

Characterizing Factors Influencing SI Engine Transient Fuel Consumption for Vehicle Simulation in ALPHA

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ABSTRACT

The U.S. Environmental Protection Agency's (EPA's) Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created to estimate greenhouse gas (GHG) emissions from light-duty vehicles. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior, and auditing of all energy flows in the model. In preparation for the midterm evaluation (MTE) of the 2017-2025 light-duty GHG emissions rule, ALPHA has been refined and revalidated using newly acquired data from model year 2013-2016 engines and vehicles.

The robustness of EPA's vehicle and engine testing for the MTE coupled with further validation of the ALPHA model has highlighted some areas where additional data can be used to add fidelity to the engine model within ALPHA. A simple model based only on a steady-state fuel map will yield fuel consumption and GHG emissions lower than what is measured during a chassis dynamometer test due to a variety of factors present during transient operation.

This paper examines a) typical transient engine operation encountered over the EPA city and highway drive cycles, b) EPA's vehicle and engine testing to characterize that transient fuel usage, and c) changes made to ALPHA to better model transient engine operation. Topics examined in this paper include spark retardation for powertrain torque management, an engine power rate based fuel adjustment, additional fueling associated with deceleration fuel cut-off, and cylinder deactivation management.

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INTRODUCTION

Vehicle simulation is an established and effective method to predict a vehicle's fuel economy (FE) and greenhouse gas (GHG) emissions from a specific set of vehicle technologies. Accurate testing and analysis of fuel consumption from currently available vehicle technologies is key to validating the simulation model. Once validated the model can then be used to estimate the potential of various combinations of vehicle technologies to meet future GHG standards [1].

EPA has developed the Advanced Light-duty Powertrain and Hybrid Analysis (ALPHA) tool to inform upcoming GHG standards [2]. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of (1) analyzing various vehicle types combined with different powertrain technologies and (2) evaluating the synergistic effects of the powertrain technologies to FE and GHG. The software tool is a MATLAB/Simulink based application. Recently, ALPHA has been enhanced to capture more realistic vehicle behaviors,

including advanced gear selection and torque converter strategies, driver behavior, tire slip, and other dynamic effects in addition to the engine improvements discussed in this paper [3].

One of the key features in the development approach for ALPHA is the identification and implementation of adjustments for various transient behaviors seen in the powertrain. To properly identify technology effectiveness and synergy, model validation simulations attempt to match not just the overall test fuel economies, but a variety of time series data as well. Observations recorded across the many engine and vehicle test programs in support of the MTE has provided valuable data enabling more robust simulation of engine behavior and rules which incorporate various adjustment factors that can influence fuel economy. One motivation for the implementation of these features and adjustment factors in ALPHA is in response to the observation that vehicle simulation models relying solely on static input maps might tend to under predict fuel consumption and GHG emissions [4, 5, 6, 7, 8]. In reality, engine operation is composed of quasi-steady-state fuel consumption, which may not be fully representative of

the engine's entire fuel consumption. Research indicates a significant difference can occur between vehicle simulations using a steady-state fueling map and experiments over various driving cycles [4]. As might be expected, EPA's experience is that the shortfall in fuel consumption is highly drive cycle dependent, with simulations of the more transient US06 cycle having a greater fuel consumption shortfall than simulations on EPA city/highway cycles. This paper will discuss some of the technical operating conditions that must be considered, and their individual effects on the determination of vehicle fuel economy.

One factor excluded from this study is the simulation of the additional fuel consumption that occurs during engine cold start conditions. Since both engine and transmission efficiency are reduced during cold start, thermal management strategies are employed on the combined powertrain system. Thus it is more appropriate to examine them in that context rather than in an engine centric study. Further information on one of the methods available in ALPHA to adjust simulation results for cold start operation required when simulating certification testing using FTP drive cycles is provided for reference [3].

