

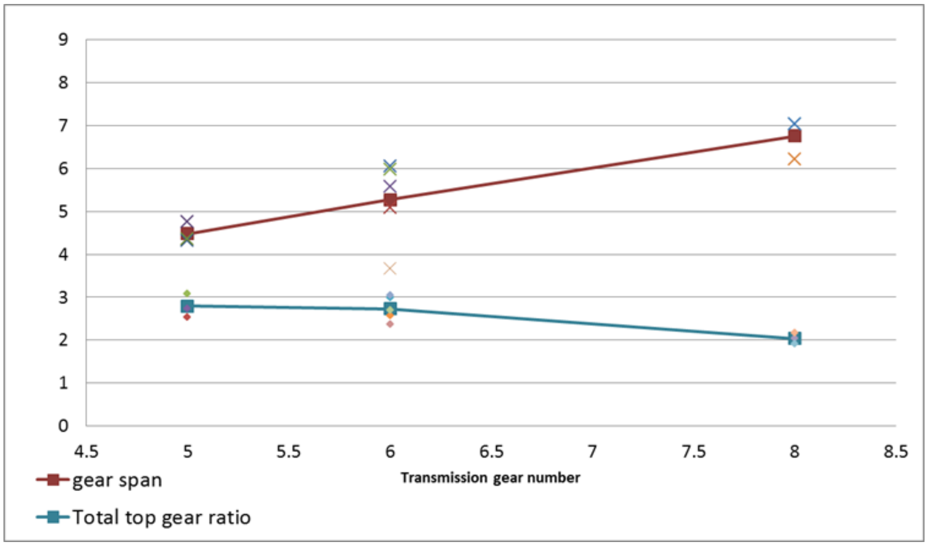


Figure 9 – Average gear span and top gear ratios from a couple of transmissions on the market current market

The values selected for this study are shown in Figure 10. The same trend is followed with gear span increasing and the top gear ratio decreasing with the number of gears. The values for the total top gear ratios are similar between the average from the current market and the study. Maintaining the same top gear across all transmissions would significantly limit the benefits of the technologies and does not represent the current market trends. The gear span is however slightly higher in the study to be able to maintain the same vehicle performance with the same engine regardless of the transmission selected.

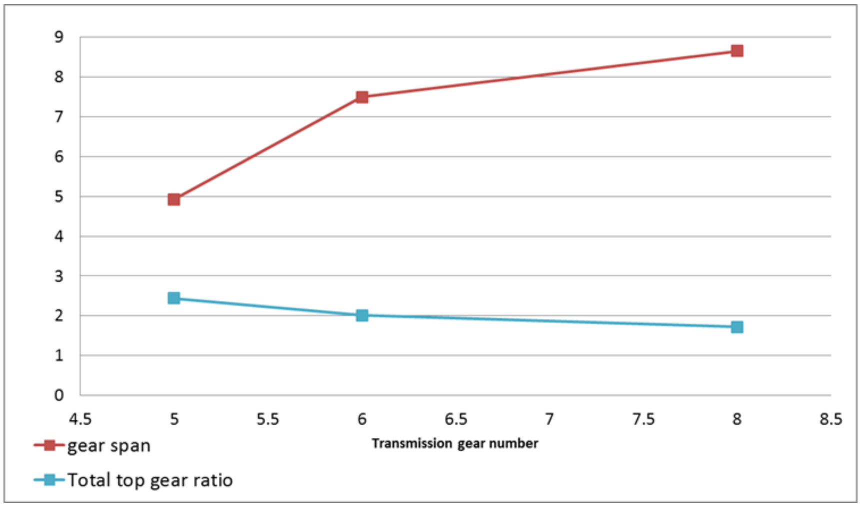


Figure 10 - Average gear span and top gear ratios from Argonne selection representing the potential future market

In order to properly compare the different transmission technologies and control options, the vehicles need to have the same vehicle performance specifications (i.e., 0–60 mph in 9.5 sec). Because the focus of this study is the transmissions, all the other components have been maintained constant (i.e., same engine power). As a result, we decided that the final drive ratios would be modified to maintain the same vehicle performances.

Table 4 shows the final drive ratios and the vehicle performance values. A constant value of 97.5% is used to represent the final drive ratio efficiency.

Table 4 – Final Drive Ratios and Vehicle Performance

	5-speed	6-speed	8-speed
Final drive ratio (auto/DCT)	4.7/-	3.8/3.69	3.3/3.3
0–60 mph performance	9.5 sec	9.5 sec	9.5 sec

4.4. Accessory Loads

Electrical and mechanical accessory base loads were assumed constant over the drive cycles, with a value of 200 W. The value, based on measured data from Argonne's APRF, is used to represent the average accessory load consumed during standard urban (Federal Test Procedure [FTP]) and highway (Highway Fuel Economy Test [HFET]) drive cycle testing on a dynamometer.

4.5. Control Algorithm

4.5.1. 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.

4.5.1.1. *Shifting Controller*

The shifting controller determines the appropriate gear command at each simulation step. A simplified schematic of the controller is shown in Figure 11. The letters and numbers in the discussion that follows correspond to those shown in the figure.

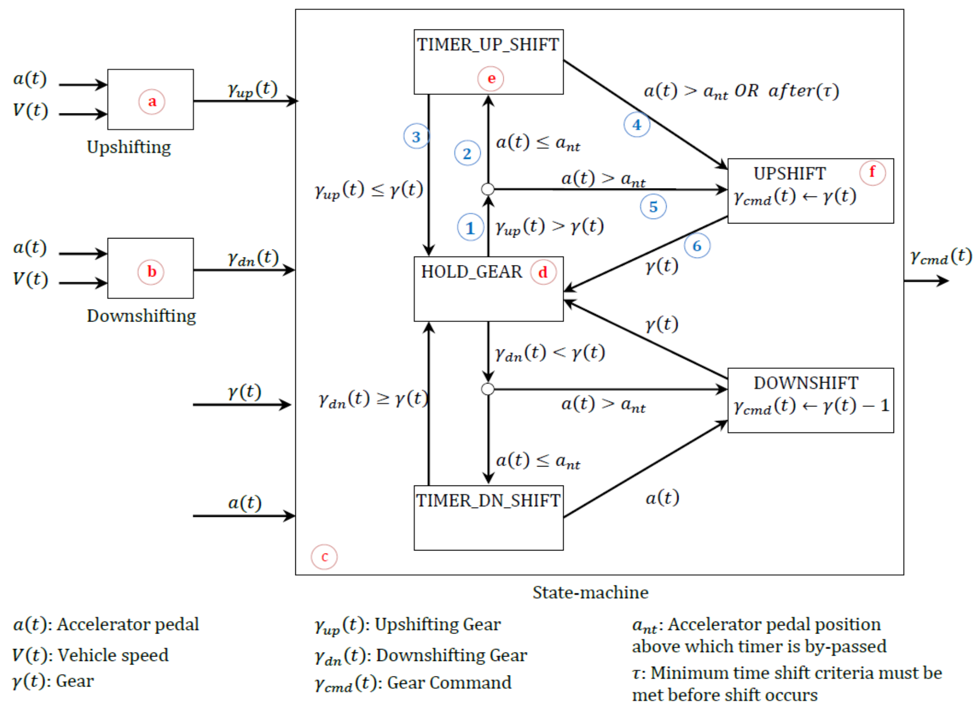


Figure 11 – Shifting Controller Schematic

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 FPT 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.

4.5.1.2. 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 12 illustrates that equivalence.

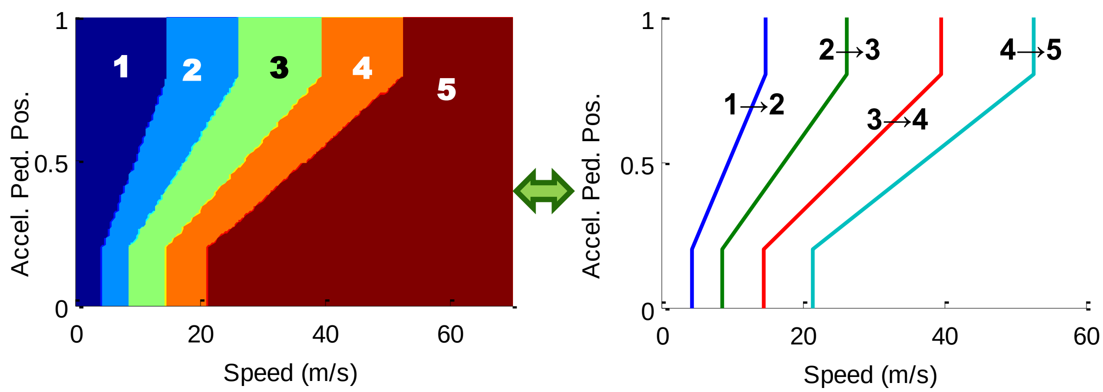


Figure 12 – Upshifting Gear Map (left), Upshifting Vehicle Speeds (right)

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 13 shows the engine speed shift points for an engine associated with a 5-speed transmission.

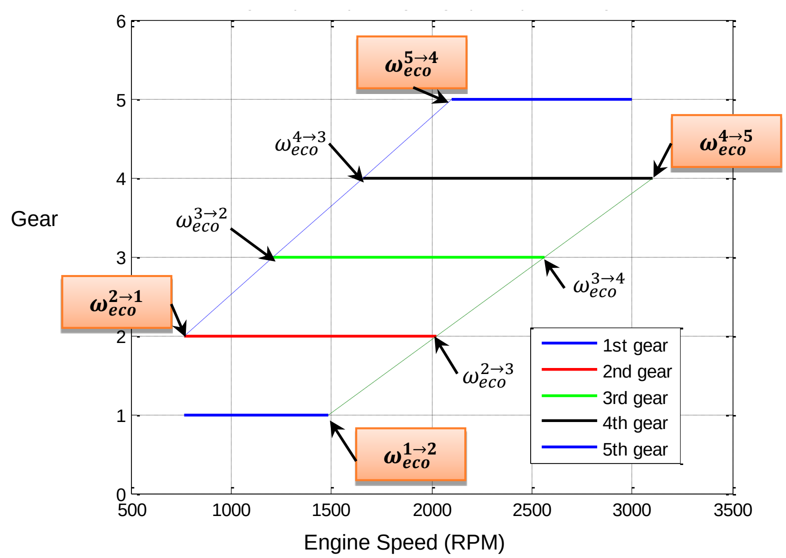


Figure 13 – Example of Engine Speed Range in Economical Driving, and Economical Shift

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: (1)

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

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:

(2)

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

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:

(3)

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

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 14 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.

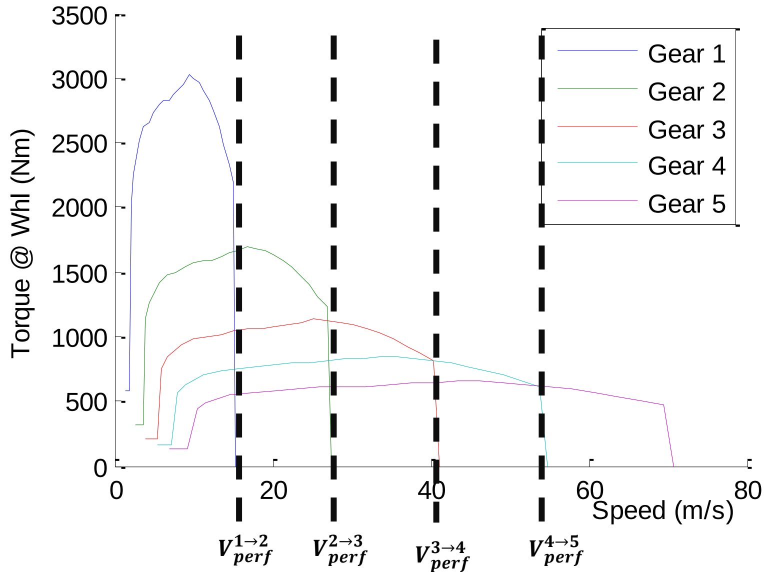


Figure 14 – Maximum Engine Torque at Wheels and Performance Upshift Speeds

The performance downshifting speed is given by the performance upshifting speed and the difference between the economical shifting speeds (see Figure 9):

$$\Delta V_{perf}^{i} = \alpha_{pf,ec} \cdot \Delta V_{eco}^{i} \iff V_{perf}^{i\to i+1} - V_{perf}^{i+1\to i} = \alpha_{pf,ec} \cdot (V_{perf}^{i\to i+1} - V_{perf}^{i+1\to i}) \tag{4}$$

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 15 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.

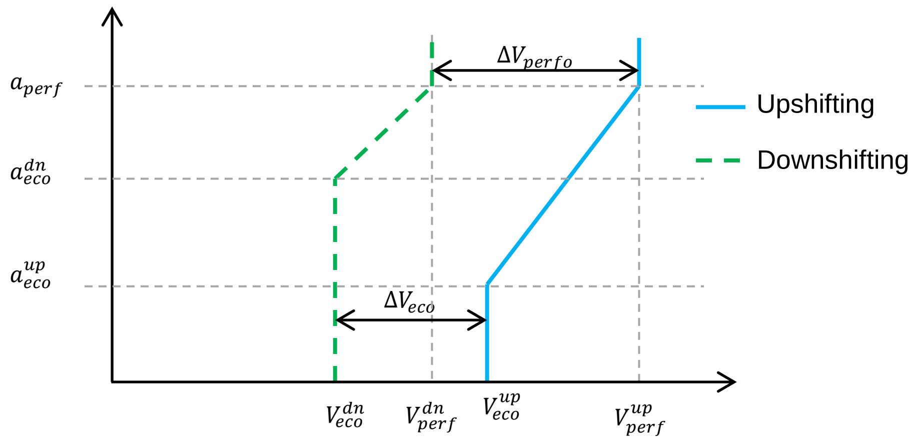


Figure 15 – Design of Upshifting and Downshifting Speed Curves for Two Adjacent Gears

Figure 16 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.

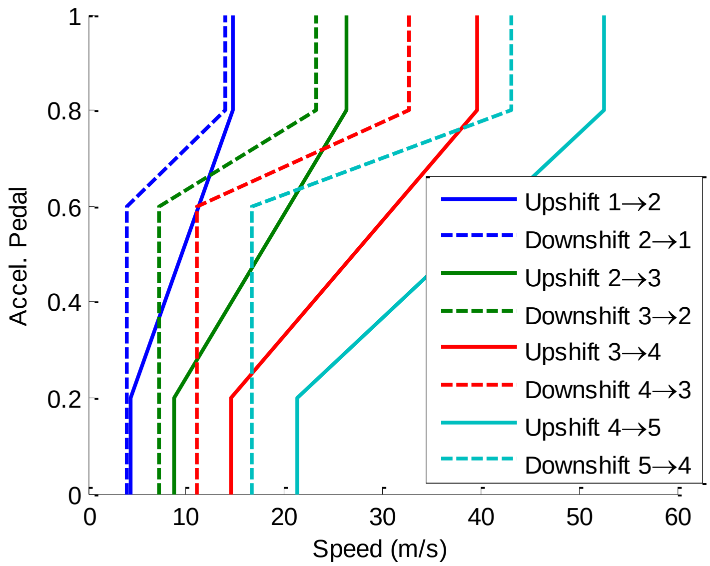


Figure 16 – Shifting Speed Curves for a Default Light-Duty Vehicle in Autonomie

4.5.1.3. Torque Control during Shifting Events

Figure 17 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.

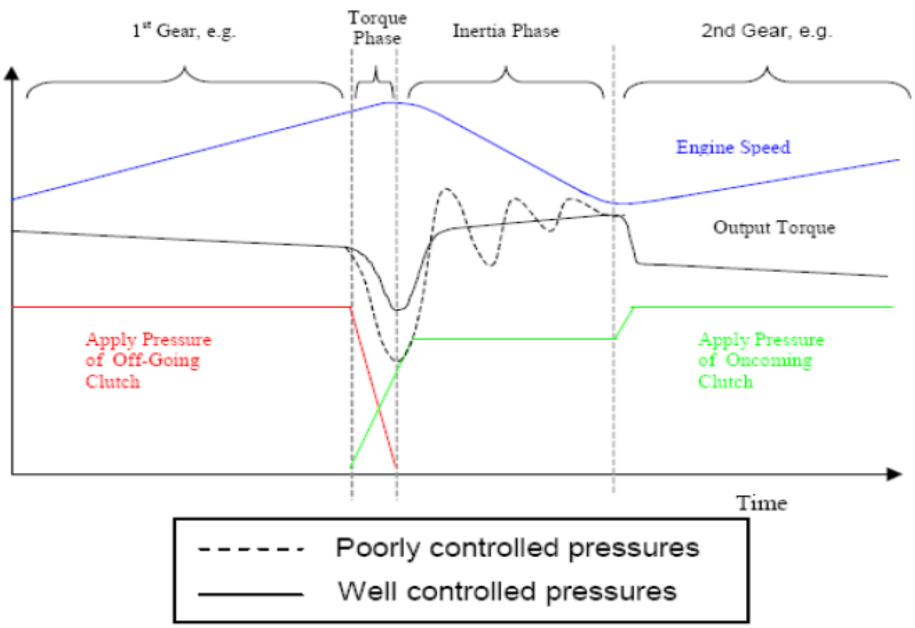


Figure 17 – Generic Shift Process for Automatic Transmission [17]

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 [20].

Autonomie integrates a low-level control algorithm that reproduces the torque hole phenomenon. Figure 18 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.

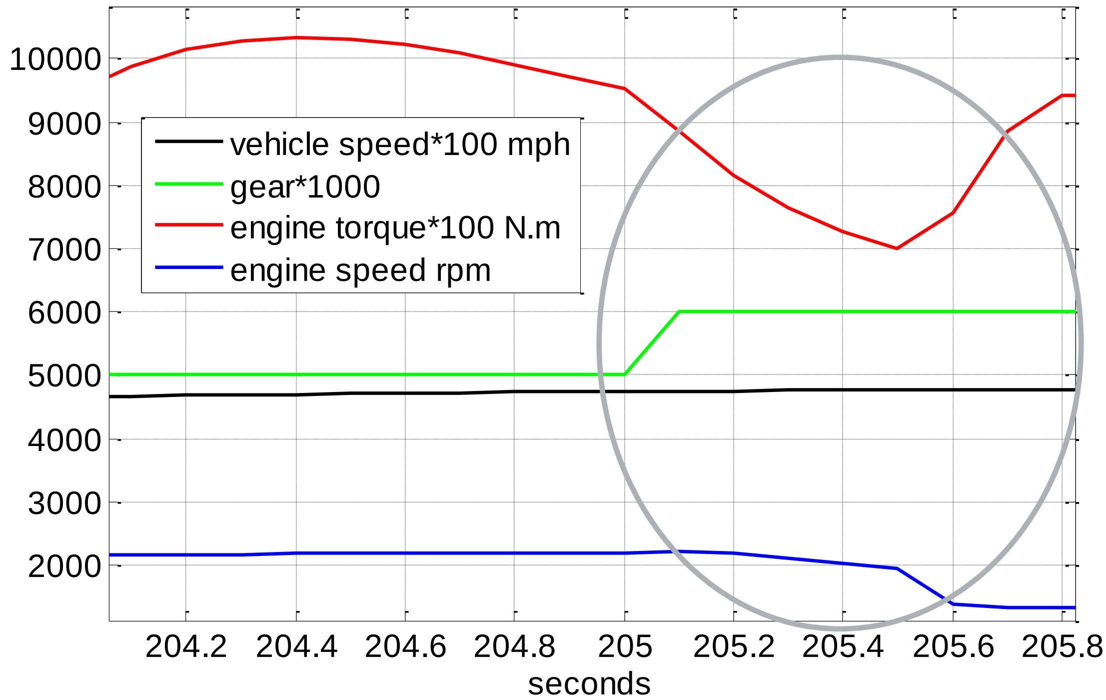


Figure 18 – Torque Hole in Autonomie during Shifting Event

4.5.1.4. 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 driveability. While plant models with higher degree of fidelity would be necessary to accurately model the impact of each technology on the driveability, 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.

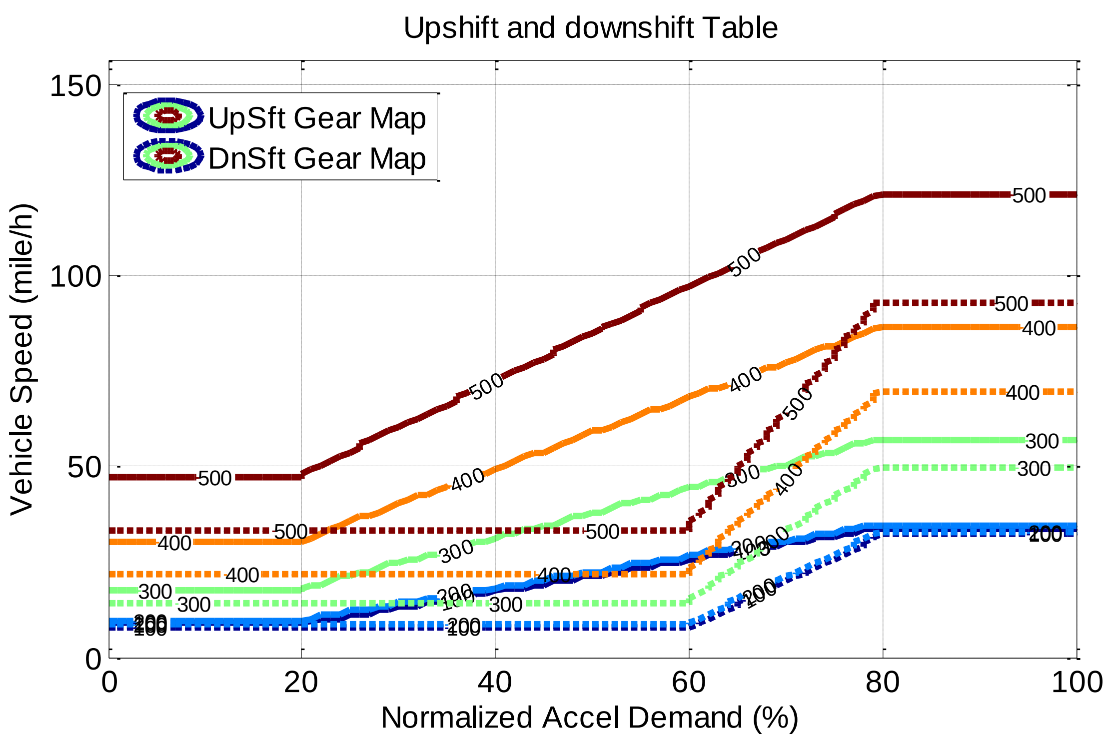


Figure 19 - 5-speed automatic up (plain lines) and down (dotted lines) shifting map

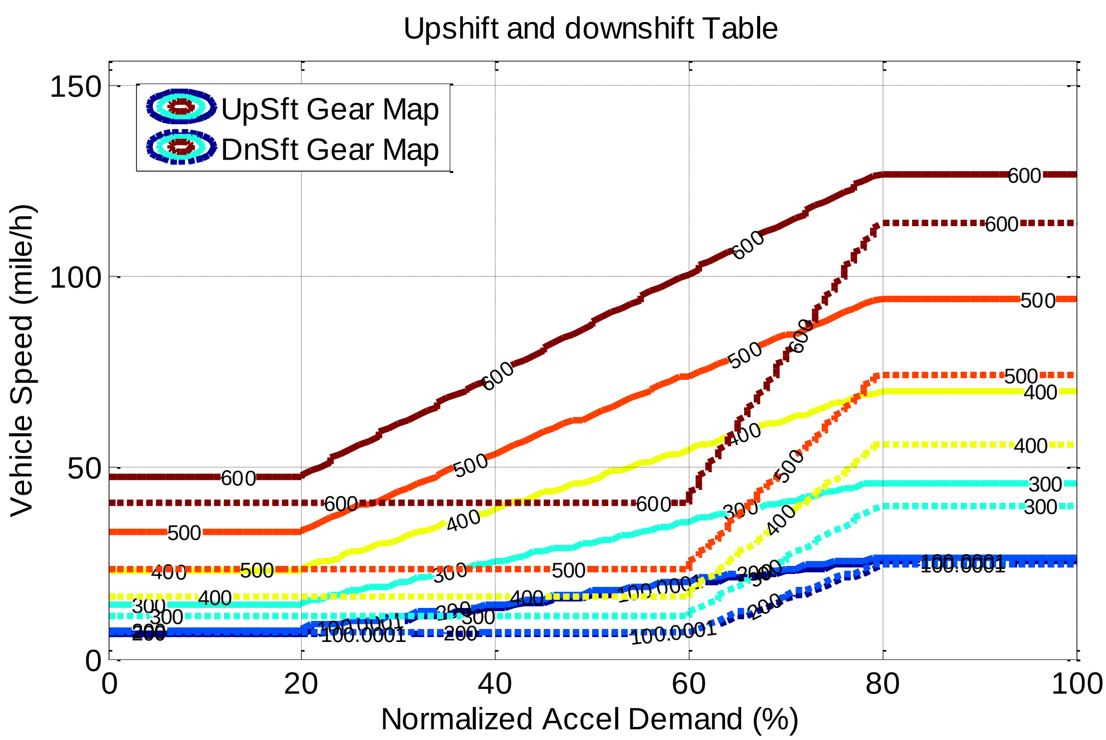


Figure 20 - 6-speed automatic up (plain lines) and down (dotted lines) shifting map

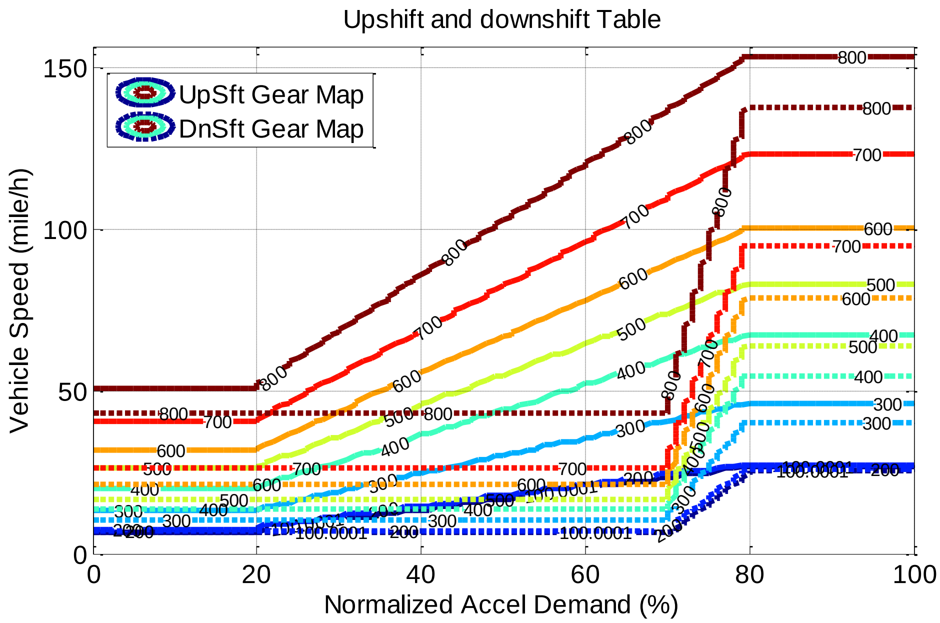


Figure 21 - 8-speed automatic up (plain lines) and down (dotted lines) shifting map

4.5.2. 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 22 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.