The approach taken when tuning ALPHA parameters and comparing the results against chassis test data is to match the instantaneous data taken throughout the test with comparable simulation parameters, rather than just matching the cumulative overall test results. For example, ALPHA validations typically compare time dependent, engine torque, speed, and fuel flow along with other powertrain quantities rather than only total cycle fuel consumption. As a result, new technologies, whose effects may be dynamic and sometimes intermittent, can be more appropriately simulated within ALPHA. This provides additional confidence when various technologies are combined to simulate possible future technology packages, to determine the technologies' GHG effectiveness when used on different platforms or in synergy with other technologies.

BENCHMARKING VEHICLES AND ENGINES

To characterize engine transient fueling behavior a variety of vehicles and engines have been studied. This paper will focus on two vehicles; a Chevrolet Silverado with the 4.3/ Ecotec engine, and a Ford F-150 with the 2.7/ EcoBoost engine. Additional details of their specifications are listed in [Table 1](#).

Table 1. Test Vehicle Specifications

Vehicle	2014 Chevrolet Silverado	2015 Ford F-150
Engine	GM Ecotec LV3	Ford EcoBoost
Displacement	4.3 liter	2.7 liter
Induction	Naturally aspirated	Turbocharger boosted
Rated Power	213 kW @ 5300 RPM	242 kW @ 5750 RPM
Rated Torque	413 Nm @ 3900 RPM	508 Nm @ 3000 RPM
Engine Technologies	VVT	Dual VVT
	Cylinder Deactivation	
Transmission	6L80 Automatic	6R80 Automatic
Other Technologies		Start-Stop

The vehicle chassis dynamometer and engine dynamometer benchmark testing for these two vehicles was performed at the National Vehicle Fuels and Emissions Laboratory (NVFEL) in Ann Arbor, Michigan. In separate tests the engines were instrumented, and many powertrain signals were recorded to capture each engine's detailed operating conditions. This data was used to construct steady-state fuel consumption maps for each engine which were used to validate ALPHA. More details about test cell equipment, instrumentation and test methods are available in [9, 10, 11].

Vehicle Testing on Chassis Dynamometer

Chassis dynamometer testing was conducted on both vehicles over the UDDS, HFET and US06 drive cycles. Triplicate tests over each drive cycle were conducted and only warm tests were considered when correlating test results to ALPHA. Inefficiencies (and additional fuel usage) related to cold start operation are influenced by both the engine and transmission. To simplify analysis, they were excluded from this study. Information on how ALPHA implements an adjustment to estimate fuel consumption during cold start conditions is available [3]. The average test results for each cycle are shown in [Table 2](#).

Table 2. Chevrolet Silverado and Ford F-150 Fuel Economy Test Results

Vehicle	Test Cycle	Phase 1 MPG	Phase 2 MPG
Chevrolet Silverado	UDDS Average	22.30	19.66
	HWFET Average	30.47	-
	US06 Average	13.24	21.83
Ford F-150	UDDS Average	25.92	24.10
	HWFET Average	35.77	-
	US06 Average	13.54	24.35

Engine Mapping Using an Engine Dynamometer

Two testing processes were used to map each engine while it was on an engine dynamometer and tethered to its respective vehicle, intending to cover both steady-state and transient operation. During the first engine mapping process, each engine was operated at "steady-state" conditions over a range of speed and load points; more description of this process can be found in [9].

The steady-state operation was designed to gather data used to develop a nonlinear quasi-steady fueling map. The resulting BSFC maps of the GM Ecotec 4.3/ and Ford EcoBoost 2.7/ engines can be seen in [Figures 1](#) and [2](#), respectively. Testing of the GM Ecotec 4.3/ engine was conducted with the cylinder deactivation (CDA) technology both enabled and disabled. The testing also characterized the range of engine speed and torque where operation of cylinder deactivation was possible. Maps were developed for this engine in both modes but only the disabled map is shown below. Additional maps can be found in [9].