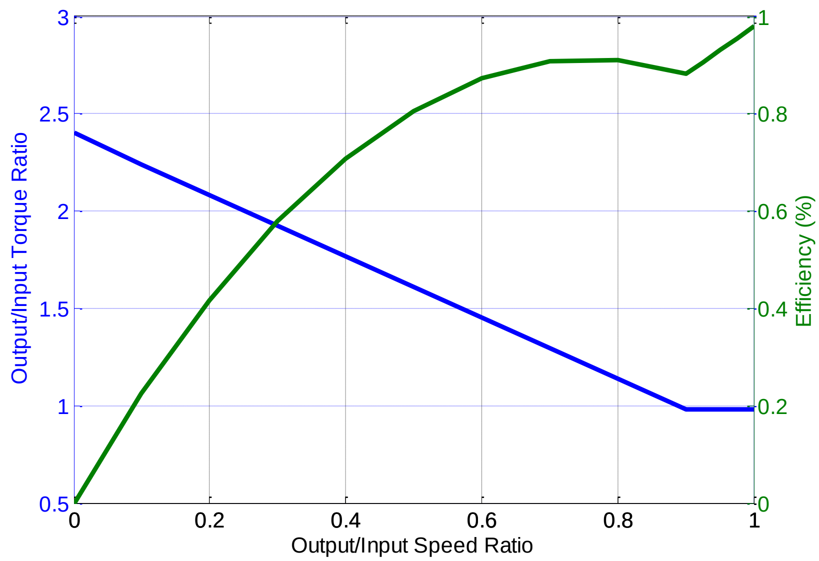


Figure 22 – Torque Converter efficiency

Figure 23 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.

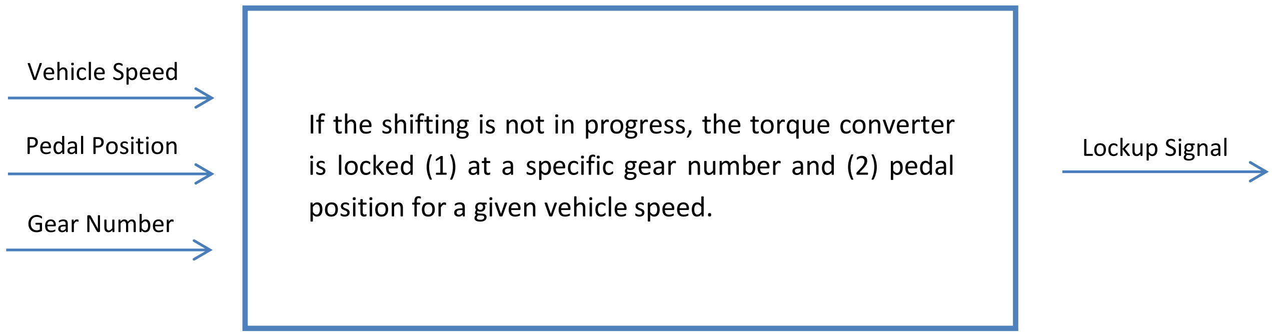


Figure 23 – Torque Converter Lockup Control Algorithm

4.6. Vehicle Simulation Conditions

All the vehicle simulations were performed under hot conditions (i.e., 20°C ambient temperature with warm components). This approach was selected on the basis of the assumption that all the transmission technologies would have similar warm-up characteristics. A two-cycle test procedure, based on the standard urban (FTP) and highway (HFET) drive cycles was used. Combined values are calculated on the basis of a 55% city and 45% highway cycle based on the standard test procedure. Figure 24 and Figure 25 show both drive cycles used in the simulations.

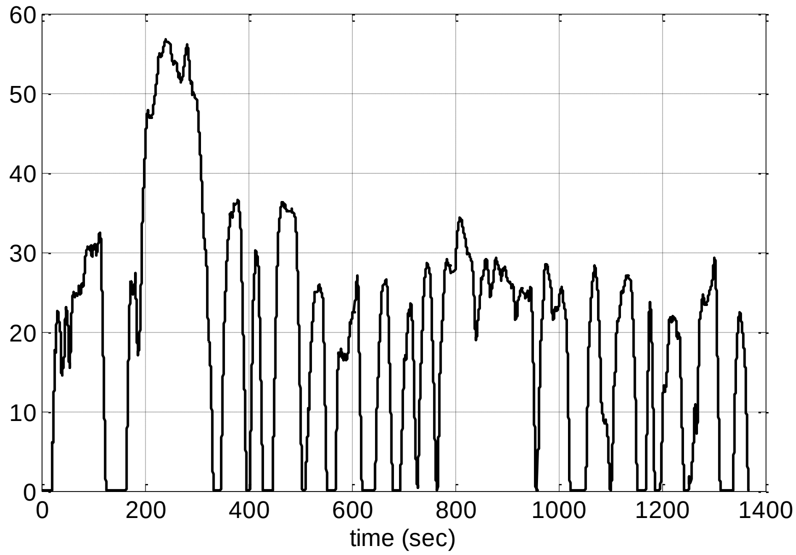


Figure 24 – FTP Drive Cycle – Vehicle Speed (mph)

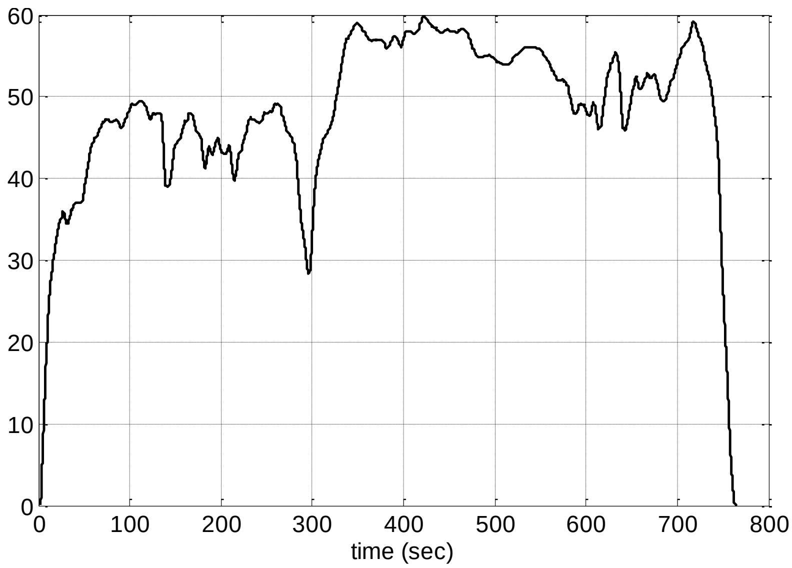


Figure 25 – HFET Drive Cycle – Vehicle Speed (mph)

5. Simulation Results

In this section, we will first present the results of the vehicle simulations performed using Autonomie for the reference vehicle, followed by a discussion of the impact of advanced automatic transmissions and DCTs. On the basis of the vehicle fuel consumption results, the decision tree used as input to the Volpe model will be presented, along with a brief discussion of the associated uncertainties based on component assumptions and vehicle class selection.

5.1. Reference Vehicle

The following sections address the reference vehicle simulation results and present the operating conditions for the primary components.

5.1.1. Engine Operating Conditions

Because the engine is the propulsion source of the vehicle, its operating conditions have a significant impact on overall fuel consumption.

FTP Drive Cycle

Figure 26 shows the engine operating points for the reference vehicle during the FTP cycle. The figure shows that the engine mostly operates at low-load conditions (i.e., low torque, low speed), which is equivalent to a low-engine-efficiency area. Despite having a peak efficiency of 36%, the engine only achieves an average efficiency of 24% on the FTP drive cycle.

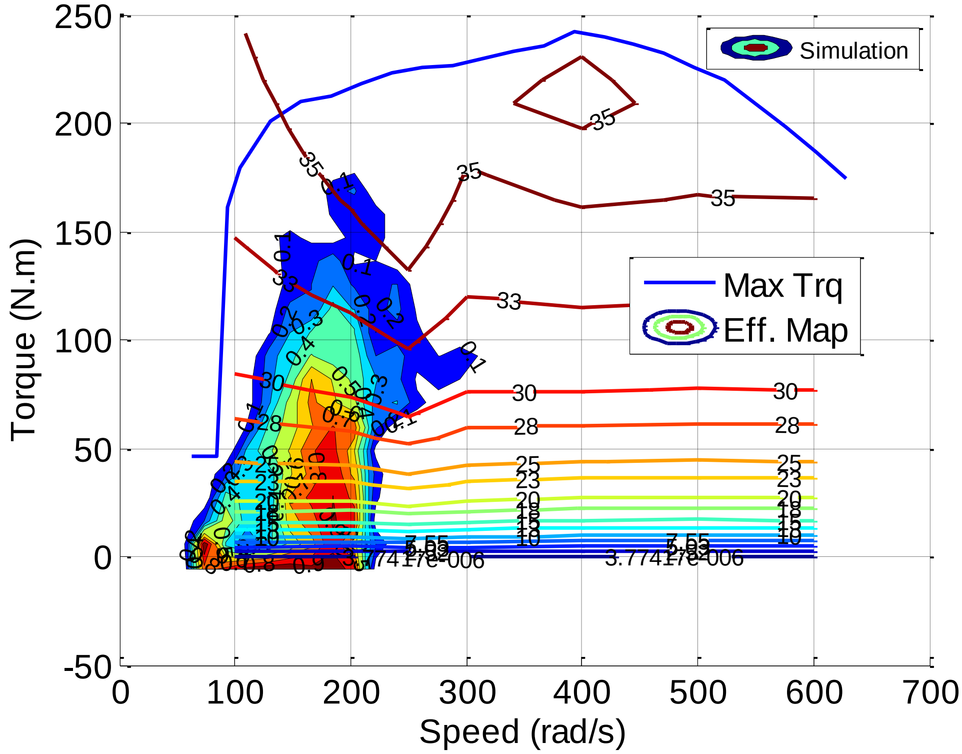


Figure 26 – Engine Operating Density Plot (FTP Cycle)

HFET Drive Cycle

Figure 27 shows the engine operating points for the baseline vehicle during simulation on the HFET cycle. The average efficiency of the engine ranges from 25 to 30%. The figures show that, as on the FTP cycle, the engine mostly operates on the bottom left-hand side of the engine map, but the red/high-density "island" is slightly shifted up, indicating a slight improvement in engine efficiency for the HFET cycle compared with the FTP cycle.

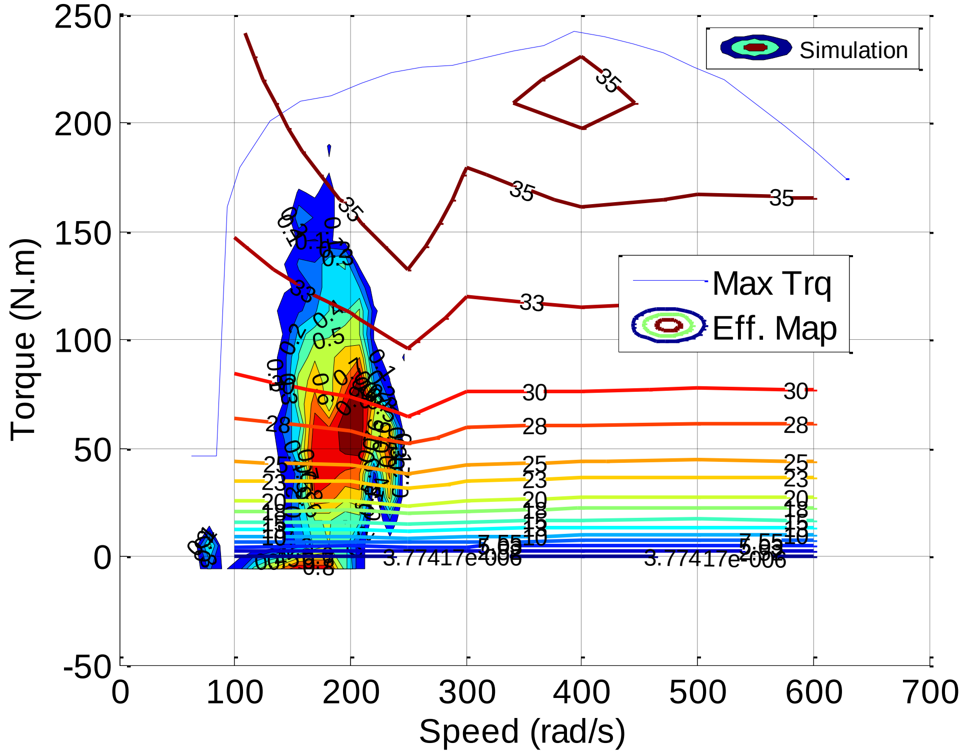


Figure 27 – Engine Operating Density Plot (HFET Cycle)

5.1.2. Gear Shifting

Figure 28 shows the vehicle speed and the shifting gear number on an FTP cycle for the reference vehicle. The top gear is reached only on the second hill of the cycle. Note that the shifting algorithm used in Autonomie considers a limited number of shifting events to provide acceptable drive quality to the drivers. The logic and the parameters were tuned based on vehicle test data collected at Argonne National Laboratory APRF. An example of number of “acceptable” shifting events from measured data are provided later in the report.

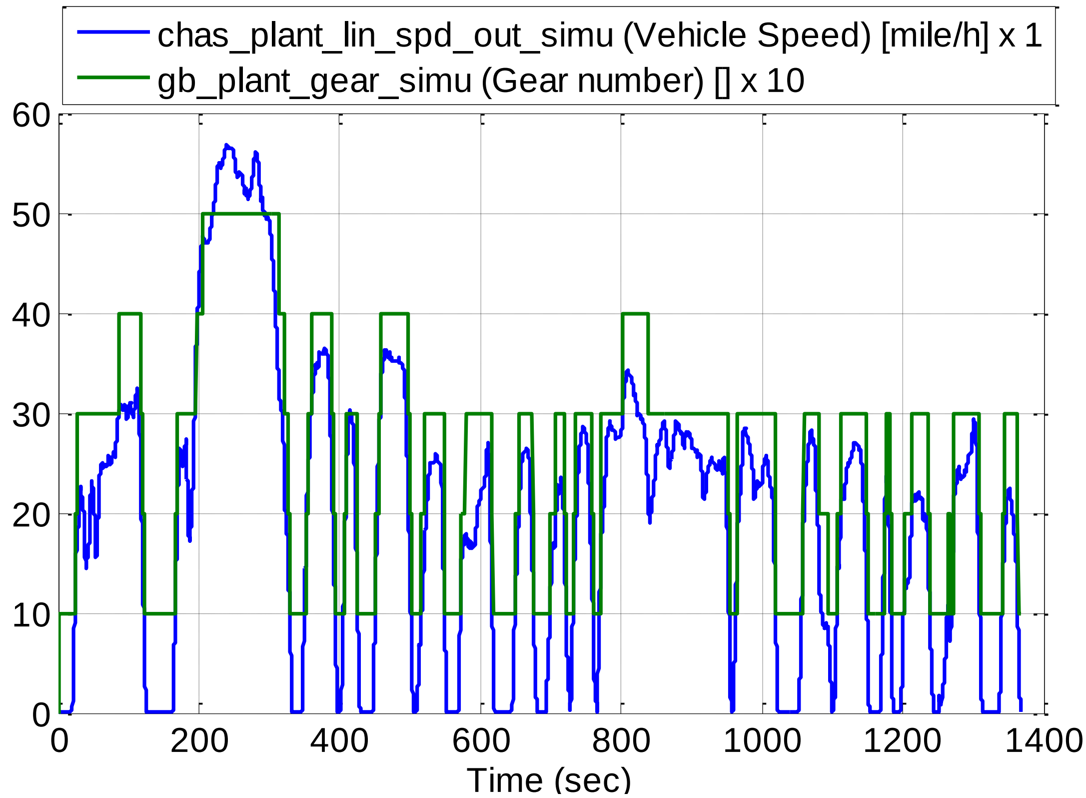


Figure 28 – Vehicle Speed and Shifting Logic (FTP Cycle)

Figure 29 shows the torque converter lockup signal on an FTP cycle. Note that the lockup occurs only twice during the entire cycle. This is because the lockup conditions are met at vehicle speeds above 40 mph, which do not frequently occur on the FTP cycle.

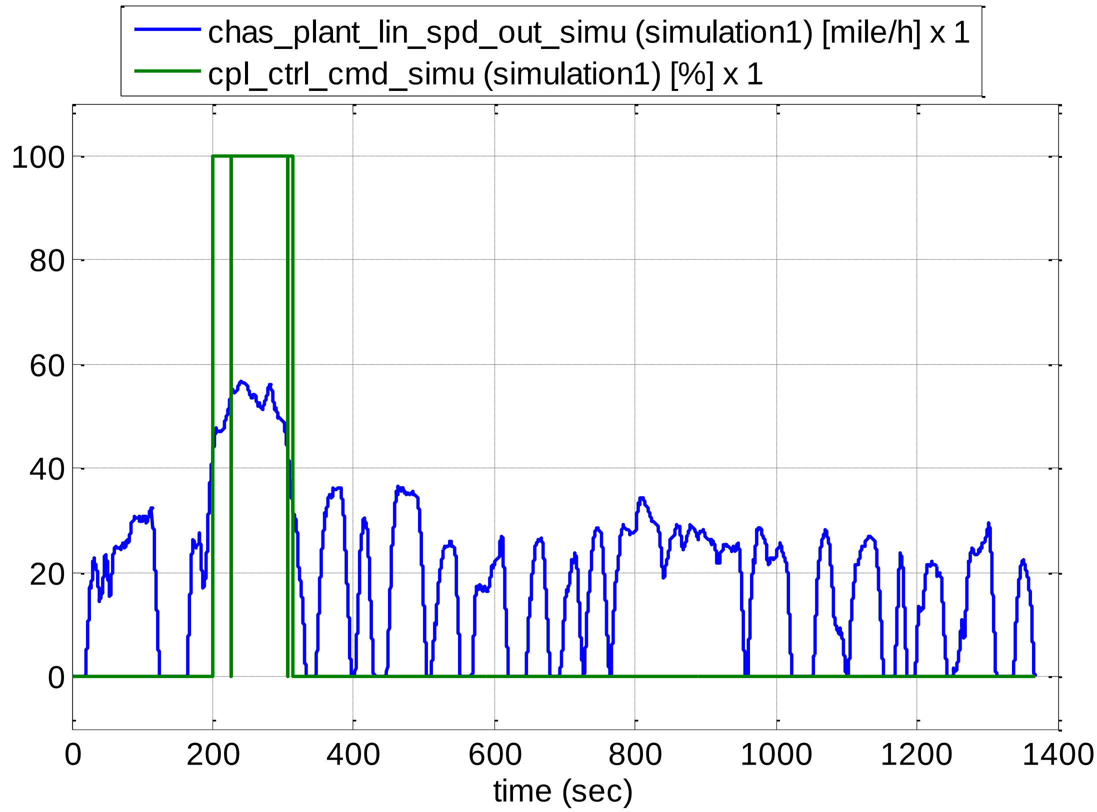


Figure 29 - Normal Torque Converter Lockup Strategies (FTP cycle)

Figure 30 shows the vehicle speed and the shifting gear number on the HFET cycle. The top gear is reached quickly and is maintained most of the time owing to the high vehicle speed during the cycle. Again, the number of shifting events is limited to provide smooth driving conditions.

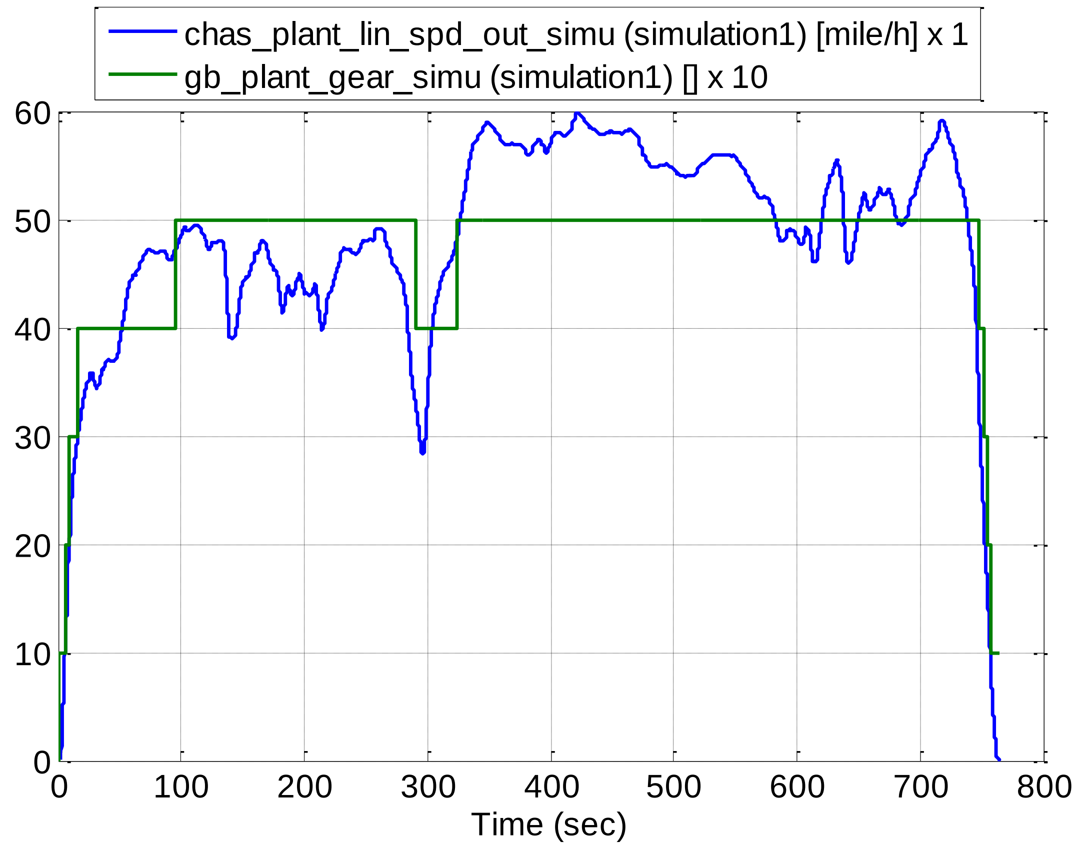


Figure 30 – Vehicle Speed and Shifting Logic (HFET Cycle)

Figure 31 shows the torque converter lockup signal on an HFET cycle. Unlike on the FTP cycle, the reference torque converter logic leads to the device being locked most of the time because of the high vehicle speeds.

Figure 31 – Normal Torque Converter Lockup Strategies (HFET Cycle)

5.2. Advanced Automatic Transmissions

5.2.1. Impact of Early Torque Converter Lockup

FTP Drive Cycle

Figure 32 and Figure 33 show the torque converter lockup events resulting from the aggressive torque converter strategy (described earlier) compared with the reference strategy on the FTP cycle. The reference lockup strategy is represented by the full line, while the aggressive lockup strategy is illustrated by the dashed line. Note that the aggressive logic results in a much higher number of locking events on the FTP cycle, leading to lower system losses.

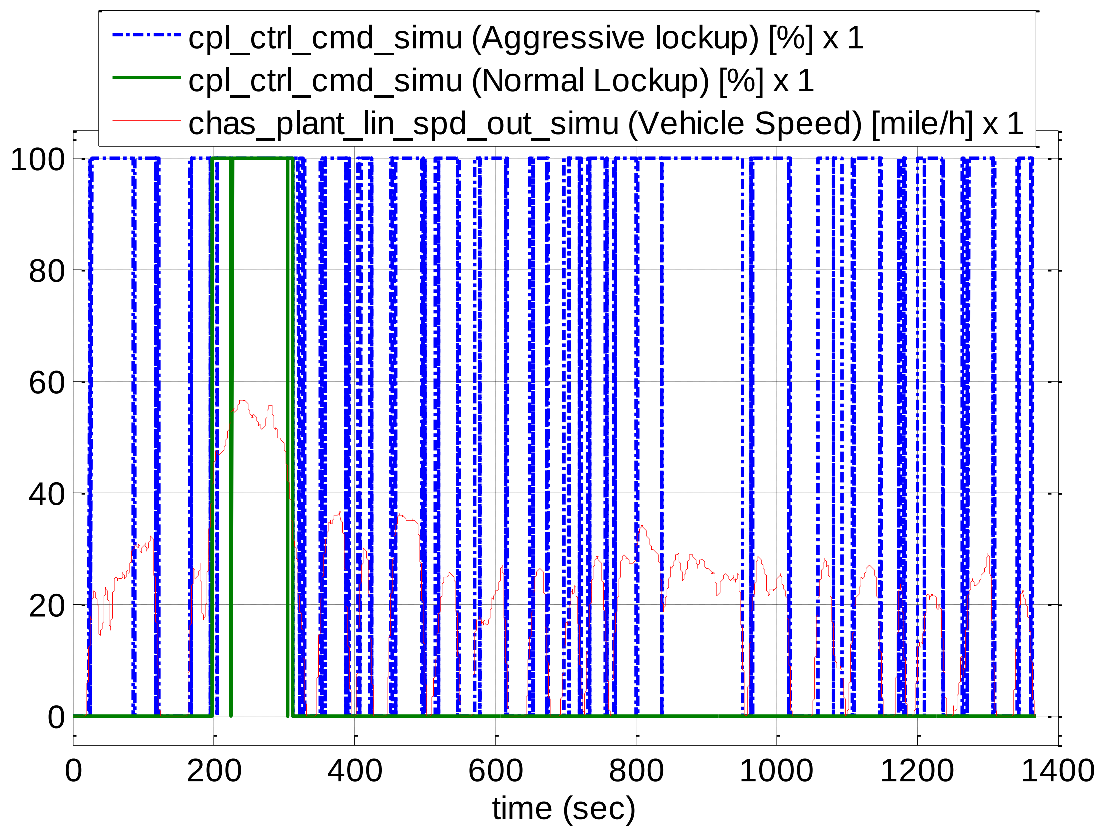


Figure 32 - Normal and Aggressive Torque Converter Lockup Strategies (FTP Cycle)

Figure 33 is a close-up of the area between 150 sec and 350 sec in Figure 32. The figures confirms that, for low vehicle speed, the aggressive strategy locks the torque converter (blue line), whereas in the normal lockup strategy, the torque converter is unlocked in low vehicle speeds (green line). It is expected that drive quality issues due to early torque converter lockup would be solved as part of the technology implementation.

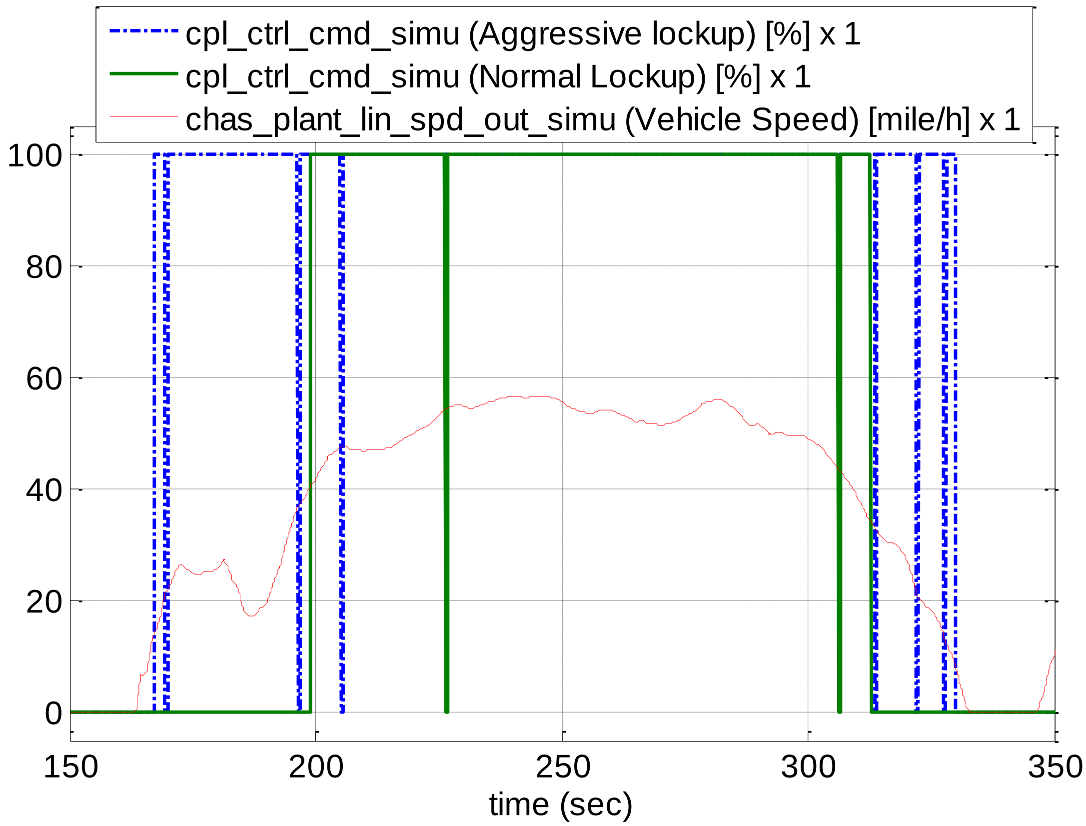


Figure 33 – 150–300 Seconds of Normal and Aggressive Torque Converter Lockup Strategies (FTP Cycle)

Table 5 shows that with the reference lockup strategy, the torque converter is locked 8.3% of the cycle time (FTP cycle), whereas the aggressive strategy allows the converter to lock 67.6% of the time. Because of the low efficiency of the torque converter when unlocked, the aggressive lockup strategy is expected to reduce fuel consumption on the FTP cycle.

Table 5 – Percentage Time Torque Converter is Locked (FTP Cycle)

FTP	Normal Strategy	Aggressive Strategy
Percentage of time torque converter is locked up	8.3%	67.6%

HFET Drive Cycle

As might be expected, the different lockup strategies have less effect on the HFET drive cycle because of the higher vehicle speed. As shown in Figure 34, the lock and unlock signals between the reference and aggressive lock up logic are similar.

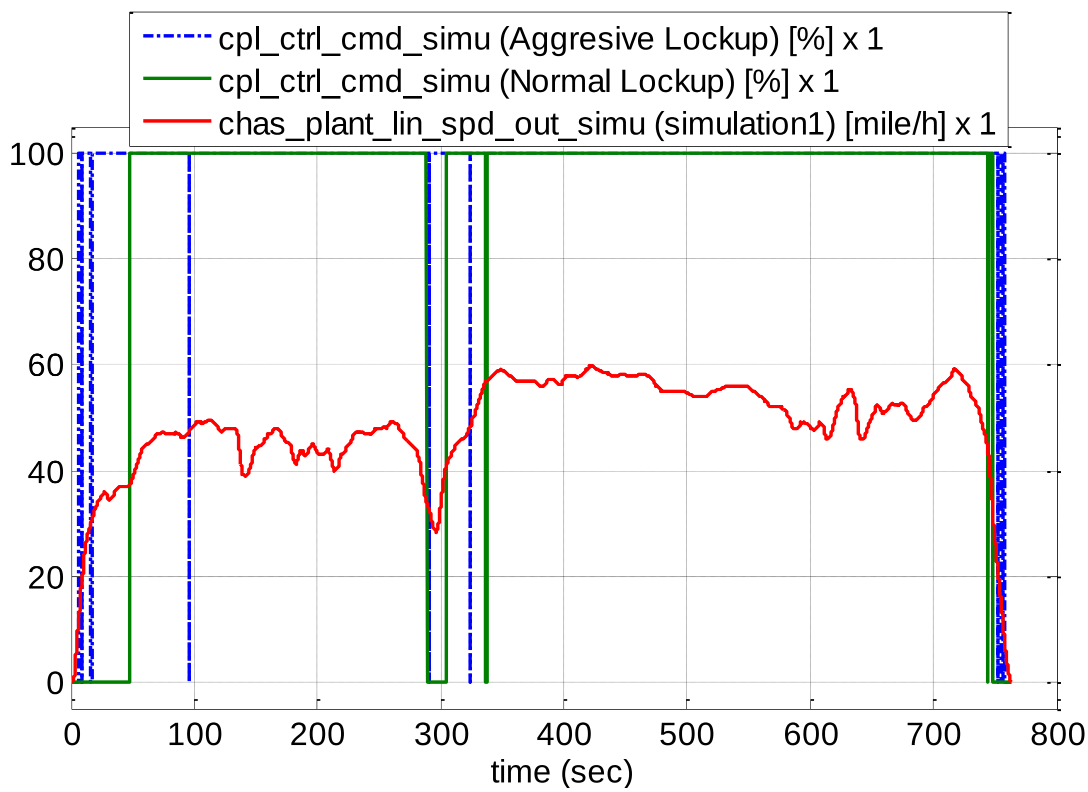


Figure 34 – Normal and Aggressive Torque Converter Lockup Strategy (HFET Cycle)

Figure 35 is a close-up of the first 60 seconds of Figure 28, illustrating that the aggressive/early lockup strategy locks up the torque converter more often than the normal lockup strategy only during the first seconds of the HFET cycle period. The rest of the cycle shows a similar behavior because of the high vehicle speed.

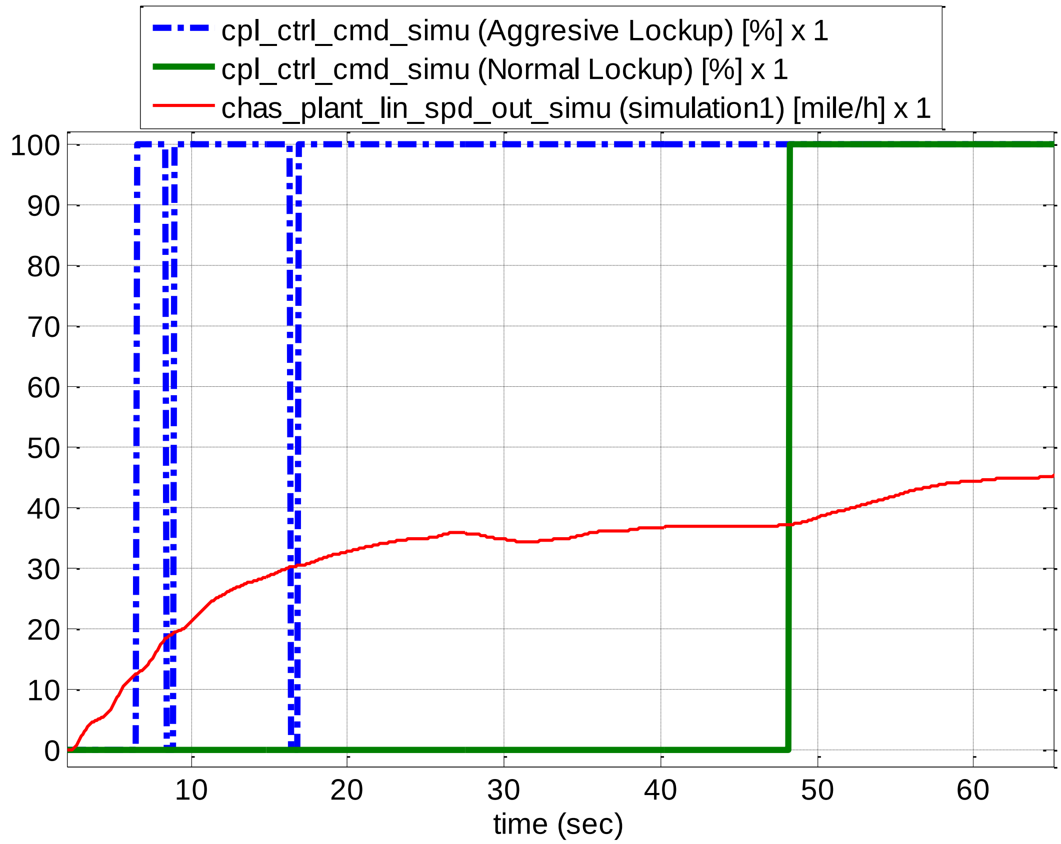


Figure 35 – First 60 Seconds of Normal and Aggressive Torque Converter Lockup Strategy (HFET Cycle)

Table 6 shows that, for the normal lockup strategy, the torque converter is locked 89.3% of the cycle time (HFET cycle), whereas the aggressive strategy allows the converter to lock 97.7% of the time. The difference is not as large as for the FTP cycle.

Table 6 – Percentage Time Torque Converter is Locked (HFET Cycle)

HFET	Normal Strategy	Aggressive Strategy
Percentage of time torque converter is locked up	89.3%	97.7%

Because of the different impacts of the locked-up times, the aggressive strategy for the torque converter will affect the FTP and HFET cycles differently. Table 7 shows the fuel consumption improvement of an aggressive torque converter lockup strategy on the FTP, HFET, and combined drive cycles. As expected, the FTP drive cycle shows a greater improvement than the HFET (2.1% versus 0.8%). Overall, a gain of 1.4% can be expected on the combined drive cycle.

Table 7 – Fuel Consumption (L/100 km) Comparison under Normal and Aggressive Lockup Strategies

	FTP	HFET	Combined
Normal lockup	**7.8**	**5.55**	**6.6**
Aggressive lockup	**7.65**	**5.5**	**6.5**
Improvement (%)	**2.1**	**0.84**	**1.44**

5.2.2. Impact of Higher Gear Number

This section evaluates the impact of higher gear number on automatic transmissions. All future results assume an aggressive torque converter lockup strategy.

FTP Behavior

Figure 36 shows the gear number for the three automatic transmissions selected (5-, 6- and 8-speeds). As expected, higher gear ratios are consistently used for the 8-speed transmission compared with the other technologies. By lowering the engine rotational speed, the engine operating torque is expected to increase, leading to lower fuel consumption. Note that the number of shifting events is limited to maintain drive quality as drivers would not accept too frequent gear shifting. Not including driver expectations would lead to higher reductions in fuel consumption due to unrealistic high number of shifting events.

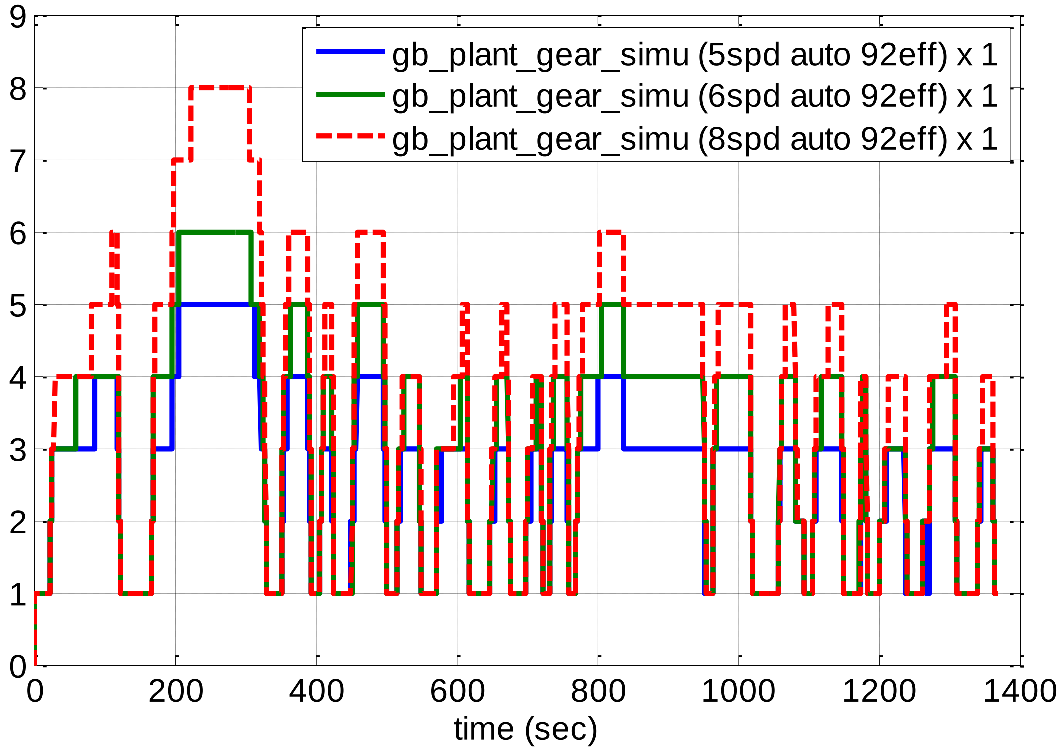


Figure 36 – Shifting Logic on FTP cycle for Automatic Transmissions

Figure 37 and Figure 38 compare the shifting events of the 5-speed automatic versus the 6-speed automatic transmission and the 6-speed automatic versus the 8-speed automatic transmission.

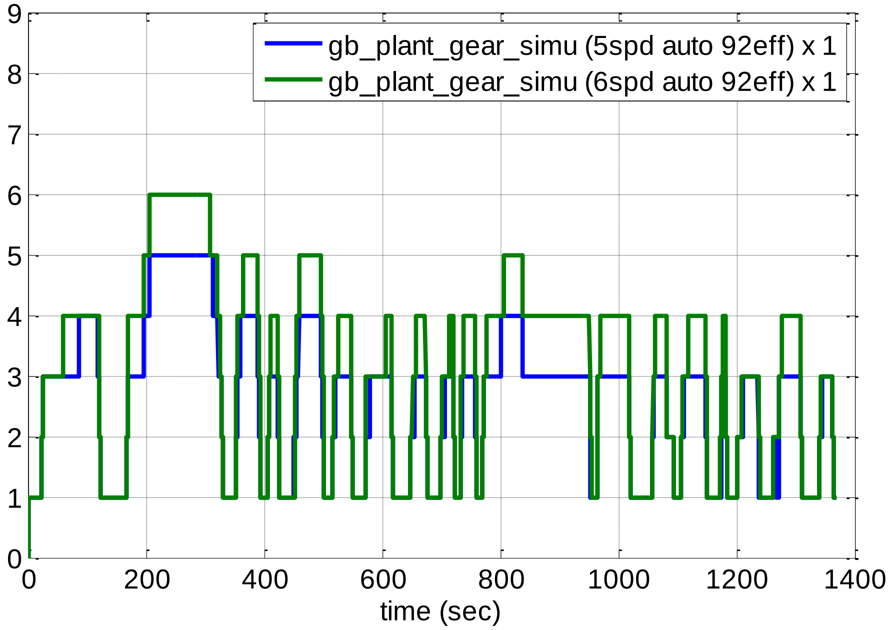


Figure 37 – Shifting Logic on FTP Cycle for 5-Speed versus 6-Speed

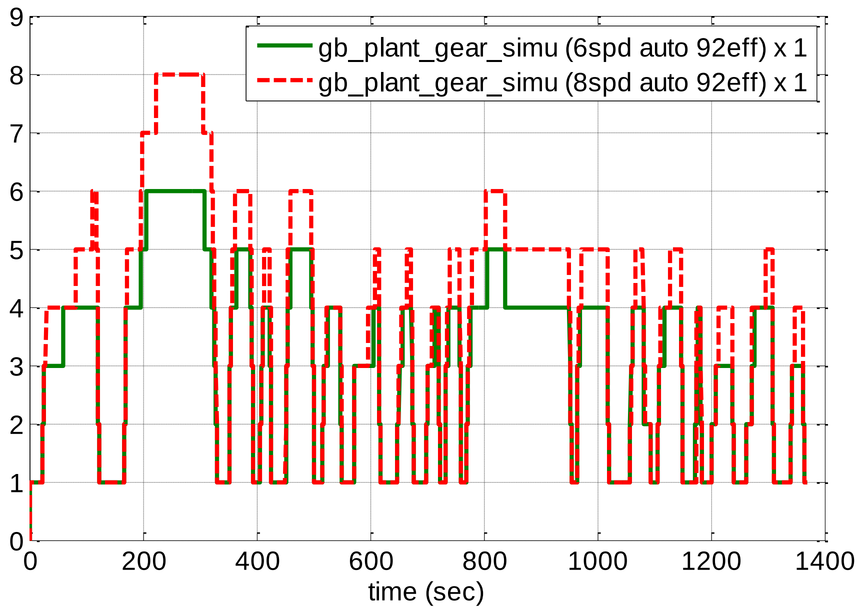


Figure 38 – Shifting Logic on FTP Cycle for 6-Speed versus 8-Speed

Table 8 shows the percentage of time spent in each gear during a FTP cycle.

Table 8 – Percentage Time Spent in Each Gear (FTP Cycle)

Percentage of time spent in each gear	5-speed	6-speed	8-speed
Gear 1	29.9%	28.4%	28.6%
Gear 2	8.3%	5.9%	5.1%
Gear 3	42.7%	15.6%	7%
Gear 4	11.1%	34%	17.7%
Gear 5	7.9%	8.5%	24.5%
Gear 6	-	7.5%	8.1%
Gear 7	-	-	2.7%
Gear 8	-	-	6.2%

Figure 39 shows the gear ratio of the different transmission considered.

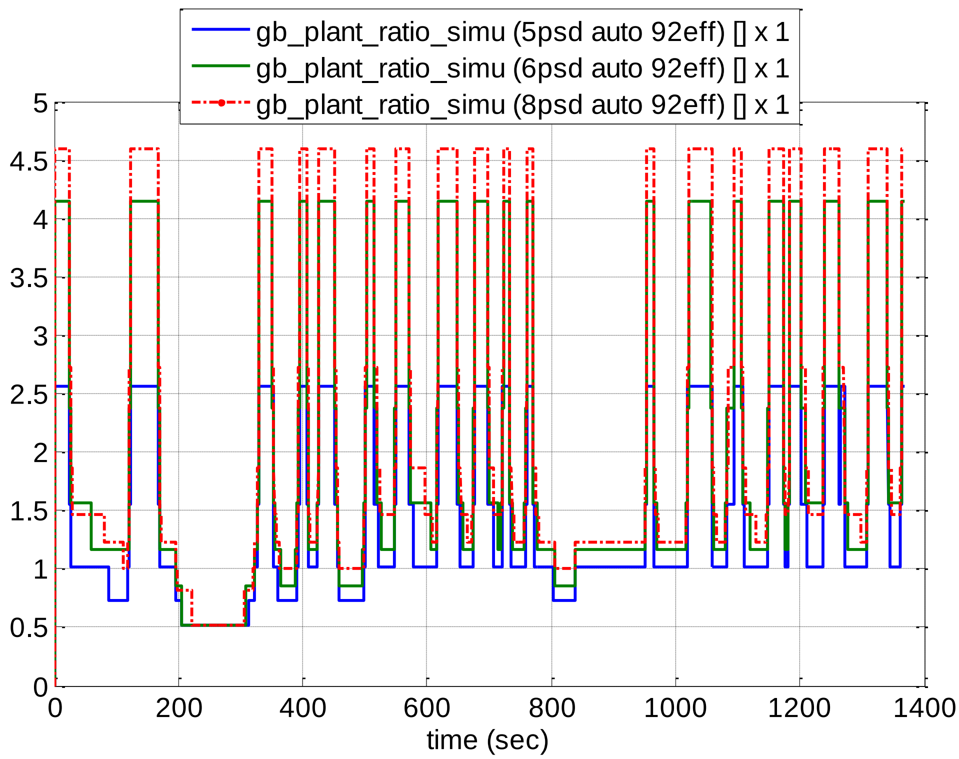


Figure 39 – Gearbox Ratios on FTP Cycle for All Automatic Transmissions Considered

Figure 40 and Figure 41 show the engine rotational speeds for the different automatic transmissions. The engine speeds decrease as the gear number increases when the final drive adjustment is taken into account. Because the engine has to provide the same power at the wheel to follow the vehicle speed trace, a lower engine speed would lead to a higher engine torque and overall higher efficiency.