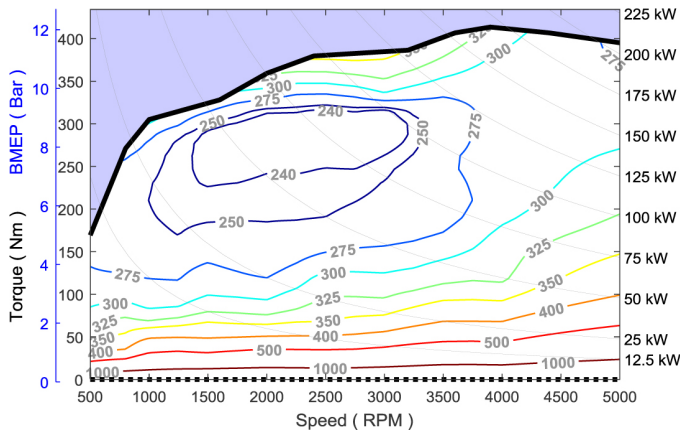


Figure 1. BSFC (g/kW-hr) map of the Silverado 4.3/ Ecotec V6 with cylinder deactivation disabled.

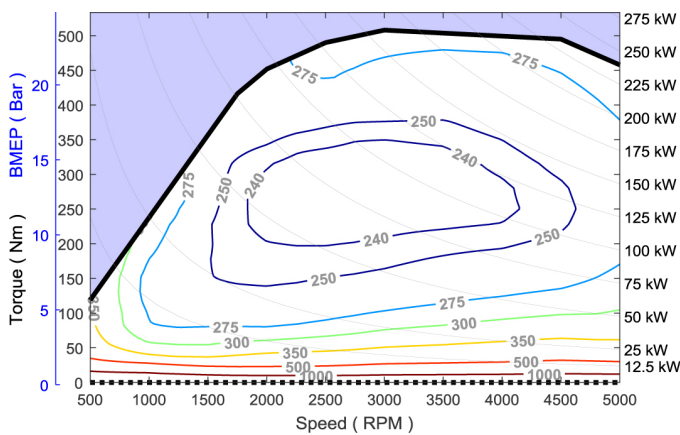


Figure 2. BSFC (g/kW-hr) map of the F-150 2.7/ EcoBoost V6

The resulting steady state maps conducted on these and other engines, along with documentation covering the conversion of the data into a format suitable for simulation within ALPHA are available on the EPA website at: <https://www.epa.gov/regulations-emissions-vehicles-and-engines/advanced-light-duty-powertrain-and-hybrid-analysis-alpha>

Steady-state mapping also provided an opportunity to gather data to calibrate each engine's fuel injection quantity versus injection duration and fuel rail pressure. This calibration could then be used to examine fueling during the transient engine tests or chassis dynamometer drive cycles. A description of this calibration is included in the next section of this paper.

During the second engine mapping process, data from each engine was taken while operating during "ramp-up" conditions. The engine "ramp-up" tests were designed to emulate changes in engine torque seen during transient operation and to capture the inefficiency associated with the transient operation relative to the steady state map.

During the "ramp-up" tests, accelerator pedal position was increased from various starting speed and load points at different rates. The ramp-up test durations ranged from a quasi-steady-state 30 seconds to a near step input of 0.1 seconds. Dyno speed was held constant on most tests to mitigate the effect of the engine's rotational inertia on the torque measurement. After characterizing the rotational inertia of the engine and associated test apparatus, additional testing was

conducted that varied speed as well. A more detailed examination of these data and their application to the engine model is discussed in the transient adjustment section of this paper.