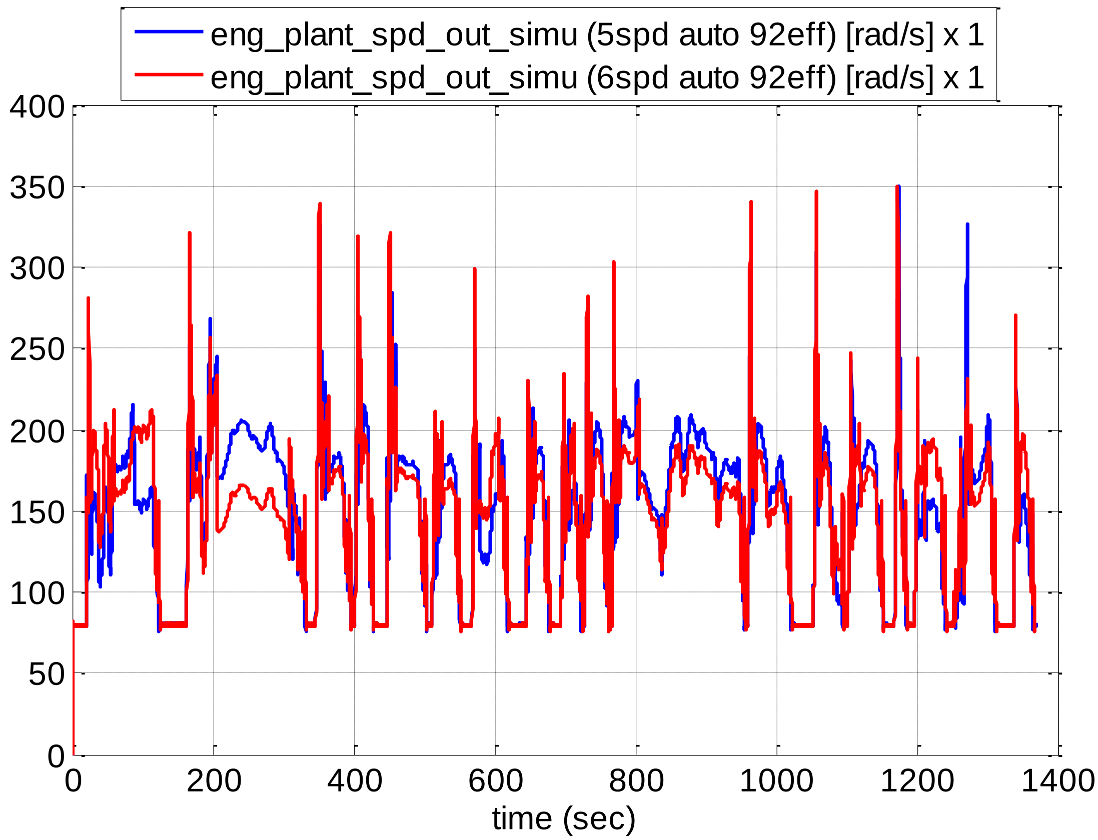


Figure 40 – Engine Speed on FTP Cycle for the 5–Speed and 6-Speed Automatic Transmissions

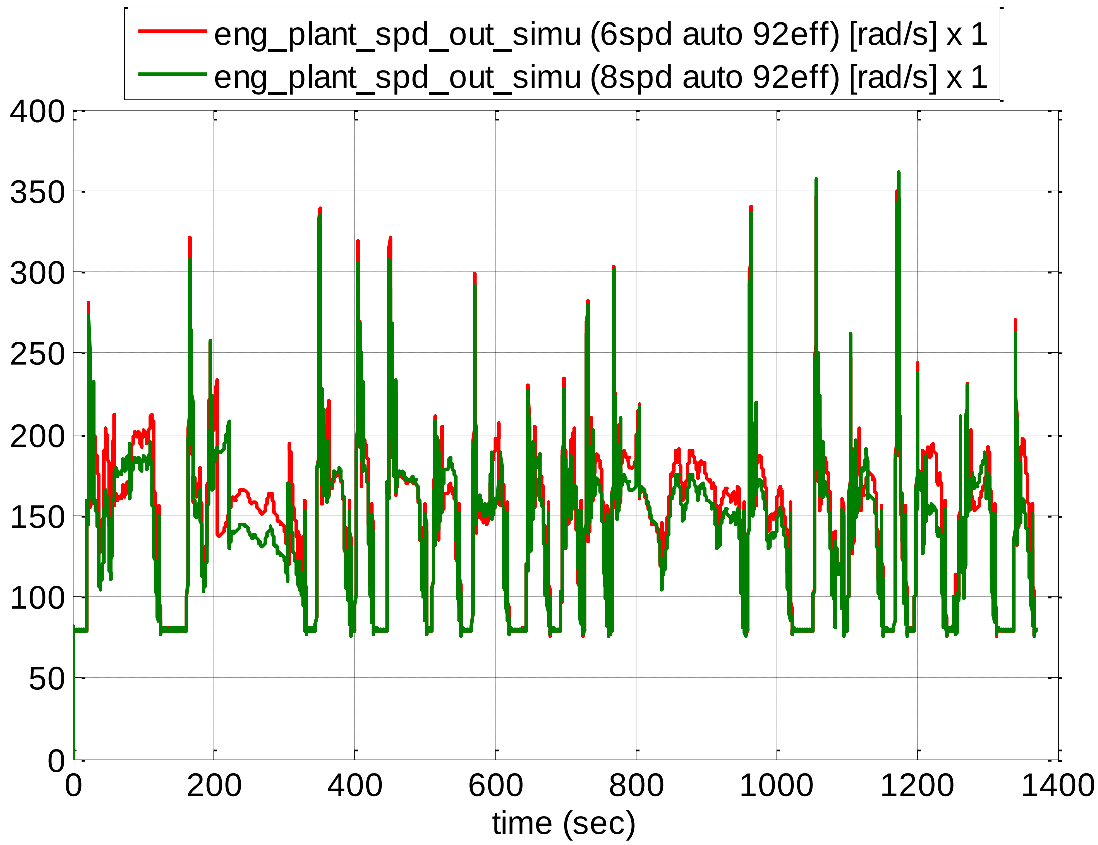


Figure 41 – Engine Speed on FTP cycle for the 6-Speed and 8-Speed Automatic Transmissions

Table 9 summarizes the engine and transmission average efficiencies, as well as the average engine speeds for each automatic transmission on the FTP cycle. For the three cases with the same transmission efficiency (92%), a decrease in average engine speed with a higher gear numbers leads to higher average engine efficiencies. The average transmission efficiency is slightly lower than the gearbox constant efficiency (92% or 96%) due to losses during shifting events. Finally, an increase in the transmission efficiency (92% to 96% for the 8-speed) leads to slightly lower average engine efficiency because the engine has to provide less power to the wheel and, consequently, operates at lower loads.

Table 9 – Summary of FTP Cycle Efficiencies and Speeds for Automatic Transmissions

	5-speeds, 92% efficiency	6-speeds, 92% efficiency	8-speeds, 92% efficiency	8-speeds, 96% efficiency
Average engine efficiency (%)	23.5	23.6	24.1	23.7
Average transmission efficiency (%)	91.3	91.1	91.2	95.1
Average engine speed (rpm)	1419	1403	1342	1335

HFET Drive Cycle

Figure 42 shows the gear-number evolution over the HFET drive cycle. Top gears are reached at a similar time regardless of transmission gear numbers. As a consequence, additional shifting events are required for higher-speed transmissions, which could lead to drive quality issues.

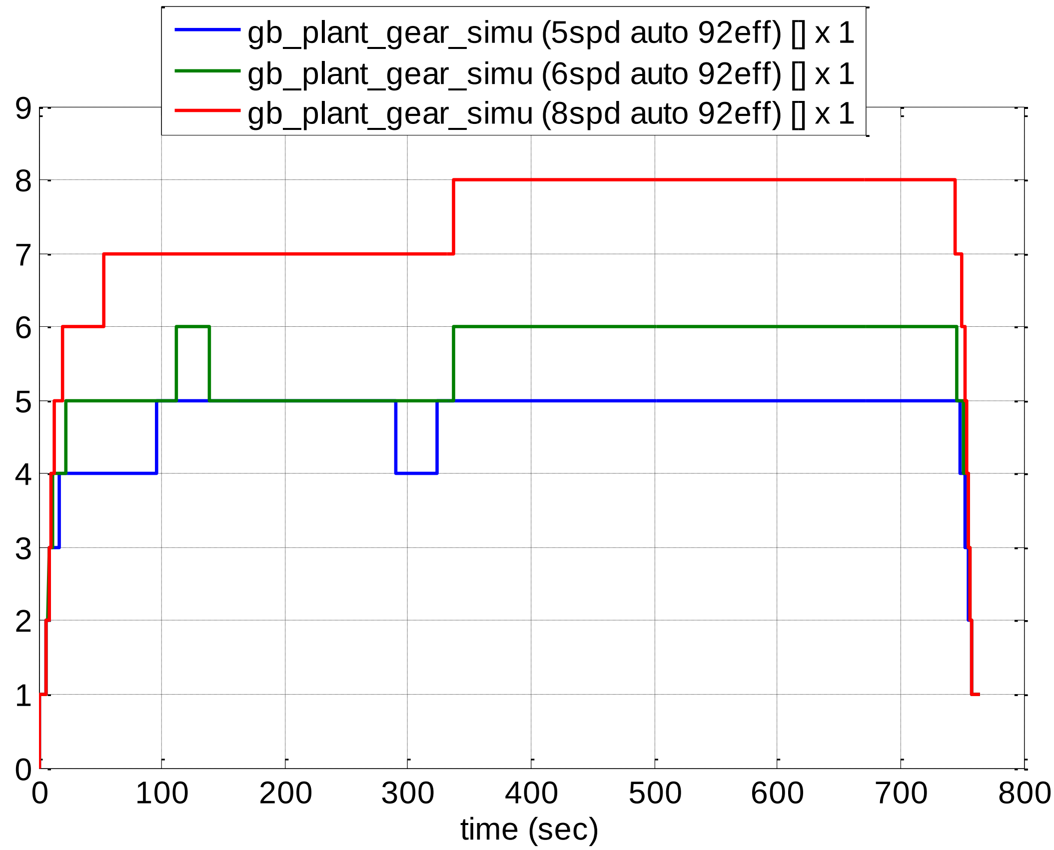


Figure 42 – Shifting Logic on HFET Cycle for All Automatic Transmissions

Table 10 shows the percentage of time spent in each gear during the HFET cycle. The most time is spent in the top gear: 81% of the time for the 5-speed, 57% for the 6-speed, and 54% for the 8-speed.

Note that the higher the number of gears, the less time is spent in the top gear because of the intermediate gear ratios.

Table 10 – Percentage Time Spent in Each Gear (HFET Cycle)

Percentage of time spent in each gear	5-speed	6-speed	8-speed
Gear 1	1.6%	1.6%	1.6%
Gear 2	0.6%	0.5%	0.4%
Gear 3	1.5%	0.7%	0.3%
Gear 4	15.3%	1.9%	0.5%
Gear 5	81%	38.5%	1.2%
Gear 6	-	56.9%	4.7%
Gear 7	-	-	37.8%
Gear 8	-	-	53.4%

Figure 43 shows the gear ratio for each automatic transmission

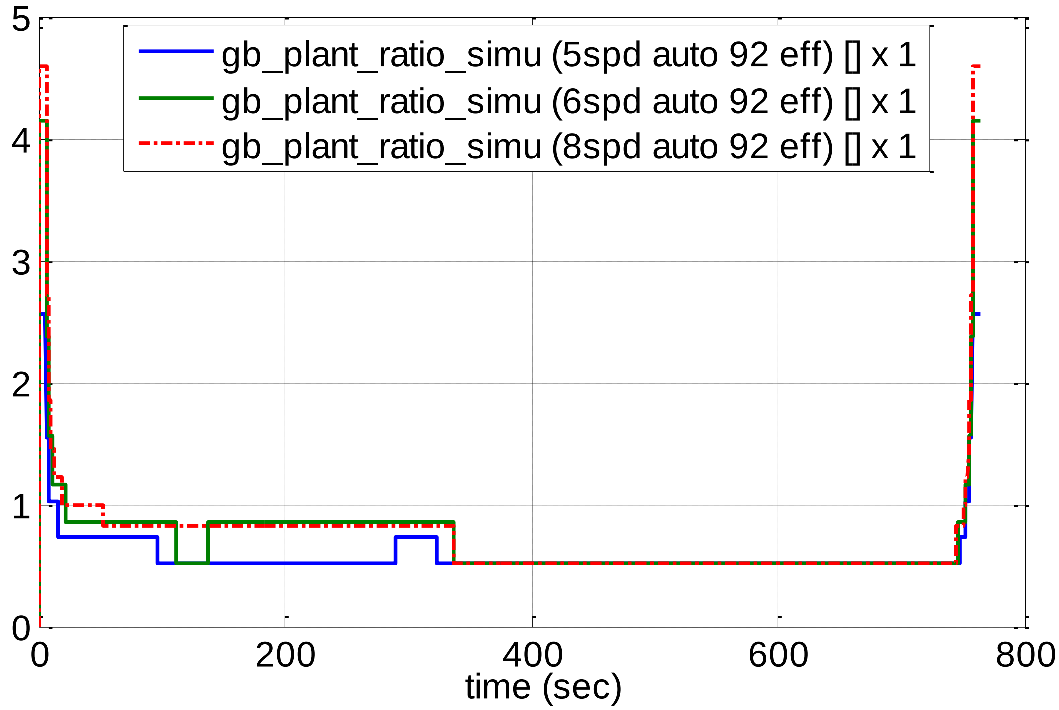


Figure 43 – Gearbox Ratios on HFET Cycle for All Automatic Transmissions

Figure 44 shows the engine speeds for the various automatic transmissions studied. For the FTP cycle, the engine operating speed consistently decreases as the number of gears increases.

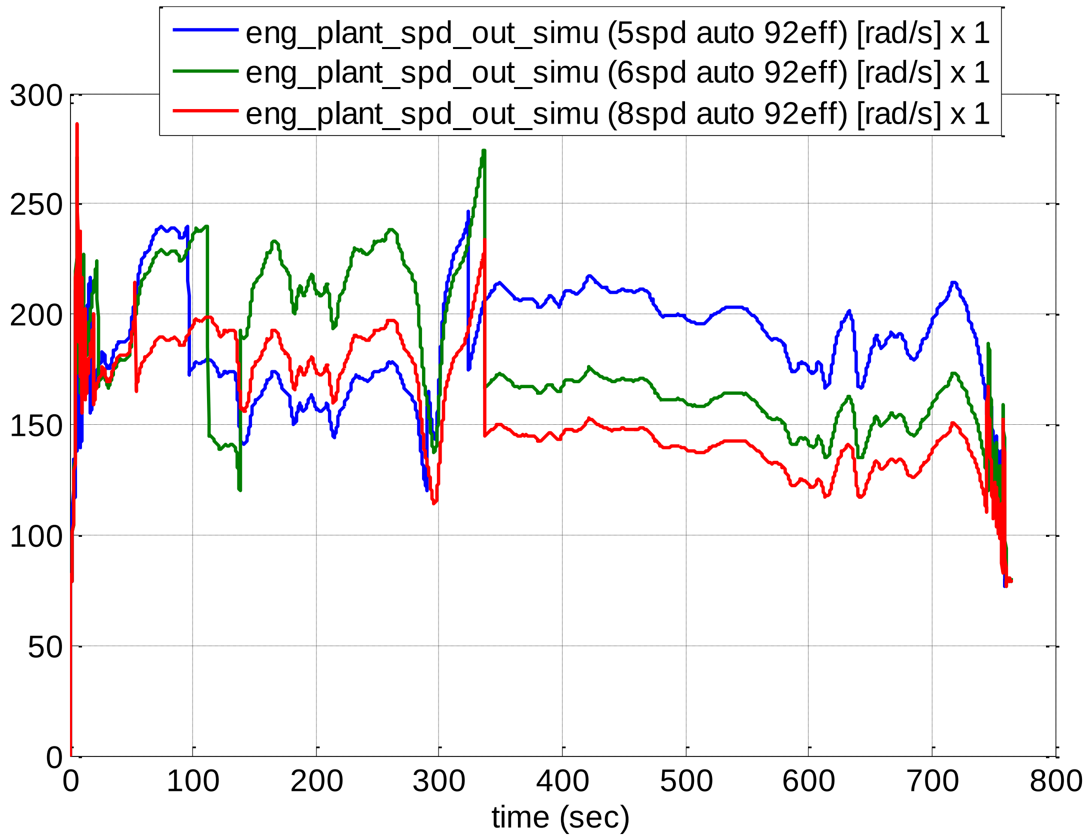


Figure 44 – Engine Speed on HFET Cycle for All Automatic Transmissions

Table 11 summarizes the results presented above. The average engine speed decreases as the number of gears increases.

Table 11 – Summary of HFET Cycle Efficiencies and Speeds for Automatic Transmissions Considered

	5-speeds, 92% efficiency	6-speeds, 92% efficiency	8-speeds, 92% efficiency	8-speeds, 96% efficiency
Average engine efficiency (%)	28.1	28.6	29.4	29.1
Average transmission efficiency (%)	92	91.9	91.9	95.9
Average engine speed (rpm)	1790	1707	1492	1489

5.2.3. Fuel Consumption Benefits

Table 12 summarizes the output fuel consumption results. Overall, the fuel consumption is lower on HFET cycles than on FTP cycles because of the lower transients and higher vehicle speeds. The results show that fuel consumption decreases by 0.77% from 5 to 6-speeds and 1.9% from 6 to 8-speeds. As a result, one additional speed provides a fuel consumption decrease ranging from 0.77% to 0.95%. In comparison, a 4% increase in transmission efficiency leads to a 3% fuel consumption improvement. This is due to the fact that increased transmission efficiency leads to lower engine power requirements and consequently lower engine efficiency.

Table 12 – Fuel Consumption Results (L/100 km) and Percentage Improvement for Automatic Transmissions

Fuel Consumption Results			
Conventional – Automatic Transmission	**FTP**	**HFET**	**Combined**
5-speed – 92% efficiency	7.64	5.50	6.50
6-speed – 92% efficiency	7.62	5.44	6.45
Improvement (%)	0.38	1.11	0.77
6-speed – 92% efficiency	7.62	5.44	6.45
8-speed – 92% efficiency	7.53	5.29	6.33
Improvement (%)	1.08	2.61	1.90
8-speed – 92% efficiency	7.53	5.29	6.33
8-speed – 96% efficiency	7.31	5.13	6.14
Improvement (%)	2.92	3.05	2.99

Table 13 – Fuel Economy Results (mpg) and Percentage Improvement for Automatic Transmissions

Fuel Economy Results			
Conventional – Automatic Transmission	**FTP**	**HFET**	**Combined**
5-speed – 92% efficiency	30.75	42.76	35.19
6-speed – 92% efficiency	30.87	43.24	35.43
Improvement (%)	0.39	1.12	0.66
6-speed – 92% efficiency	30.87	43.24	35.43
8-speed – 92% efficiency	31.21	44.4	36.02
Improvement (%)	1.1	2.68	1.67
8-speed – 92% efficiency	31.21	44.4	36.02
8-speed – 96% efficiency	32.15	45.8	37.13
Improvement (%)	3.01	3.15	3.06

5.3. Dual Clutch Transmission

Although automatic transmissions currently dominate the U.S. market, numerous manufacturers are offering vehicles with DCTs and are continuing to fund considerable research and development to increase their efficiencies.

5.3.1. Impact of Transmission Technology

This section presents vehicle parameters and results of our comparison of the 6-speed automatic transmission with a DCT with the same number of gears.

FTP Drive Cycle

Figure 45 shows the shifting logic comparison on the FTP cycle between the 6-speed automatic and the DCT. The shifting control behaves similarly for both transmissions. The main difference occurs between 804 sec and 834 sec due to different final drive ratios.

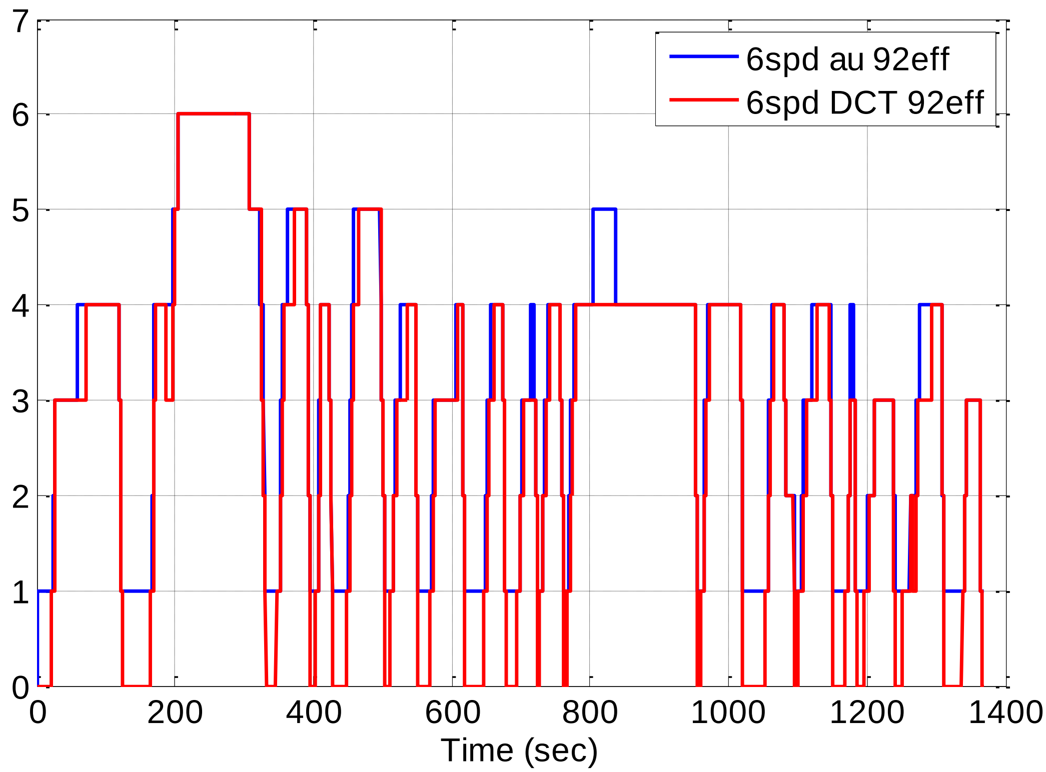


Figure 45 – Gear Number on FTP Cycle for the 6-Speed Automatic versus 6-Speed DCT

Figure 46 shows the engine speed of the automatic compared with the DCT on the FTP cycle. The difference in operating conditions is due to the different final drive ratios (3.8 is used for the automatic case and 3.69 for the DCT). The final drive ratios are different because of the gear ratio selection process adopted for the study, in which we decided to maintain a constant gearbox ratio and only change the final drive ratio to achieve similar vehicle performance. Selecting different gear ratios and final drive ratios would certainly impact the component operating conditions and the overall results, but such a sensitivity analysis was not considered in the current study.

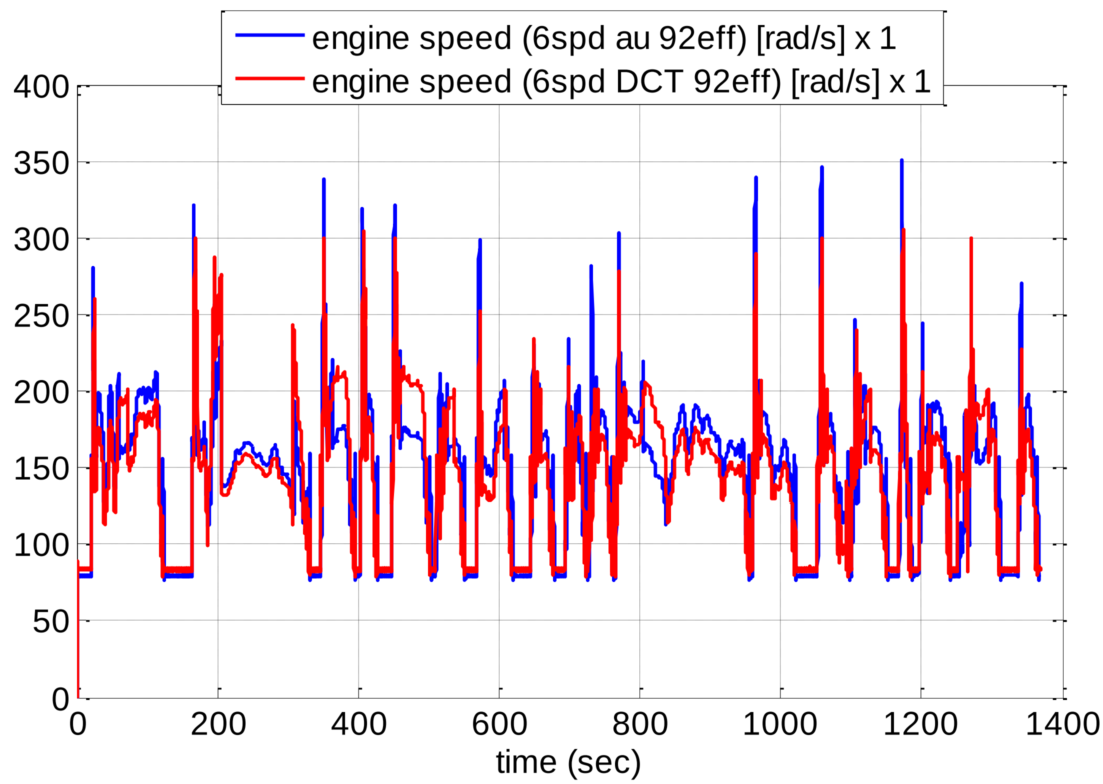


Figure 46 – Engine Speed on FTP Cycle for 6-Speed Automatic versus 6-Speed DCT

HFET Drive Cyle

Figure 47 compares the shifting logic on the HFET cycle for the 6-speed automatic versus the DCT. Similar to the FTP, the gear numbers selected are similar for both technologies on the HFET.

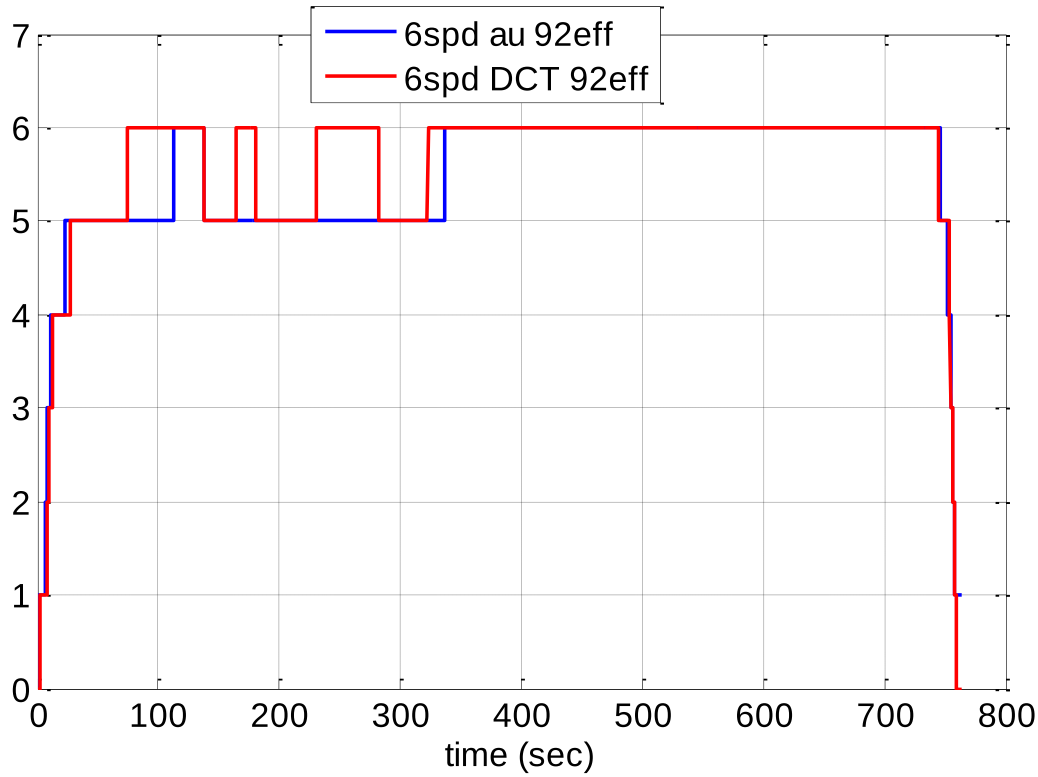


Figure 47 – Gear Number on HFET Cycle for the 6-Speed Automatic versus 6-Speed DCT

Figure 48 shows the engine speeds of the 6-speed automatic and DCT on the HFET cycle. As previously mentioned, the difference comes from our selection of different final drive ratios.

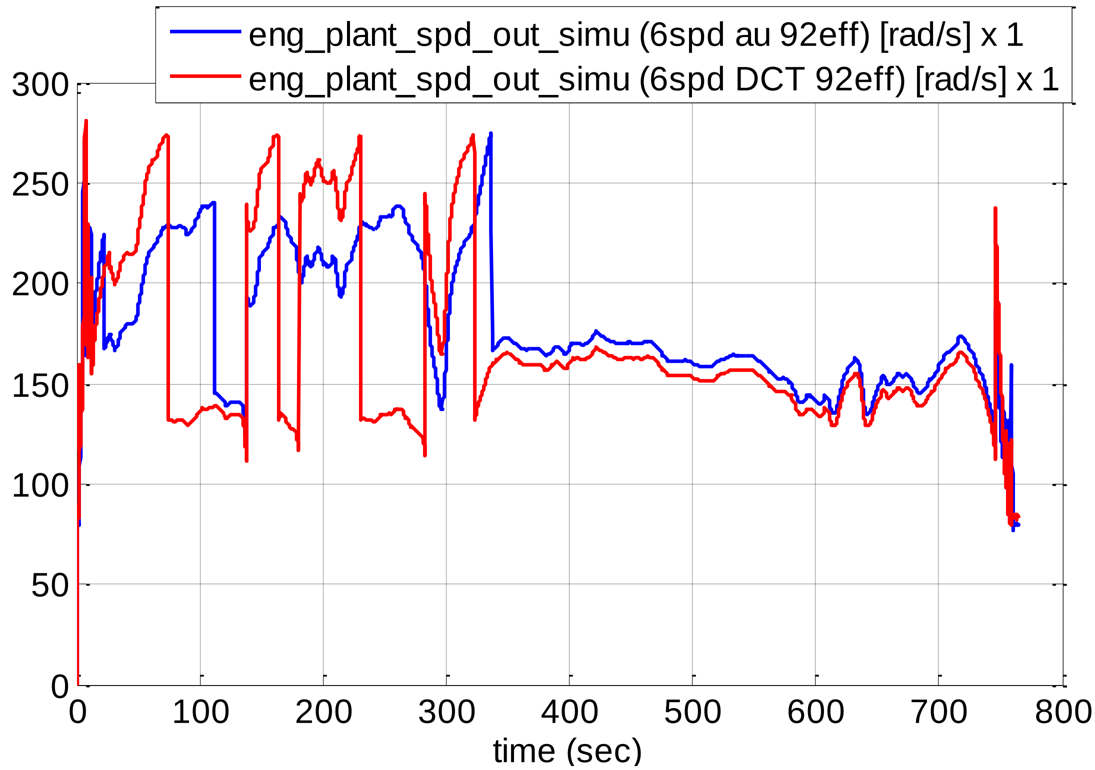


Figure 48 – Engine Speed on HFET Cycle for 6-Speed Automatic versus 6-Speed DCT

5.3.2. Impact of Higher Gear Number

Figure 49 and Figure 50 confirm the same trend seen in the automatic transmission comparison for FTP and HFET driving cycles: transmissions that have a higher number of gears operate in the higher gears to reduce engine operating speed and increase efficiency. A higher number of shifting events naturally occurs but, in all cases, the shifting algorithm limited the number of shifting events to provide acceptable drive quality.

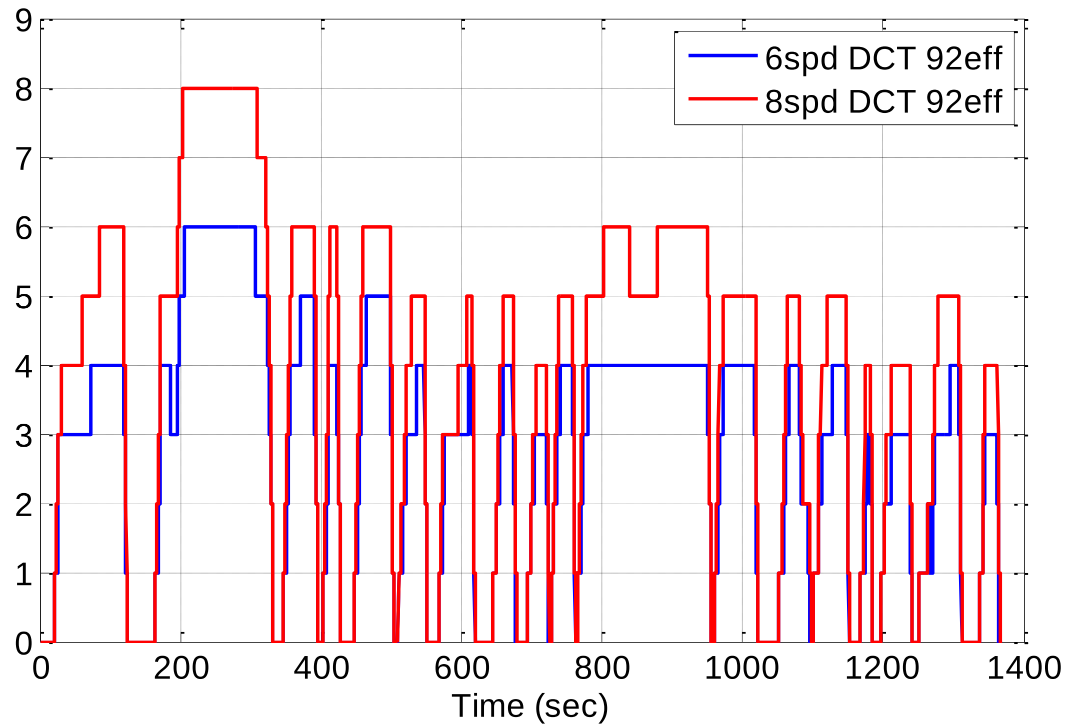


Figure 49 – Shifting Logic on FTP Cycle for all DCTs

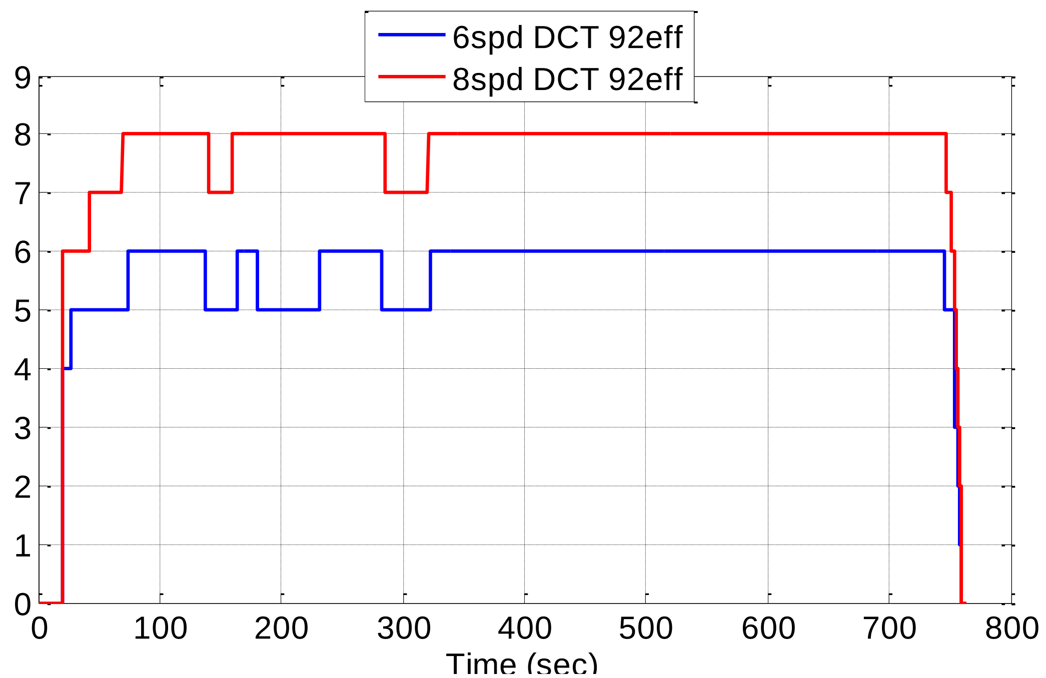


Figure 50 – Shifting Logic on HFET Cycle for all DCTs

Table 14 and Table 15 list the percentage of time spent in each gear during the FTP and HFET cycles, respectively. Again, the behavior is similar to that of the automatic transmission. In the DCT case, the most time is spent on the top gear: 73% for the 6-speed and 81% for the 6-speed on the HFET.

In the next section, the number of shifting events will be discussed.

Table 14 – Percentage Time Spent in each Gear, FTP Cycle

Percentage of time spent in each gear	6-speed	8-speed
Gear 1	9.1%	6%
Gear 2	6.512%	5.2%
Gear 3	19.713%	6.712%
Gear 4	30%	12.214%
Gear 5	5.513%	22.914%
Gear 6	7.412%	16.613%
Gear 7	–	1.2%
Gear 8	–	7.713%

Table 15 – Percentage of Time Spent in each Gear, HFET Cycle

Percentage of time spent in each gear	6-speed	8-speed
Gear 1	0.813%	0.5%
Gear 2	0.5%	0.4%
Gear 3	0.514%	0.4%
Gear 4	2 %	0.4%
Gear 5	22.4%	0.7%
Gear 6	72.5%	3.6%
Gear 7	–	11.5%
Gear 8	–	81.3%

As expected, and similar to the automatic-transmission case, a higher gear number helps keep the engine operating in a higher-efficiency area by lowering its speed and increasing its torque. Indeed, Figure 51 and Figure 52 show lower engine speeds for the 8-speed transmission than for the 6-speed transmission.

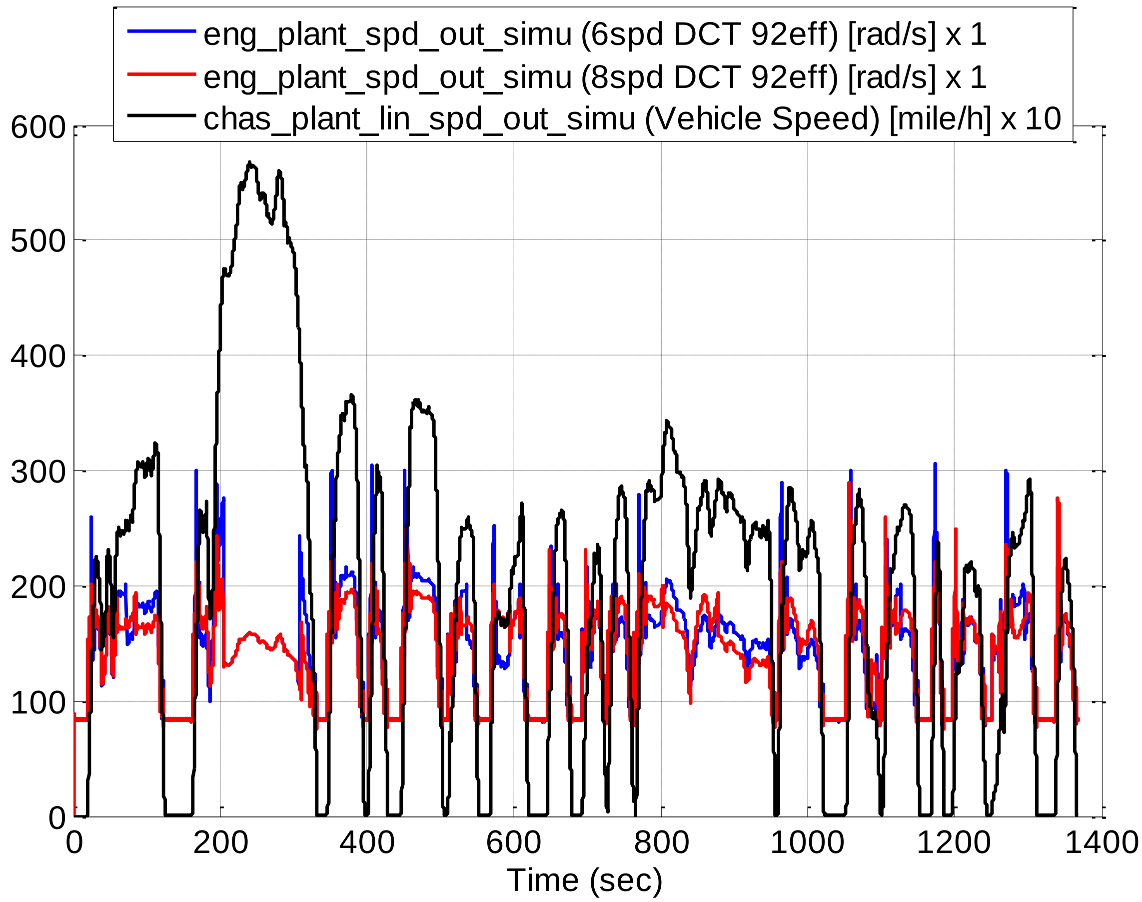


Figure 51 – Engine Speed on FTP Cycle for all DCTs

Engine speed on the HFET cycle shows less variation. Overall, the 8-speed DCT shows lower engine load in Figure 52, except when the top gear is reached.

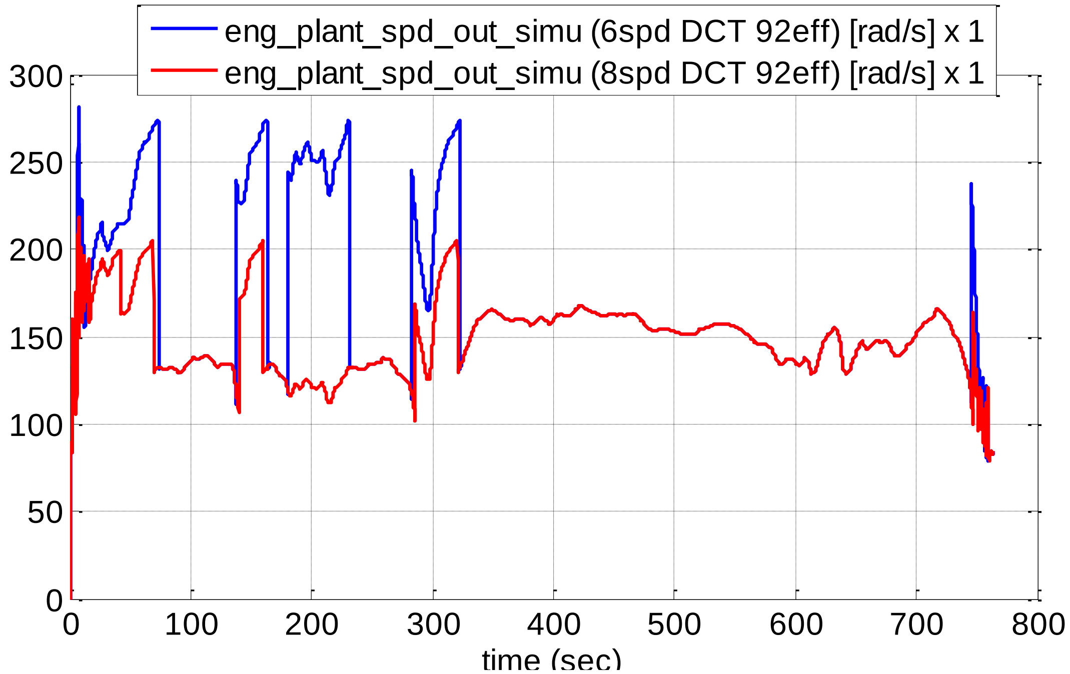


Figure 52 – Engine Speed on HFET Cycle for all DCTs

Table 16 and Table 17 summarize the results presented in Figures 45 and 46. For the automatic transmission case, the average engine speed decreases as the number of gears increases, and the average speed remains the same for the two 8-speed transmissions with different efficiencies.

Table 16 – Summary of FTP Cycle Efficiencies and Speeds for DCTs

	6-speed, 92% efficiency	8-speed, 92% efficiency	8-speed, 96% efficiency
Average engine efficiency (%)	23.4	23.4	23.1
Average transmission efficiency (%)	92	92	96
Average engine speed (rpm)	1,382	1,354	1350

Table 17 – Summary of HFET Cycle Efficiencies and Speeds for DCTs

	6-speed, 92% efficiency	8-speed, 92% efficiency	8-speed, 96% efficiency
Average engine efficiency (%)	28.75	29.5	29.2
Average transmission efficiency (%)	92	92	96
Average engine speed (rpm)	1,604	1,425	1,425

5.3.3. Fuel Consumption Benefits

Table 18 and Table 19 summarize the output fuel consumption and fuel economy results. Like other conventional vehicles, the fuel consumption is lower on the HFET cycle than on the FTP cycle. Simulations demonstrate that fuel consumption can be improved by 2.1% on the combined cycle by increasing the number of gears from 6 to 8 (an increase of 1% per additional gear). A 4% increase in gearbox efficiency leads to a 2.78% reduction in fuel consumption (or 0.7% for each additional efficiency point).

Table 18 – Fuel Consumption Results (L/100 km) and Percentage Improvement for DCTs; Automatic Transmission/DCT Comparison

DCT			
Conventional – DCT	**FTP**	**HFET**	**Combined**
6-speed – 92% efficiency	7.35	5.22	6.21
8-speed – 92% efficiency	7.23	5.09	6.08
Improvement (%)	1.63	2.51	2.10
8-speed – 92% efficiency	7.23	5.09	6.08
8-speed – 96% efficiency	7.05	4.94	5.91
Improvement (%)	2.49	3.04	2.78
Comparison of automatic transmission (Table 9) with DCT	FTP	HFET	Combined
6-speed automatic – 92% efficiency	7.62	5.44	6.45
6-speed DCT – 92% efficiency	7.35	5.22	6.21
Improvement (%)	3.47	3.91	3.70

Table 19 – Fuel Economy Results (mpg) and Percentage Improvement for DCTs; Automatic Transmission/DCT Comparison

DCT			
Conventional – DCT	**FTP**	**HFET**	**Combined**
6-speed – 92% efficiency	31.98	45	36.76
8-speed – 92% efficiency	32.51	46.16	37.5
Improvement (%)	1.65	2.57	1.99
8-speed – 92% efficiency	32.51	46.16	37.5
8-speed – 96% efficiency	33.34	47.61	38.53
Improvement (%)	2.55	3.14	2.76
Comparison of automatic transmission (Table 9) versus DCT	FTP	HFET	Combined
6-speed automatic – 92% efficiency	30.87	43.24	35.43
6-speed DCT – 92% efficiency	31.98	45	36.76
Improvement (%)	3.59	4.07	3.77

5.4. Shift Event Comparison with Vehicle Test Data

This section provides a comparison of the simulation results with different vehicle test data collected at Argonne's APRF.

The number of shifting events is a critical factor in properly estimating fuel consumption. The main objective of transmissions is to allow the engine to operate at high efficiency, so a higher number of shifting events would certainly lead to lower fuel consumption. However, such a control approach would provide unacceptable drive quality. This problem is well documented for continuously variable transmissions (CVTs); when engineers decided to continuously change the ratios of the CVT to optimize engine operating conditions, the resulting vehicle drive quality could be very poor. Automakers must be very careful to properly balance the fuel efficiency offered by a higher number of shifting events with consideration of drive quality.

It is reasonable to expect that the number of shifts will increase for an 8-speed transmission compared with a 6-speed transmission, but the increase needs to be within reasonable constraints.

Numerous conventional vehicles were tested on the FTP cycle at Argonne's APRF, including the Ford F150 (4-speed), Crown Victoria (4-speed), and Fusion (6-speed); the Toyota Echo (5-speed); the Mercedes Benz S400 (7-speed); and the Volkswagen Jetta (7-speed DCT). The number of shifting events was calculated on the basis of measured engine and vehicle speeds; a range was developed (+/-5 shifting) to estimate the variation of vehicles with the same number of gears. The results are listed below:

- 4-speed automatic: 100 to 110
- 5-speed automatic: 110 to 120
- 6-speed automatic: 110 to 120
- 7-speed automatic: 130 to 140
- 7-speed DCT: 130 to 140

In general, on the FTP cycle, the driver will notice an average of 10 additional shifting events per additional transmission gear number. This can be explained by the number of hills in the FTP drive cycle (total of 18), considering that several of them are too short and low speed to provide the transmission enough time to reach a higher gear. Autonomie baseline 6-speed simulation yielded 115 shifts on the FTP cycle, which is within the range estimated from vehicle test data.

For reference, Autonomie simulation results show the following number of shifting events on the FTP cycle:

- 5-speed automatic: around 89
- 6-speed automatic: around 115
- 8-speed automatic: around 149
- 6-speed DCT: approximately 130 (112 if the neutral position is skipped)
- 8-speed DCT: approximately 170 (152 if the neutral position is skipped)

Note: DCTs naturally have more gear shifts than automatic transmissions because they have to go to an additional neutral position at low vehicle speeds; automatic transmissions stay in first gear. To make the counting comparison valid, this additional neutral "gear" has to be taken out of the counting. Basically a 6-speed DCT/manual has 7 gears, including the neutral.

6. Transmission Decision Tree from Simulations

Figure 53 shows the decision tree resulting from the Autonomie simulation runs. All percentage increases represent fuel consumption improvements. The *incremental value* represents the actual improvement achieved by moving from one step to another, whereas the *absolute value* signifies the overall improvement starting from the reference baseline vehicle.

Absolute values are multiplicatively calculated as follows:

$$Abs_n = 1 - ((1 - Abs_{n-1}) \times (1 - Inc_n)) \tag{5}$$

This equation makes the final absolute value, calculated multiplicatively, lower than the straight summation of the absolute improvement numbers.

The two paths shown in Figure 53 are the automatic transmission and DCT paths. These two paths were selected to compare the advances offered by each technology.

The two steps of the common pathway preceding the split are described as follows:

- IATC: This step shows the percentage improvement gained by aggressive torque converter lockup for a 5-speed automatic transmission (1.4%).
- NAUTO: This step provides the fuel consumption improvement of a 6-speed automatic transmission compared with a 5-speed transmission. The fuel consumption improvement resulting from that step is 0.77%; the absolute value is the multiplicative sum of the previous step and the current step: 1.4% + 0.8% = 2.2%.

The following steps occur after the tree splits into the two paths (i.e., automatic transmission and DCT). As discussed above the shift optimizer (SHFTOPT) technology was not evaluated as part of this study so the HETRANS technology is the last step in these paths.

Automatic Transmission Path

- 8SP: This step provides the incremental fuel consumption of an 8-speed automatic transmission compared to a 6-speed automatic: 1.9%, with a resulting absolute value of 4%.
- HETRANS: This step provides the incremental fuel consumption of an 8-speed automatic transmission due to a 4% higher efficiency. This efficiency increase yields a 3% incremental fuel consumption improvement
- The overall absolute improvement — from the baseline to the final step — is 6.9%.

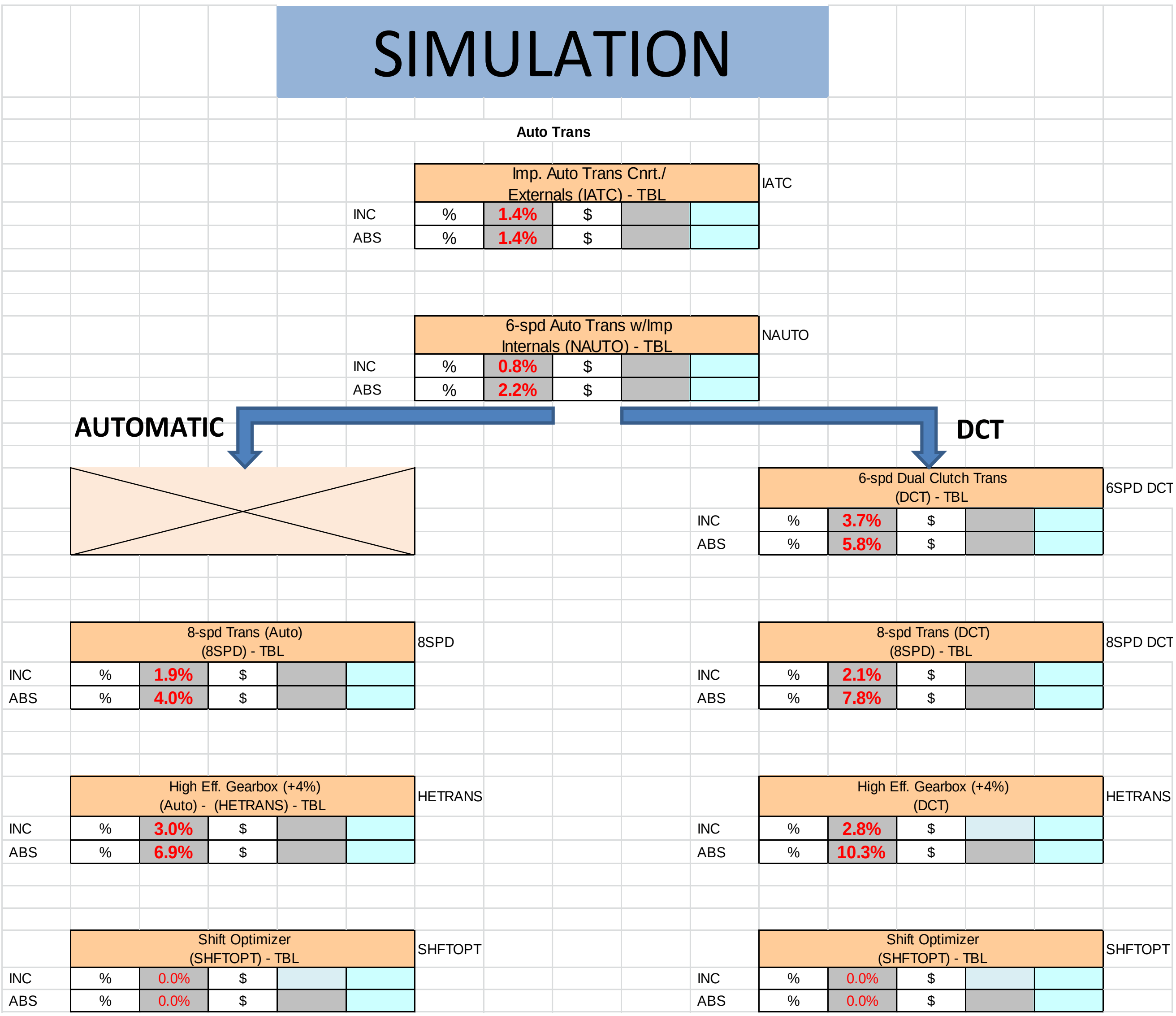


Figure 53 – Transmission Decision Tree Resulting from Simulations

DCT Path

- DCT (6-speed DCT): This step shows the benefit of a 6-speed DCT compared with an automatic transmission with the same number of gears. The simulation results show that applying this new transmission technology produces a 3.7% incremental fuel consumption improvement and a 5.8% absolute improvement.
- 8SPD (8-speed DCT): In this step, moving to an 8-speed DCT yields a 2.1% incremental fuel consumption improvement.
- HETRANS: This is the last step of the DCT path in the tree. It represents the high-efficiency version of the 8-speed DCT. In this case, the 4% increase in transmission efficiency leads to a 2.8% incremental fuel consumption improvement.

The overall absolute improvement — from the baseline to the final step — is 10.3%.

The automatic transmission path provides a total fuel consumption improvement of 6.9%; the DCT path provides a 10.3% fuel consumption improvement.

6.1. Uncertainty Analysis

6.1.1. Impact of Engine Technology

6.1.1.1. Port Fuel Injected Engine

In this section, to evaluate the impact of this trend on the transmission decision tree results, we replaced the naturally aspirated 2.2L Ecotec engine with a port fuel injected engine technology. In order to maintain the same performance as the reference direct injection engine with the initial gear and final drive ratios, the new engine was scaled to 115 kW. All other vehicle parameters are the same as the above evaluation with the 2.2L Ecotec engine.

Table 20 and Table 21 list the fuel consumption and fuel economy results for the advanced turbocharged engine.

Table 20 – Fuel Consumption Results (L/100 km) and Percentage Improvement for Automatic Transmissions with Port Fuel Injected Engine

Fuel Consumption Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% efficiency	8.71	5.68	7.02
6-speed – 92% efficiency	8.71	5.62	6.98
Improvement (%)	0	1.03	0.53
6-speed – 92% efficiency	8.71	5.62	6.98
8-speed – 92% efficiency	8.54	5.38	6.76
Improvement (%)	1.85	4.23	3.20
8-speed – 92% efficiency	8.54	5.38	6.76
8-speed – 96% efficiency	8.33	5.23	6.58
Improvement (%)	2.48	2.78	2.65

Table 21 – Fuel Economy Results (mpg) and Percentage Improvement for Automatic Transmissions with Port Fuel Injected Engine

Fuel Economy Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% efficiency	27.1	48.23	41.44
6-speed – 92% efficiency	27.1	48.73	41.58
Improvement (%)	0	1.04	0.35
6-speed – 92% efficiency	27.0	41.9	32.1
8-speed – 92% efficiency	27.5	43.7	33.0
Improvement (%)	1.9	4.4	2.7
8-speed – 92% efficiency	27.5	43.7	33.0
8-speed – 96% efficiency	28.2	45.0	33.9
Improvement (%)	2.5	2.9	2.7

Figure 54 shows the updated decision tree based on the new engine. The fuel consumption improvement due to advanced transmission, combined with port injected engine, is 9.0%. This value is higher than the 6.9% previously simulated for the reference engine.

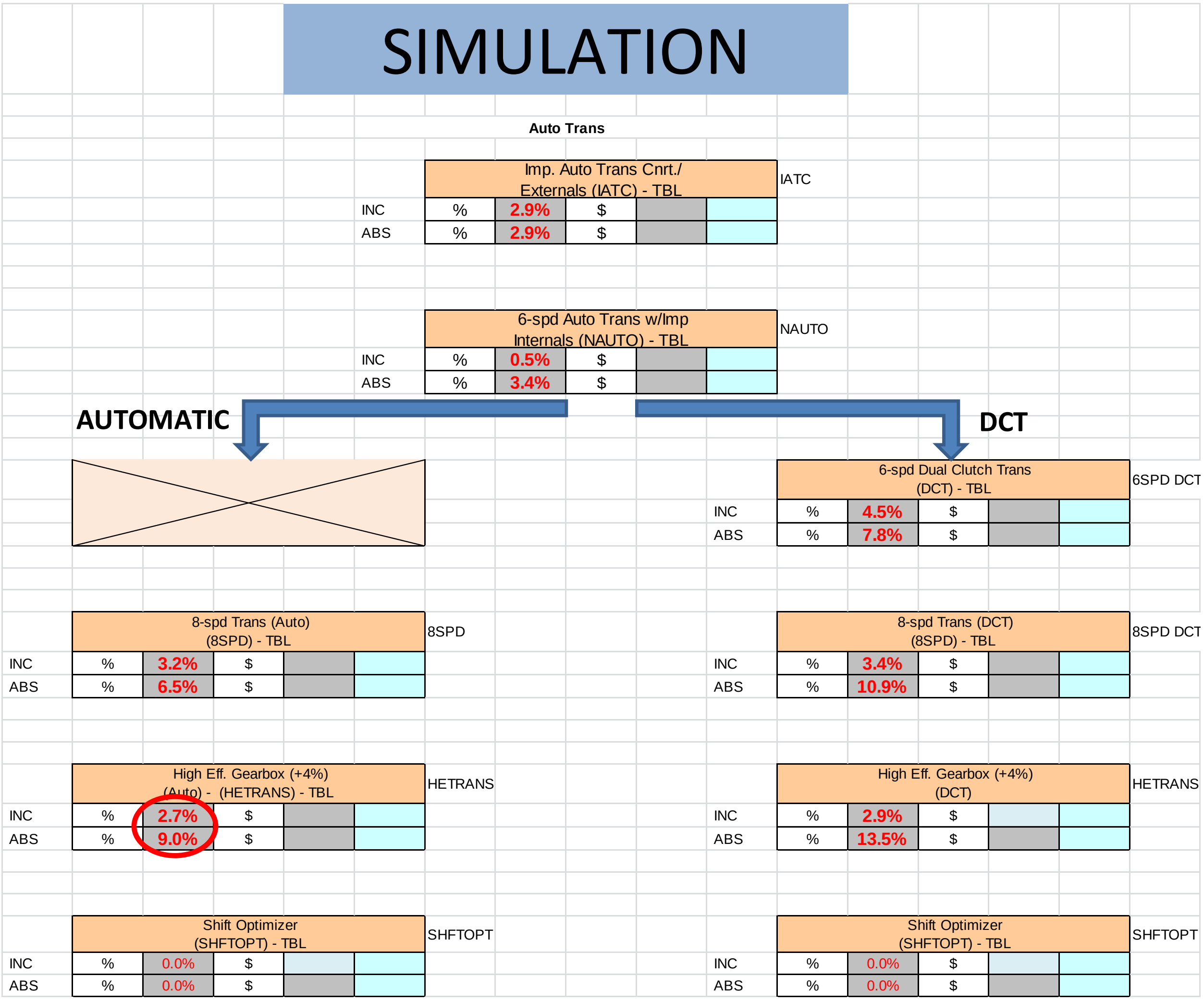


Figure 54 – Transmission Decision Tree with Port Fuel Injected Engine

6.1.1.2. Downsized Turbocharged Engine

The transmission performance characteristics that most influence consumer preferences are launch quality, shift quality, and acceleration.

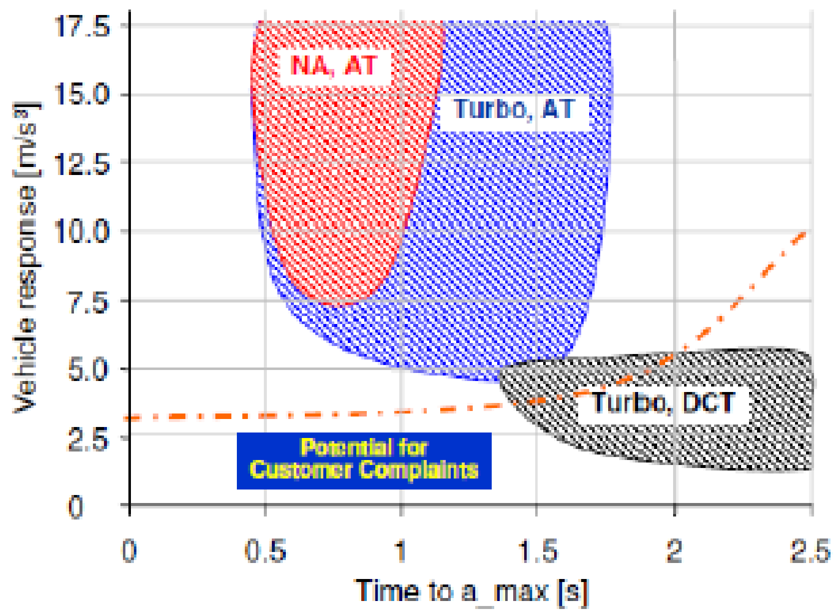


Figure 55 – Launch Response Comparison between AT and DCT with Turbo-Boosting [25]

However, the trend toward engine down-sizing and turbo-boosting introduces challenges in terms of launch quality, largely through the torque delivery lag associated with turbocharging. As shown in Figure 55, according to FEV, there is potential for significant consumer dissatisfaction with the time taken to reach maximum acceleration when a DCT is used on a turbocharged engine, whereas the torque converter on an automatic transmission, whether boosted or not, can reduce acceleration time [25].

To evaluate the impact of this trend on the transmission decision tree results, we replaced the naturally aspirated 2.2L Ecotec engine with a highly downsized, turbocharged engine. This engine is proprietary are in nature thus we are not able to provide any detailed data (*e.g.* the engine map) on this engine. In order to maintain the same performance as the reference engine with the initial gear and final drive ratios, the turbocharged engine was scaled to 115 kW. All other vehicle parameters are the same as the above evaluation with the naturally aspirated 2.2L Ecotec engine.

Advanced engines will achieve not only higher peak efficiency, but also a wider constant efficiency area across different torque values and speeds. As a result, the impact of gear shifting on fuel consumption is expected to decrease with advanced engine technologies. In the extreme case, if one assumes that engine efficiency is completely flat, adding gears will not affect fuel economy at all. On the other hand, one would also expect higher transmission efficiency would be more beneficial to an advanced engine. Indeed, as discussed previously, the benefits of lower transmission losses are offset by lower engine efficiency (because the current engines would operate at lower efficiency to provide a lower load). But the wider constant efficiency area of advanced engines would not penalize higher-efficiency transmissions (because advanced engine efficiency would remain very close despite operating at lower loads).

Table 22 and Table 23 list the fuel consumption and fuel economy results for the advanced turbocharged engine.

Table 22 – Fuel Consumption Results (L/100 km) and Percentage Improvement for Automatic Transmissions with Downsized Turbocharged Engine

Fuel Consumption Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% efficiency	6.33	4.88	5.58
6-speed – 92% efficiency	6.33	4.83	5.55
Improvement (%)	0	1.03	0.49
6-speed – 92% efficiency	6.33	4.83	5.55
8-speed – 92% efficiency	6.33	4.81	5.54
Improvement (%)	0	0.31	0.17
8-speed – 92% efficiency	6.33	4.81	5.54
8-speed – 96% efficiency	6.10	4.65	5.35
Improvement (%)	3.63	3.38	3.50

Table 23 – Fuel Economy Results (mpg) and Percentage Improvement for Automatic Transmissions with Downsized Turbocharged Engine

Fuel Economy Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% efficiency	37.16	48.23	41.44
6-speed – 92% efficiency	37.13	48.73	41.58
Improvement (%)	0	1.04	0.35
6-speed – 92% efficiency	37.13	48.73	41.58
8-speed – 92% efficiency	37.14	48.88	41.64
Improvement (%)	0	0.31	0.13
8-speed – 92% efficiency	37.14	48.88	41.64
8-speed – 96% efficiency	38.54	50.59	43.17
Improvement (%)	3.77	3.50	3.67

Figure 56 shows the updated decision tree based on the advanced engine technology. The fuel consumption improvement due to advanced transmission, combined with an advanced engine, is 5.2%. This value is lower than the 6.9% previously simulated for the reference engine.

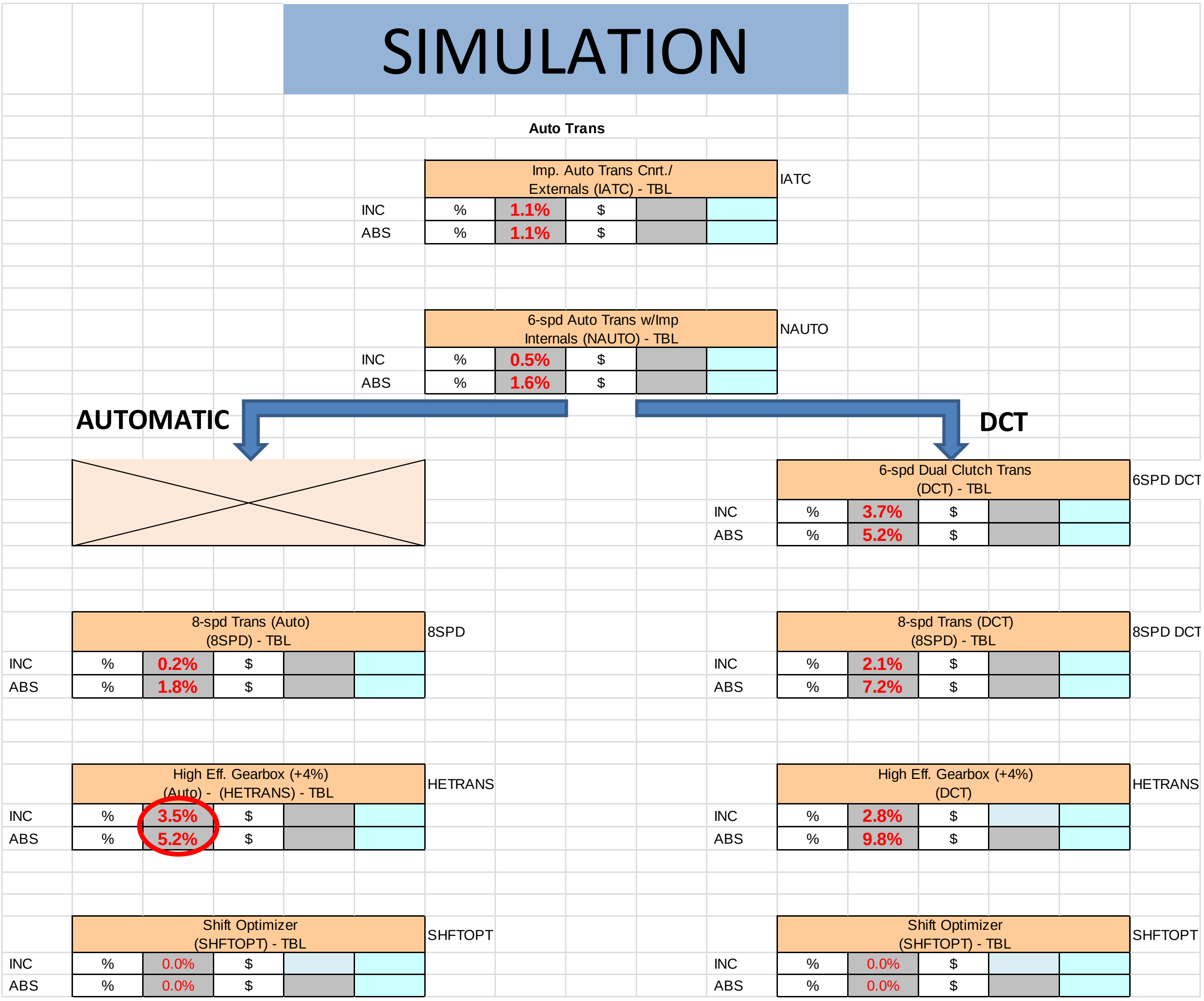


Figure 56 – Transmission Decision Tree with Downsized Turbocharged Engine

6.1.2. Expert and Literature Analysis

Because numerous assumptions have been made in the study, ranging from component technology (e.g., engine efficiency, gearbox and final drive ratio selection) to sizing and control (i.e., shifting), it is important to consider the uncertainties associated with these results. Because too much additional time would be required to quantify the uncertainty associated with each assumption, we turned to literature reviews [19, 20, 21, 22], as well as discussions with experts, to provide low and high values.

Table 24 and Table 25 summarize the fuel consumption improvement ranges for each step in the automatic-transmission and DCT paths of the decision tree shown in Figure 53. The associated decision trees are presented in Figure 57 and Figure 58.

Table 24 – Fuel Consumption Improvement Summary, Automatic Transmission Path

Path[a]		Low	Simulation	High
IATC	Incremental	1.0%	1.4%	3.0%
	Absolute	1.0%	1.4%	3.0%
NAUTO	Incremental	0.5%	0.8%	0.8%
	Absolute	1.5%	2.2%	3.8%
8-speed	Incremental	0.2%	1.9%	3.5%
	Absolute	1.7%	4%	7.1%
HETRANS	Incremental	3.0%	3.0%	3.1%
	Absolute	4.6%	6.9%	10.0%

[a] ITAC: Aggressive torque converter lockup
NAUTO: 5- to 6-speed automatic
8-speed: 6 -to 8-speed automatic
HETRANS: High-efficiency 8-speed automatic

Table 25 – Fuel Consumption Improvement Summary – DCT Path

Path[a]		Low	Simulation	High
IATC	Incremental	1.0%	1.4%	3.0%
	Absolute	1.0%	1.4%	3.0%
NAUTO	Incremental	0.5%	0.8%	0.8%
	Absolute	1.5%	2.2%	3.8%
6-speed DCT	Incremental	3.0%	3.7%	4.4%
	Absolute	4.5%	5.8%	8.0%
8-speed DCT	Incremental	1.0%	2.1%	3.3%
	Absolute	5.4%	7.8%	11%
HETRANS	Incremental	2.5%	2.8%	3.3%
	Absolute	7.8%	10.3%	14.0%

[a] ITAC: Aggressive torque converter lockup
NAUTO: 5 to 6-speed automatic
6-speed DCT: 6-speed automatic to 6-speed DCT
8-speed DCT: 6 to 8-speed DCT
HETRANS: High-efficiency 8-speed DCT

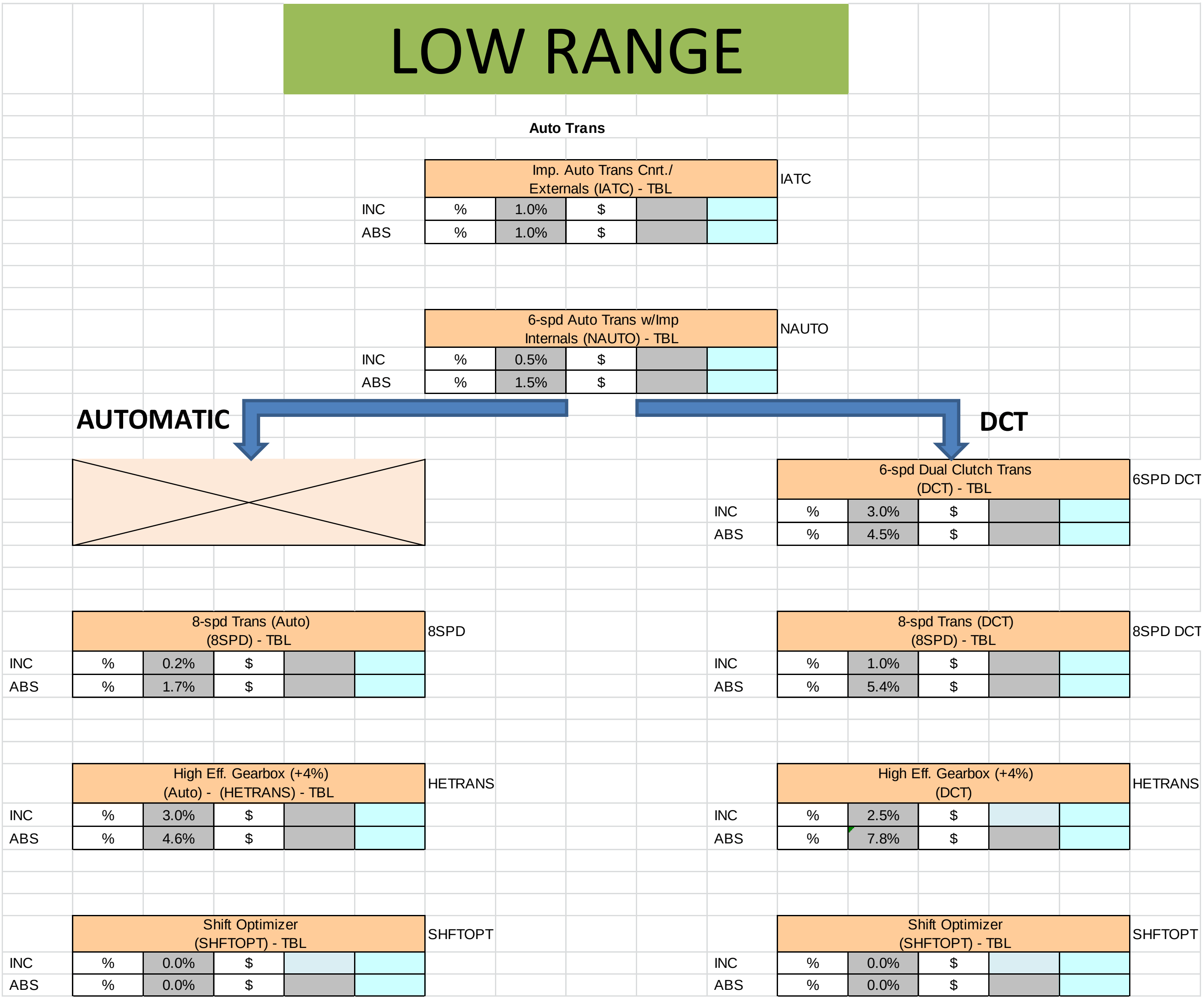


Figure 57 – Low-Range Estimates Decision Tree

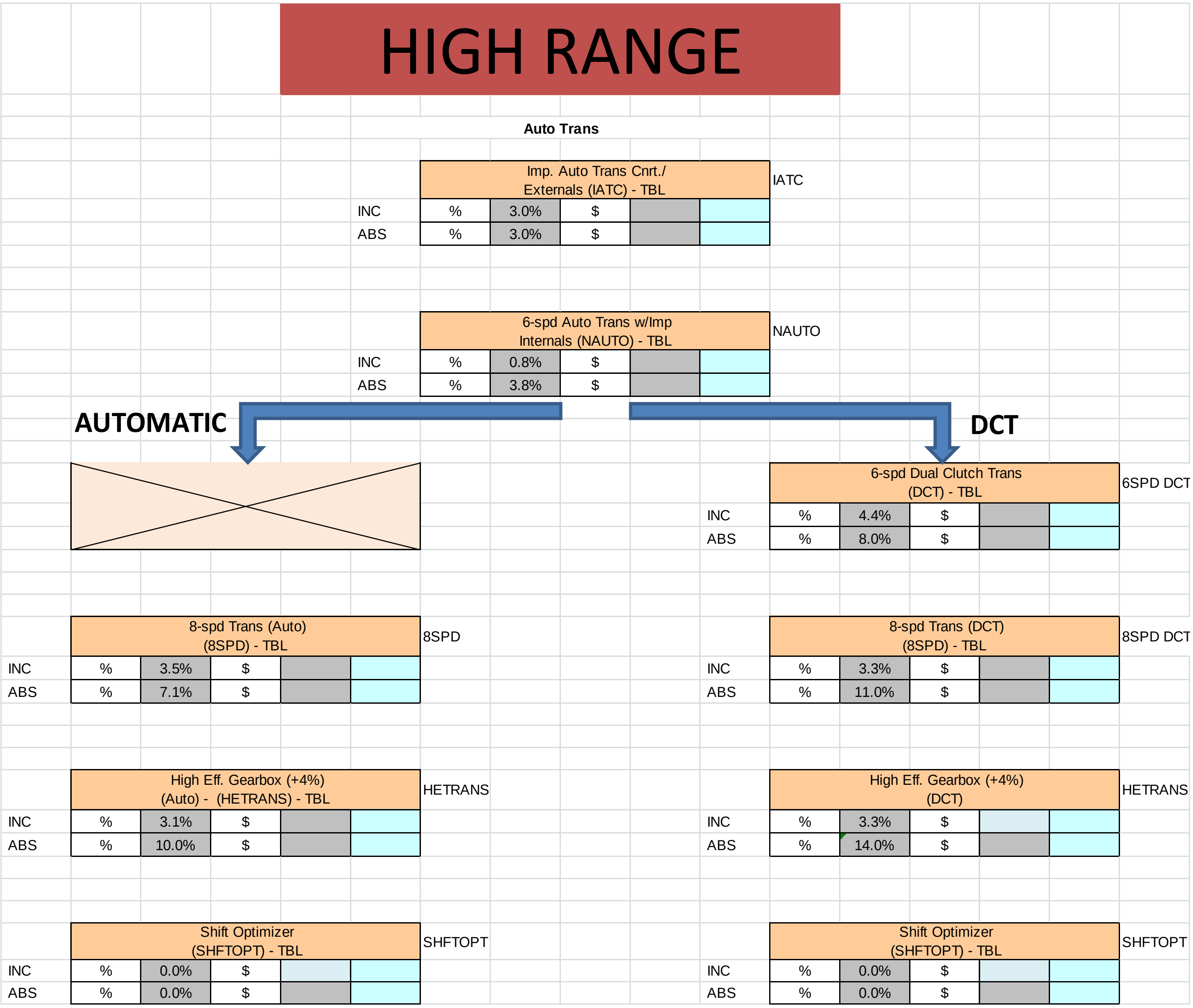


Figure 58 – High-Range Estimates Decision Tree

7. Simulation Results for Additional Vehicle Classes

Previous sections of the report focused solely on the mid-size car class. Because the effectiveness of the technology depends on the vehicle class, this section focuses on additional vehicle classes. Because of the high number of potential simulations, we did not simulate all vehicle classes, but rather evaluated the following four major options: compact car, small sport utility vehicle (SUV), mid-size SUV, and pickup truck.

The same two transmission technologies (automatic transmission and DCT) were considered as potential options for each additional vehicle class. Because of the high input transmission torque for the mid-size SUV and the pickup truck, only automatic transmissions were considered for those classes. We employed the same process used for the mid-size car to evaluate the other vehicle classes.

For all the other classes, the study process consists of starting from a reference vehicle and changing the transmission technology and/or efficiency step by step. The baseline does not change except for the transmission properties. In addition, the final drive ratio was adjusted to produce similar performance for all the transmissions. The performance target (0 to 60 mph in 9.5 sec) is maintained constant for all the vehicles. For the mid-size car, the main goal is to make all the steps comparable and consistent.

The main difference resides in the assumptions used (e.g., vehicle weight, engine power, vehicle losses, tire losses), as well as the transmission and final drive ratios.

7.1. Compact Car Class

Figure 59 shows the transmission steps for the compact class. Because of the low transmission input torque, Argonne researchers decided that most transmissions are likely to be DCT in the near future. As a result, the following steps were implemented:

- **Step 1:** Going from 5-speed transmission with aggressive lockup to 6-speed transmission with the same efficiency.
- **Step 2:** Going from 6-speed automatic transmission to 6-speed DCT with the same efficiency.
- **Step 3**: Going from 6-speed DCT to 8-speed DCT with the same efficiency.
- **Step 4:** Going from 8-speed DCT to 8-speed DCT with higher efficiency (+4% efficiency).

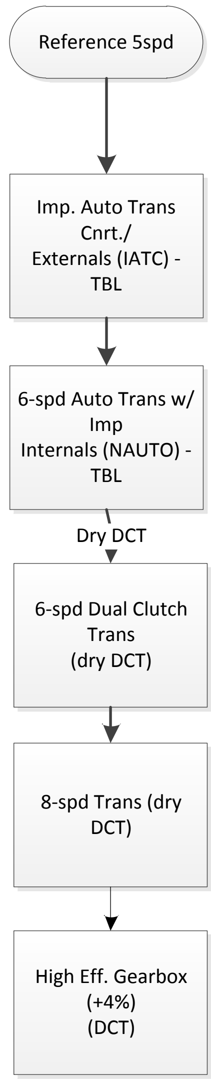


Figure 59 – Compact Car Decision Tree Definition

Vehicle Assumptions/Specifications

The baseline vehicle chosen is a conventional compact vehicle with an automatic 5-speed gearbox and a test weight of 1,356 kg. The engine power was sized to meet vehicle performance targets. Table 26 provides other specifications.

Table 26 – Compact Car Specifications

Component	Value
Final Drive Ratio	4.7
Engine Power (kW)	98
Test Weight (kg)	1356
Drag coefficient	0.31
Frontal area (m^2)	2.193
Rolling-resistance coefficient 1	0.0075
Rolling-resistance coefficient 2 (speed term)	0.00012

Transmission Selection

Table 27 shows the transmission and final ratios for the different gear numbers considered. Note that the same ratios are used for the 8-speed automatic transmission and the DCT.

Table 27 – Compact Car Gearbox Ratios

	Transmission Ratio	Final Drive Ratio
5-speed	[0, 2.56, 1.55, 1.02, 0.72, 0.52]	4.7
6-speed	[0, 4.15, 2.37, 1.56, 1.16, 0.86, 0.52]	3.8 (Automatic) / 3.6 (DCT)
8-speed	[0, 4.6, 2.72, 1.86, 1.46, 1.23, 1, 0.82, 0.52]	3.3

For the compact car, aggressive/early torque-convertor lockup was applied. Figure 60 shows the torque converter lockup strategy on the FTP cycle for the compact vehicle class. The blue line represents the normal lockup strategy; note that the lockup occurs only twice during the entire cycle. The reason is that, as in the mid-size car anlysis, the normal strategy locks the torque converter around 40 mph only, something that happens rarely on the FTP cycle. On the other hand, the green line illustrates how often the torque converter is locked up using an aggressive-lockup logic (i.e., lockup occurs as soon as the second gear is engaged). Because the other vehicle classes show similar patterns, only the overall fuel consumption benefits are shown.

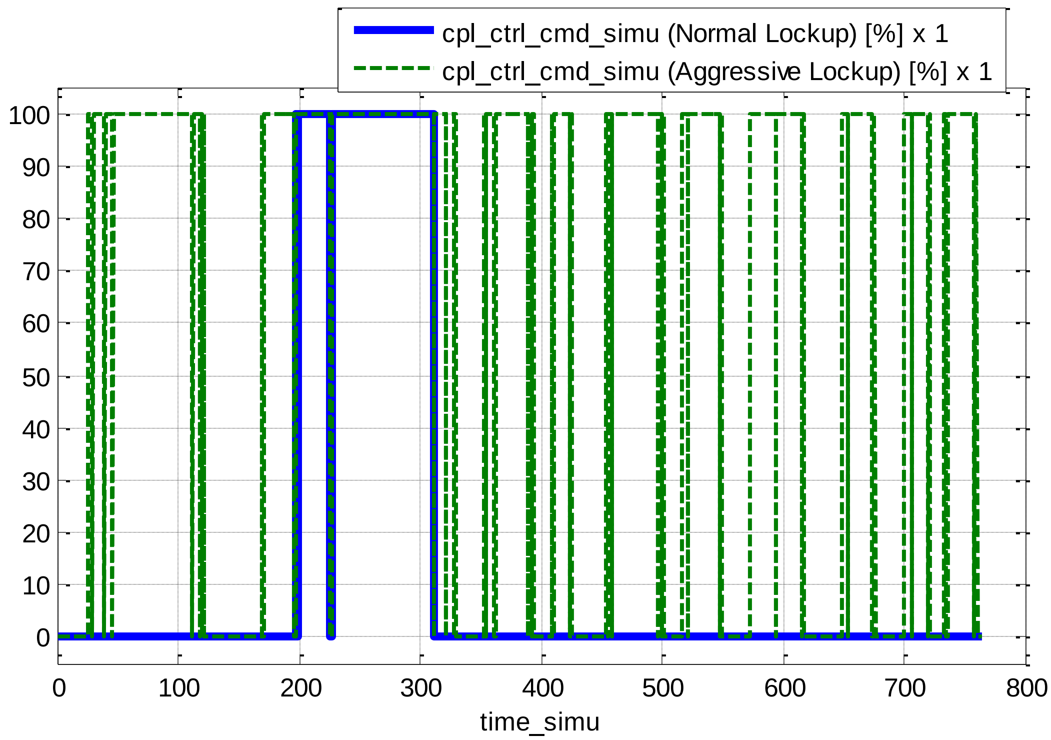


Figure 60 – Compact Car Normal and Aggressive Torque Converter Lockup Strategies on FTP Cycle

The early aggressive lockup strategy provides better fuel savings owing to fewer losses related to the torque converter mechanism, as shown in Table 28. In fact, a combined-cycle fuel consumption improvement of 0.89% can be achieved by using the aggressive lockup logic. We have seen why the differences are minor (0.26% fuel consumption improvement) on the HFET; most of the benefit comes from applying the aggressive lockup strategy on the FTP cycle (1.58% fuel consumption improvements)

Table 28 – Compact Car Comparison of Fuel Consumption (L/100 km) under Normal and Aggressive Lockup Strategies

	FTP	HFET	Combined
Normal lockup	7.40	5.49	6.4
Aggressive lockup	7.28	5.47	6.34
Improvement (%)	1.58	0.26	0.89

The early aggressive lockup strategy provides better torque converter efficiency, as shown in Table 29.

Table 29 – Compact Car Torque Converter Efficiency

	FTP	HFET
Normal lockup torque converter efficiency	87.7%	92.5%
Aggressive lockup torque converter efficiency	89.7%	92.9%

Simulation Results

Detailed signals will not be illustrated in the following sections because the behavior of the compact car class is quite similar to that of the mid-size car.

Table 30 summarizes the main simulation results. The average engine speed decreases with an increase in the number of gears. Average transmission efficiencies are very close to the defined efficiency because some losses occur during shifting.

Table 30 – Compact Car Summary of FTP Efficiencies and Speeds for Automatic

		5-speed, 92% efficiency	6-speed, 92% efficiency	6-speed DCT, 92% efficiency	8-speed DCT, 92% efficiency	8-speed DCT, 96% efficiency
FTP	Average engine efficiency (%)	23.45	23.47	21.61	21.68	21.33
	Average transmission efficiency (%)	91.18	91.12	92	92	96
	Torque converter/clutch efficiency (%)	89.76	90.37	97.25	98.17	98.12
	Average engine speed (rpm)	1,462	1,464	1,434	1,416	1,412
HFET	Average engine efficiency (%)	26.49	27.16	26.04	26.67	26.34
	Average transmission efficiency (%)	91.93	91.93	92	92	96
	Torque converter/clutch efficiency (%)	92.91	93.76	99.91	99.92	99.89
	Average engine speed (rpm)	1,965	1,750	1,910	1,761	1,757

Table 31 and Table 32 summarize the output fuel consumption and fuel economy results for the compact car.

Table 31 – Compact Car Fuel Consumption Results (L/100 km) and Percentage Improvement

Fuel Consumption Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	7.28	5.47	6.34
6-speed – 92% AU	7.25	5.29	6.21
Improvement (%)	0.52	3.39	2.04
6-speed – 92% AU	7.25	5.29	6.21
6-speed – 92% DCT	6.79	5.20	5.97
Improvement (%)	6.29	1.68	3.91
6-speed – 92% DCT	6.79	5.20	5.97
8-speed – 92% DCT	6.71	5.07	5.86
Improvement (%)	1.20	2.46	1.85
8-speed – 92% DCT	6.71	5.07	5.86
8-speed – 96% DCT	6.54	4.92	5.70
Improvement (%)	2.53	2.95	2.75

Table 32 – Compact Car Fuel Economy Results (mpg) and Percentage Improvement

Fuel Economy Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	32.29	42.97	36.36
6-speed – 92% AU	32.46	44.48	36.95
Improvement (%)	0.53	3.51	1.64
6-speed – 92% AU	32.46	44.48	36.95
6-speed – 92% DCT	34.64	45.24	38.72
Improvement (%)	6.72	1.71	4.79
6-speed – 92% DCT	34.64	45.24	38.72
8-speed – 92% DCT	35.06	46.38	39.39
Improvement (%)	1.21	2.52	1.71
8-speed – 92% DCT	35.06	46.38	39.39
8-speed – 96% DCT	35.97	47.79	40.47
Improvement (%)	2.60	3.04	2.76

The values in these fuel consumption tables are inputs for the decision tree provided in the introduction of this section. Each improvement value represents a predefined step in the tree.

Transmission Decision Tree

Figure 61 shows the decision tree resulting from the Autonomie simulation values. All percentage increases represent fuel consumption improvements. The incremental value represents the actual improvement achieved by moving from one step to another; the absolute value signifies the overall improvement compared with the reference baseline vehicle.

The transmission path gives a total fuel consumption improvement of 11% for a compact car.

Compact

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	0.9%	$		
ABS	%	0.9%	$		
	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	2.0%	$		
ABS	%	2.9%	$		
	6-spd Dual Clutch Trans (DCT) - TBL				
INC	%	3.9%	$		
ABS	%	6.7%	$		
	8-spd Trans (DCT) (8SPD) - TBL				
INC	%	1.9%	$		
ABS	%	8.4%	$		
	High Eff. Gearbox (+4%) (DCT)				
INC	%	2.7%	$		
ABS	%	11.0%	$		

Figure 61 – Compact Car Transmission Decision Tree

7.2. Small SUV Class

Figure 62 shows the transmission steps for the small SUV class.

- **Step 1:** Going from 5-speed transmission with aggressive lockup to 6-speed transmission with the same efficiency.
- **Step 2:** Going from 6-speed automatic transmission to 6-speed DCT with the same efficiency.
- **Step 3:** Going from 6-speed DCT to 8-speed DCT with the same efficiency.
- **Step 4:** Going from 8-speed DCT to 8-speed DCT with higher efficiency (+4% efficiency).

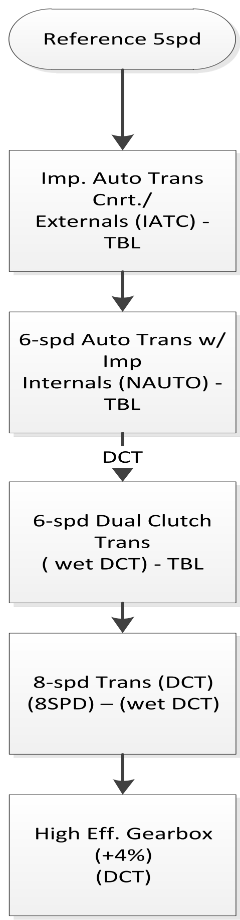


Figure 62 – Small SUV Decision Tree Definition

Vehicle Assumptions/Specifications

The baseline vehicle chosen is a conventional small SUV vehicle with an automatic 5-speed gearbox and a test weight of 1,684 kg. The engine was sized to meet the vehicle performance targets. Other specifications are given in Table 33.

Table 33 – Small SUV Specifications

Component	Value
Final Drive Ratio	4.7
Engine Power (kW)	98
Test Weight (kg)	1,684
Drag coefficient	0.4
Frontal area (m^2)	2.57
Rolling-resistance coefficient 1	0.0084
Rolling-resistance coefficient 2 (speed term)	0.00012

Transmission Control

Table 34 shows the transmission and final ratios for the different gear numbers considered. Note that the same ratios are used for the 8-speed automatic transmission and the DCT.

Table 34 – Small SUV Gearbox Ratios

	Transmission Ratio	**Final Drive Ratio**
5-speed	**[0, 2.56, 1.55, 1.02, 0.72, 0.52]**	**4.7**
6-speed	[0, 4.15, 2.37, 1.56, 1.16, 0.86, 0.52]	3.8 (Au) / 3.6 (DCT)
8-speed	[0, 4.6, 2.72, 1.86, 1.46, 1.23, 1, 0.82, 0.52]	3.3

Again, aggressive/early torque-convertor lockup is applied (i.e., the lockup occurs as soon as the second gear is engaged).

Torque Converter/Early Lockup

The early aggressive lockup strategy provides better fuel savings owing to fewer losses related to the torque converter mechanism, as shown in Table 35. In fact, a combined-cycle fuel consumption improvement of 0.88% can be achieved by using aggressive lockup logic. We have seen why the differences are minor (0.21% fuel consumption improvement) on the HFET cycle; most of the benefit comes from applying the aggressive lockup strategy on the FTP cycle (1.58% fuel consumption improvements).

Table 35 – Small SUV Comparison of Fuel Consumption (L/100 km) under Normal and Aggressive Lockup Strategies

	FTP	HFET	Combined
Normal lockup	**8.97**	**7.01**	**7.97**
Aggressive lockup	**8.83**	**6.99**	**7.90**
Improvement (%)	**1.58**	**0.21**	**0.88**

Simulation Results

Detailed vehicle parameters are not illustrated in the following sections because the behavior of the small SUV is quite similar to that of the compact and mid-size vehicles. Table 36 and Table 37 summarize the output fuel consumption and fuel economy results.

Table 36 – Small SUV Fuel Consumption Results (L/100 km) and Percentage Improvement

Fuel Consumption Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	8.83	7.00	7.90
6-speed – 92% AU	8.78	6.85	7.80
Improvement (%)	0.56	2.04	1.32
6-speed – 92% AU	8.78	6.85	7.80
6-speed – 92% DCT	8.43	6.90	7.67
Improvement (%)	3.98	-0.73	1.63
6-speed – 92% DCT	8.43	6.90	7.67
8-speed – 92% DCT	8.30	6.81	7.56
Improvement (%)	1.59	1.35	1.47
8-speed – 92% DCT	8.30	6.81	7.56
8-speed – 96% DCT	8.08	6.61	7.34
Improvement (%)	2.60	2.99	2.80

Table 37 – Small SUV Fuel Economy Results (mpg) and Percentage Improvement

Fuel Economy Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	26.63	33.62	29.38
6-speed – 92% AU	26.78	34.32	29.72
Improvement (%)	0.56	2.08	1.16
6-speed – 92% AU	26.78	34.32	29.72
6-speed – 92% DCT	27.89	34.07	30.37
Improvement (%)	4.14	-0.72	2.19
6-speed – 92% DCT	27.89	34.07	30.37
8-speed – 92% DCT	28.34	34.54	30.83
Improvement (%)	1.61	1.36	1.51
8-speed – 92% DCT	28.34	34.54	30.83
8-speed – 96% DCT	29.10	35.60	31.70
Improvement (%)	2.67	3.09	2.84

These fuel consumption tables are inputs for the decision tree defined in the introduction of this section. Each improvement value represents a predefined step in the tree.

Transmission Decision Tree

Figure 63 shows the decision tree resulting from the Autonomie simulation values. All percentage increases represent fuel consumption improvements. The incremental value represents the actual improvement achieved by moving from one step to another; the absolute value signifies the overall improvement compared with the reference baseline vehicle.

The transmission path gives a total fuel consumption improvement of 8.5% for a small SUV.

Small SUV

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.1%	$		
ABS	%	1.1%	$		
	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	1.2%	$		
ABS	%	2.2%	$		
	6-spd Dual Clutch Trans (DCT) - TBL				
INC	%	2.2%	$		
ABS	%	4.3%	$		
	8-spd Trans (DCT) (8SPD) - TBL				
INC	%	1.5%	$		
ABS	%	5.8%	$		
	High Eff. Gearbox (+4%) (DCT)				
INC	%	2.8%	$		
ABS	%	8.5%	$		

Figure 63 – Small SUV Transmission Decision Tree

7.3. Mid-Size SUV Class

Figure 64 shows the transmission steps for the mid-size SUV class. The steps are slightly different compared with the three previous classes studied (compact, midsize, small SUV). DCTs have not been considered for mid-size SUVs or pickups because of the high torque at the input shaft. As a result, the following steps were implemented:

- **Step 1:** Going from 5-speed transmission with aggressive lockup to 6-speed transmission with the same efficiency.
- **Step 2:** Going from 6-speed automatic transmission to 8-speed automatic with the same efficiency.
- **Step 3:** Going from 8-speed automatic to 8-speed automatic with higher efficiency (+4% efficiency).

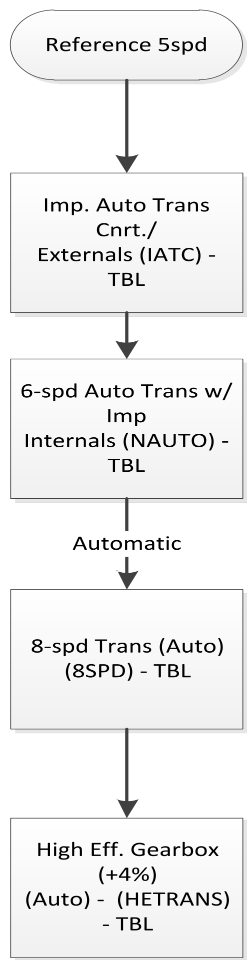


Figure 64 – Mid-Size SUV Decision Tree Definition

Vehicle Assumptions/Specifications

The baseline vehicle chosen is a conventional mid-size SUV vehicle with an automatic 5-speed gearbox and a test weight of 1,876 kg. The engine was sized to meet the vehicle performance targets. Other specifications are given in Table 38.

Table 38 – Mid-Size SUV Vehicle Specifications

Component	Value
Final Drive Ratio	4.7
Engine Power (kW)	132
Test Weight (kg)	1,876
Drag coefficient	0.41
Frontal area (m^2)	2.94
Rolling-resistance coefficient 1	0.0084
Rolling-resistance coefficient 2 (Speed term)	0.00012

Transmission and Control

Table 39 shows the transmission and final ratios for the different gear numbers considered. Note that the same ratios are used for the 8-speed automatic transmission and the DCT.

Table 39 – Midsize SUV Gearbox Ratios

	Trans. Ratio	**Final Drive Ratio**
5-speed	[0, 2.56, 1.55, 1.02, 0.72, 0.52]	4.7
6-speed	[0, 4.15, 2.37, 1.56, 1.16, 0.86, 0.52]	3.8 (Automatic) / 3.6 (DCT)
8-speed	[0, 4.6, 2.72, 1.86, 1.46, 1.23, 1, 0.82, 0.52]	3.3

Torque Converter/Early Lockup

The early aggressive lockup strategy provides better fuel savings owing to fewer losses related to the torque converter mechanism, as shown in Table 40. In fact, a combined-cycle fuel consumption improvement of 1.18 % can be achieved by using aggressive lockup logic. We have seen why the differences are minor (0.23% fuel consumption improvement) on the HFET cycle; most of the benefit comes from applying the aggressive lockup strategy on the FTP cycle (2.13 % fuel consumption improvement)

Table 40 – Midsize SUV Comparison of Fuel Consumption (L/100 km) under Normal and Aggressive Lockup Strategies

	FTP	HFET	Combined
Normal lockup	10.37	8.34	9.34
Aggressive lockup	10.15	8.32	9.23
Improvement (%)	2.13	0.23	1.18

Simulation Results

Detailed vehicle parameters will not be illustrated in the following sections because the behavior of the mid-size SUV is quite similar to that of the compact and mid-size car and the small SUV. Table 41 and Table 42 summarize the output fuel consumption and fuel economy results.

Table 41 – Mid-Size SUV Fuel Consumption Results (L/100 km) and Percentage Improvement

Fuel Consumption Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	10.15	8.32	9.24
6-speed – 92% AU	10.14	8.20	9.16
Improvement (%)	0.12	1.53	0.83
6-speed – 92% AU	10.14	8.20	9.16
8-speed – 92% AU	10.02	8.14	9.07
Improvement (%)	1.20	0.69	0.94
8-speed – 92% AU	10.02	8.14	9.07
8-speed – 96% AU	9.76	7.95	8.85
Improvement (%)	2.59	2.29	2.44

Table 42 – Mid-Size SUV Fuel Economy Results (mpg) and Percentage Improvement

Fuel Economy Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	23.18	28.26	25.22
6-speed – 92% AU	23.20	28.70	25.39
Improvement (%)	0.12	1.55	0.69
6-speed – 92% AU	23.20	28.70	25.39
8-speed – 92% AU	23.48	28.90	25.65
Improvement (%)	1.21	0.70	1.01
8-speed – 92% AU	23.48	28.90	25.65
8-speed – 96% AU	24.11	29.57	26.30
Improvement (%)	2.66	2.35	2.53

These fuel consumption tables are inputs for the decision tree defined in the introduction of this section. Each improvement value represents a predefined step in the tree.

Transmission Decision Tree

Figure 65 shows the decision tree resulting from the Autonomie simulation values. All percentage increases represent fuel consumption improvements. The incremental value represents the actual improvement achieved by moving from one step to another; the absolute value signifies the overall improvement compared with the reference baseline vehicle.

The transmission path gives a total fuel consumption improvement of 5.5% for a mid-size SUV.

Midsize SUV

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.4%	$		
ABS	%	1.4%	$		
	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	0.7%	$		
ABS	%	2.1%	$		
	8-spd Auto Trans (Auto) (8SPD) - TBL				
INC	%	1.0%	$		
ABS	%	3.1%	$		
	High Eff. Gearbox (+4%) (Auto) - (HETRANS) TBL				
INC	%	2.5%	$		
ABS	%	5.5%	$		

Figure 65 – Mid-Size SUV Transmission Decision Tree

7.4. Pickup Truck Class

Figure 66 shows the transmission steps for the midsize SUV class. The steps are slightly different compared with those for the compact and mid-size car and the small SUV but mirror the midsize SUV. DCTs have not been considered for mid-size SUVs or pickups because of the high torque at the input shaft. As a result, the following steps were implemented:

- **Step 1:** Going from 5-speed transmission with aggressive lockup to 6-speed transmission with the same efficiency.
- **Step 2:** Going from 6-speed automatic transmission to 8-speed automatic with the same efficiency.
- **Step 3:** Going from 8-speed automatic to 8-speed automatic with higher efficiency (+4% efficiency).

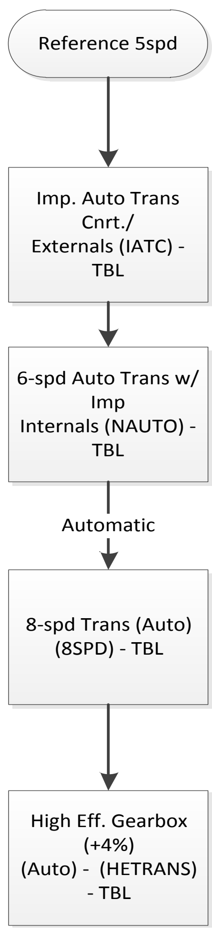


Figure 66 – Pickup Truck Decision Tree Definition

Vehicle Assumptions/Specifications

The baseline vehicle chosen is a conventional pickup truck with an automatic 5-speed gearbox and a test weight of 2,141 kg. The engine was sized to meet the vehicle performance targets. Other specifications are given in Table 43.

Table 43 – Pickup Truck Vehicle Specifications

Component	Value
Final Drive Ratio	4.7
Engine Power (kW)	152
Test Weight (kg)	2141
Drag coefficient	0.45
Frontal area (m^2)	3.27
Rolling-resistance coefficient 1	0.009
Rolling-resistance coefficient 2 (speed term)	0.00012

Transmission Selection

Table 44 shows the transmission and final ratios for the different gear numbers considered. Note that the same ratios are used for the 8-speed automatic transmission and the DCT.

Table 44 – Pickup Truck Gearbox Ratios

	Transmission Ratio	**Final Drive Ratio**
5-speed	**[0, 2.56, 1.55, 1.02, 0.72, 0.52]**	**4.7**
6-speed	[0, 4.15, 2.37, 1.56, 1.16, 0.86, 0.52]	3.8 (Automatic) / 3.6 (DCT)
8-speed	[0, 4.6, 2.72, 1.86, 1.46, 1.23, 1, 0.82, 0.52]	3.3

Again, aggressive/early torque-convertor lockup is applied (i.e., the lockup occurs as soon as the second gear is engaged).

Torque Converter/Early Lockup

The early aggressive lockup strategy provides better fuel savings owing to fewer losses related to the torque converter mechanism, as shown in Table 45. In fact, a combined-cycle fuel consumption improvement of 1.64 % can be achieved by using aggressive lockup logic. We have seen why the differences are minor (0.29% fuel consumption improvement) on the HFET cycle; most of the benefit comes from applying the aggressive lockup strategy on the FTP cycle (2.57 % fuel consumption improvement).

Table 45 – Pickup Truck Comparison of Fuel Consumption (L/100 km) under Normal and Aggressive Lockup Strategies

	FTP	HFET	Combined
Normal lockup	19.58	23.62	21.21
Aggressive lockup	20.08	23.69	21.55
Improvement (%)	2.57	0.29	1.64

Simulation Results

Detailed vehicle parameters will not be illustrated in the following sections because the behavior of the mid-size pickup truck is quite similar to that of the compact and mid-size car and small and mid-size SUV.

Table 46 and Table 47 summarize the output fuel consumption and fuel economy results. For this vehicle, it is more beneficial to raise the transmission efficiency than to increase the number of gears, as shown by considering the 0.49% fuel consumption improvement gained in moving from 5 to 6 speeds (with the same transmission efficiency) compared with the almost 2.86% fuel consumption improvement gained by increasing the transmission efficiency by 4%.

Table 46 – Pickup Truck Fuel Consumption Results (l/100 km) and Percentage Improvement

Fuel Consumption Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	11.71	9.93	10.84
6-speed – 92% AU	11.70	9.84	10.78
Improvement (%)	0.14	0.85	0.49
6-speed – 92% AU	11.70	9.84	10.78
8-speed – 92% AU	11.56	9.66	10.62
Improvement (%)	1.15	1.89	1.52
8-speed – 92% AU	11.56	9.66	10.62
8-speed – 96% AU	11.25	9.37	10.32
Improvement (%)	2.71	3.02	2.86

Table 47 – Pickup Truck Fuel Economy Results (mpg) and Percentage Improvement

Fuel Economy Results			
Conventional – Automatic Transmission	FTP	HFET	Combined
5-speed – 92% AU	20.08	23.69	21.56
6-speed – 92% AU	20.11	23.89	21.65
Improvement (%)	0.14	0.86	0.43
6-speed – 92% AU	20.11	23.89	21.65
8-speed – 92% AU	20.34	24.35	21.97
Improvement (%)	1.17	1.93	1.47
8-speed – 92% AU	20.34	24.35	21.97
8-speed – 96% AU	20.91	25.11	22.61
Improvement (%)	2.78	3.11	2.92

These fuel consumption tables are inputs for the decision tree defined in the introduction of this section. Each improvement value represents a predefined step in the tree.

Transmission Decision Tree

Figure 67 shows the decision tree resulting from the Autonomie simulation values. All percentage increases represent fuel consumption improvements. The incremental value represents the actual improvement achieved by moving from one step to another; the absolute value signifies the overall improvement starting compared with the reference baseline vehicle.

The transmission path gives a total fuel consumption improvement of 6.3% for a pickup truck.

Pickup

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.6%	$		
ABS	%	1.6%	$		
	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	0.4%	$		
ABS	%	2.1%	$		
	8-spd Auto Trans (Auto) (8SPD) - TBL				
INC	%	1.5%	$		
ABS	%	3.5%	$		
	High Eff. Gearbox (+4%) (Auto) - (HETRANS) TBL				
INC	%	2.9%	$		
ABS	%	6.3%	$		

Figure 67 – Pickup Truck Transmission Decision Tree

8. Summary

The objective of the study was to estimate the fuel consumption benefits offered by several advanced transmissions. A full vehicle simulation tool was used to build and simulate different technologies. As part of the process, Argonne researchers made a number of assumptions regarding the component technologies (e.g., engine fuel rate map, transmission gear ratio), control (e.g., shifting, torque converter lockup), and component sizing. As for any simulation study, the results are valid for the set of assumptions considered. The transmission benefits for the different vehicle classes are summarized below.

- For the mid-size car, the automatic transmission provides a total fuel consumption improvement of up to 6.9%; the DCT path provides a fuel consumption improvement of up to 10.3%.
- For the compact car, the transmission provides a total fuel consumption improvement of up to 11%.
- For a small SUV, the transmission provides a total fuel consumption improvement of up to 8.5%.
- For a mid-size SUV, the transmission provides a total fuel consumption improvement of up to 5.5%
- For a pickup truck, the transmission provides a total fuel consumption improvement of up to 6.3%

Different approaches were used to try to quantify the impact of uncertainties. A review of the literature, combined with discussions with experts, was used to generate uncertainties for the mid-size car decision tree. Advanced engine technologies (i.e., turbocharger) were also simulated for the mid-size car to demonstrate the impact of future technologies. The uncertainties associated with transmission benefits are summarized below:

- When considering uncertainties based on experts and literature, the automatic transmission benefits range from 5 to 11%, and the DCT benefits range from 7.5 to 13.5%.
- Advanced engine technologies tend to decrease the transmission benefits, with a fuel consumption improvement of 5.2% for the automatic transmission and 9.8% for the DCT. Both of these values are within the ranges provided by the experts and in the literature.

Compact

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	0.9%	$		
ABS	%	0.9%	$		

	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	2.0%	$		
ABS	%	2.9%	$		

	6-spd Dual Clutch Trans (DCT) - TBL				
INC	%	3.9%	$		
ABS	%	6.7%	$		

	8-spd Trans (DCT) (8SPD) - TBL				
INC	%	1.9%	$		
ABS	%	8.4%	$		

	High Eff. Gearbox (+4%) (DCT)				
INC	%	2.7%	$		
ABS	%	11.0%	$		

Midsize Car

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.4%	$		
ABS	%	1.4%	$		

	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	0.8%	$		
ABS	%	2.2%	$		

	6-spd Dual Clutch Trans (DCT) - TBL				
INC	%	3.7%	$		
ABS	%	5.8%	$		

	8-spd Trans (DCT) (8SPD) - TBL				
INC	%	2.1%	$		
ABS	%	7.8%	$		

	High Eff. Gearbox (+4%) (DCT)				
INC	%	2.8%	$		
ABS	%	10.3%	$		

Small SUV

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.1%	$		
ABS	%	1.1%	$		

	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	1.2%	$		
ABS	%	2.2%	$		

	6-spd Dual Clutch Trans (DCT) - TBL				
INC	%	2.2%	$		
ABS	%	4.3%	$		

	8-spd Trans (DCT) (8SPD) - TBL				
INC	%	1.5%	$		
ABS	%	5.8%	$		

	High Eff. Gearbox (+4%) (DCT)				
INC	%	2.8%	$		
ABS	%	8.5%	$		

Midsize SUV

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.4%	$		
ABS	%	1.4%	$		

	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	0.7%	$		
ABS	%	2.1%	$		

	8-spd Auto Trans (Auto) (8SPD) - TBL				
INC	%	1.0%	$		
ABS	%	3.1%	$		

	High Eff. Gearbox (+4%) (Auto) - (HETRANS) TBL				
INC	%	2.5%	$		
ABS	%	5.5%	$		

Pickup

	Imp. Auto Trans Cnrt./ Externals (IATC) - TBL				
INC	%	1.6%	$		
ABS	%	1.6%	$		

	6-spd Auto Trans w/Imp Internals (NAUTO) - TBL				
INC	%	0.4%	$		
ABS	%	2.1%	$		

	8-spd Auto Trans (Auto) (8SPD) - TBL				
INC	%	1.5%	$		
ABS	%	3.5%	$		

	High Eff. Gearbox (+4%) (Auto) - (HETRANS) TBL				
INC	%	2.9%	$		
ABS	%	6.3%	$		

9. References

1. National Academies of Sciences "Assessment of Fuel Economy Technologies for Light Duty Vehicles", National Research Council, 2010
2. "Ricardo Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe (PDF)" can be found at http://www.epa.gov/otaq/climate/publications.htm#vehicletechnologies
3. www.autonomie.net
4. Halbach, S., P. Sharer, P. Pagerit, C. Folkerts, and A. Rousseau, 2010, "Model Architecture, Methods, and Interfaces for Efficient Math-Based Design and Simulation of Automotive Control Systems," Society of Automotive Engineers (SAE) 2010-01-0241, SAE World Congress, Detroit, MI, April.
5. Kim, N., A. Rousseau, and E. Rask, 2012, "Autonomie Model Validation with Test Data for 2010 Toyota Prius," SAE 2012-01-1040, SAE World Congress, Detroit, MI, April 12.
6. Kim, N., R. Carlson, F. Jehlik, and A. Rousseau, 2009, "Tahoe HEV Model Development in Powertrain System Analysis Toolkit (PSAT)," SAE paper 2009-01-1307, SAE World Congress, Detroit, MI, April.
7. Cao, Q., S. Pagerit, R. Carlson, and A. Rousseau, 2007, "PHEV Hymotion Prius Model Validation and control improvements," 23rd International Electric Vehicle Symposium (EVS23), Anaheim, CA, (Dec. 2007).
8. Rousseau, A., P. Sharer, S. Pagerit, and M. Duoba, 2006, "Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT," SAE paper 2006-01-0667, SAE World Congress, Detroit, MI April.
9. Moawad, A., N. Kim, and A. Rousseau, 2012, "Impact of Technology on Electric Drive Fuel Consumption and Cost," SAE 2012-01-1011, SAE World Congress, Detroit, MI, April 12.
10. Fellah, M., G. Singh, A. Rousseau, and S. Pagerit, 2009, "Impact of Real-World Drive Cycles on Plug-In Hybrid Electric Vehicle (PHEV) Battery Requirements," SAE paper 2009-01-1383, SAE World Congress, Detroit, MI, April.
11. Sharer, P., A. Rousseau, S. Pagerit, and P. Nelson, 2007, "Midsize and SUV Vehicle Simulation Results for Plug-in HEV Component Requirements," SAE paper 2007-01-0295, SAE World Congress, Detroit, MI, April.
12. Sharer, P., A. Rousseau, P. Nelson, and S. Pagerit, 2006, "Vehicle Simulation Results for PHEV Battery Requirements," 22nd International Electric Vehicle Symposium (EVS22), Yokohama, Japan, Oct.
13. Ward, J., A. Moawad, N. Kim, and A. Rousseau, 2012, "Light-Duty Vehicle Fuel Consumption, Cost and Market Penetration Potential by 2020," EVS26, Los Angeles, CA, May.
14. Da Costa, A., N. Kim, F. Le Berr, N. Marc, F. Badin, and A. Rousseau, 2012, "Fuel Consumption Potential of Different Plug-in Hybrid Vehicle Architectures in the European and American Contexts," EVS26, Los Angeles, CA, May.

15. Moawad, A., N. Kim, and A. Rousseau, 2012, "Impact of Technology on Electric Drive Fuel Consumption and Cost," SAE 2012-01-1011, SAE World Congress, Detroit, MI, April 12.
16. Moawad, A., and A. Rousseau, 2011, "Impact of Vehicle Performance on Cost Effective Way to Meet CAFE 2017–2025,"Vehicle Power and Propulsion Conference, 2011, Chicago, IL, Sept.
17. Elgowainy, A., A. Burnham, M. Wang, J. Molburg, and A. Rousseau, 2009, "Well-To-Wheels Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles," SAE 2009-01-1309, SAE World Congress, Detroit, MI, April.
18. Gaines, L., A. Burnham, A. Rousseau, and D. Santini, 2007, "Sorting through the Many Total-Energy-Cycle Pathways Possible with Early Plug-In Hybrids," EVS23, Anaheim, CA, Dec.
19. World Academy of Science, 2011, "Simulation and Analysis of the Shift Process for an Automatic Transmission," *Engineering and Technology* 76, April.
20. Kulkarni et al., 2007, "Shift Dynamics and Control of Dual-Clutch Transmissions," *Mechanism and Machine Theory*, 42, pp. 168–182
21. Moawad, A., 2011, *How to Meet CAFE 2017–2025,* DOE Report, Feb.
22. The National Academies Press, *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*, available at www.nap.edu/catalog/12924.html, accessed June 2012.
23. Duleep, K.G., 2007, *Technologies to Improve Light-Duty Fuel Economy*, Report for the National Academies of Science, Sept.
24. AutoSector Research, *Transmissions Report*, 2012 Edition.
25. FEV, 2011, 6th International CTI Symposium and Exhibition, "Innovative Automotive Transmissions and Hybrid & Electric Drive, North America," May.

APPENDIX 1 – Peer Review Comments and Responses

Comment #	Reviewer	Comment summary	Response	Related Report Section(s)
1	Midlam-Mohler	Show the impact of running simulation with the same top gear ratio & how it impacts results	Modified report. The transmissions currently on the market all have a lower top gear ratio with higher gear number. Running simulations with the same top gear would not only significantly limit the benefits of transmissions with higher gear number but also does not represent the technology currently in the market	p29-30
2	Midlam-Mohler	Show impact of using a complete transmission efficiency map vs. using a constant value	Modified report. An efficiency for the gearbox (i.e., not including the torque converter) of 92% was selected for the study. A constant value was selected after running simulations using several proprietary detailed transmission data to provide transparent results.	p29
3	Midlam-Mohler	Is transmission warm-up considered?	Modified report. As for all the other models, the study assumed that all components are fully warmed-up. As a result, the potential difference in warm-up between all the different transmission technologies is not considered.	p29
4	Midlam-Mohler	In moving from a 92% efficiency transmission to a 96% efficient transmission you are cutting the internal heat generation in two. This will have an impact of warm-up time and thus efficiency potentially costing you significant fuel consumption on the first bag of the FTP.	All the simulations are performed under hot conditions	p29
5	Midlam-Mohler	Describe torque converter model and data	Modified report.	p42-43

Comment #	Reviewer	Comment summary	Response	Related Report Section(s)
6	Midlam-Mohler	List final drive ratio efficiency	Modified report. A constant value of 97.5% is used to represent the final drive ratio efficiency.	p31
7	Midlam-Mohler	Prove that improvements made do not lead to drivability issues	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.	p40-42
8	Midlam-Mohler	Point to other sources to explain drivability in terms of comparisons made on p.73	Modified report by adding section 4.5.1.4. 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.	p40-42

Comment #	Reviewer	Comment summary	Response	Related Report Section(s)
9	Midlam-Mohler	Try to get other publications, esp. for DCT	While additional publications and references would have been desirable, due the time constraints placed on the publication of the report, additional references were not able to be researched.	
10	Midlam-Mohler	Looks like the 5 speed auto has 89 shifts while current vehicles have 100 to 110 --> what is the impact of being more aggressive?	The impact of adding 10 shifts on the UDDS (which has 18 segments) would be minimal on the fuel consumption.	
11	Midlam-Mohler	Explain why DCT and auto trans have same avg. efficiency (or if not, explain assumptions/modeling of this)	The gearboxes have the same efficiency but this does not include the torque converter losses of the automatic transmissions.	
12	Midlam-Mohler	Explain that additional/different sim would be required for more fine analysis of launch performance and drivability.	Modified report by adding section 4.5.1.4. 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.	p40-42
13	Midlam-Mohler	Additional validation data should be presented to give full confidence in the tool's ability to predict fuel economy gains.	The plant models and control strategies used for all the powertrain configurations considered have been validated based on vehicle test data. Detailed information can be found at http://www.autonomie.net/overview/papers_validation.html	

Comment #	Reviewer	Comment summary	Response	Related Report Section(s)
14	Midlam-Mohler	Limiting DCTs to smaller vehicles may not be valid; they've been applied to larger trucks, too.	The scope of this report was predicated by the joint, NHTSA and EPA, technology related assumptions that were made for each agencies respective MYs 2017-2025 Fuel Economy/GHG standards. The agencies made the determination that based on current data and technology projections there is a high likelihood that large vehicles with towing requirements may still require the torque multiplication found in automatic transmissions with torque converters. While it is possible that DCTs can be used on larger vehicles the agencies have assumed that a majority of these vehicles will still use automatic transmissions.	
15	Bell	Run several BSFC maps for two cases (i.e., 5 and 6 speeds) to show the range of benefits	Modified report by adding section 6.1.1.1 with one more bsfc map for final report (total: 2 maps).	p83-84
16	Bell	Is vehicle weight impacted by the type of transmission?	The vehicle weight is calculated based on all the other component weights (i.e., clutch, torque converter, gearbox in the case of the transmission). However, due to the small change of the total transmission weight compared to the vehicle weight, the impact on the fuel consumption and performance is not significant.	
17	Bell	Impact of lower firing frequency and vibration levels not addressed in the simulation.	While Noise, Vibration and Harshness (NVH) evaluations and the implementation of subsequent mitigation solutions can impact the effectiveness of technologies, NVH analyses are more appropriate when evaluating specific vehicles. Given that these results are used to inform fleet modeling and thus applied to numerous vehicles, detailed NVH analyses are likely not to improve the accuracy of the results.	
18	Bell	Omitting multi-gear downshifts because they did not occur on the FTP could lead to real world acceptability issues.	Only FTP and HFET drive cycles were simulated for this report because these are the only cycles used for CAFE compliance testing.	

Comment #	Reviewer	Comment summary	Response	Related Report Section(s)
19	Bell	Additional validation test data could have been presented.	The plant models and control strategies used for all the powertrain configurations considered have been validated based on vehicle test data. Detailed information can be found at http://www.autonomie.net/overview/papers_validation.html	

DOT HS 811 667
August 2012

U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

www.nhtsa.gov