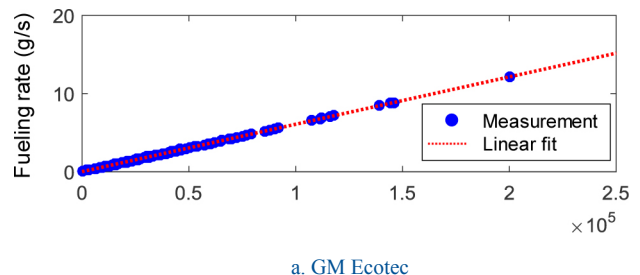
QUANTIFYING FUEL FLOW USING FUEL INJECTION

During steady-state mapping, an engine's fueling rate is usually measured with an external fuel flow meter. This approach works well for totalizing the amount of fuel consumed over steady-state or long-term operation such as that observed during drive cycle operation. However, because of the dynamics of an engine's fuel rail system, the instantaneous amount of fuel measured using the external fuel flow meter may not be the same as the actual amount of fuel injected to cylinders during a specific short time period.

Therefore, another technique was needed to determine the amount of fuel consumed by the engine during a short duration transient event. Using measurements of fuel rail pressure and commanded fuel injection duration from the steady state mapping, the relationship can be accurately characterized for analyzing short duration transient events. In general, the flow through a fuel injector can be modeled as flow through an orifice, so the fuel amount passing through the injector is proportional to the square root of the rail pressure, P_{rail} (as in the classic orifice equation) and the injection duration, Δt_{inj} . The total measured fueling rate for the engine, $\dot{m}_f$, is then proportional to the flow through each injector and the engine speed ω_{eng} . The general proportionality function is shown in equation 1.

$$\dot{m}_f \propto \omega_{eng} \Delta t_{inj} \sqrt{P_{rail}} \quad (1)$$

To determine each engine's proportionality constant, data from the steady-state engine tests for both engines were obtained, and the measured fuel rate from the external flow meter was plotted against $\omega_{eng} \Delta t_{inj} \sqrt{P_{rail}}$. Figure 3 shows the linear fits that were used to determine the proportionality constants for the two engines which were used to compute the estimated actual amount of injected fuel during the duration of specific transient events.



a. GM Ecotec

Figure 3. Linear relation between fueling rate and a nonlinear function of engine speed, injection duration and rail pressure: (a) GM Ecotec engine and (b) Ford EcoBoost engine. Coefficients of the linear functions are identified by using a least square regression.

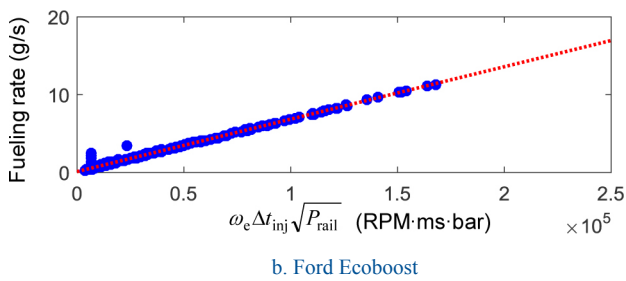


Figure 3. (cont.) Linear relation between fueling rate and a nonlinear function of engine speed, injection duration and rail pressure: (a) GM Ecotec engine and (b) Ford EcoBoost engine. Coefficients of the linear functions are identified by using a least square regression.

DETERMINE FUEL CONSUMPTION ADJUSTMENT FACTORS FOR TYPICAL TRANSIENT EVENTS

An engine operating in either regulatory drive cycle tests or real world driving situations is constrained by many factors such as meeting a driver's demand, satisfying tail-pipe emissions limits, mitigating NVH concerns, and maintaining combustion stability. As stated earlier a quasi-steady-state fuel map is not fully representative of actual engine fuel consumption and becomes increasingly less representative with increasingly aggressive driving. This section describes the implementation of four specific examples of transient fuel consumption adjustments that are built into ALPHA to deal with the individual effects on vehicle fuel consumption for:

- Powertrain torque management
- Changes in engine power (tip-in demand)
- Deceleration fuel cutoff
- Cylinder deactivation transitions

Fuel Adjustments for Powertrain Torque Management

Modern powertrains often involve multiple electronic devices that coordinate activities to provide the driver with a safe and comfortable driving experience. The primary interaction visible over regulatory drive cycles is coordination between the engine and transmission to maintain smooth operation during transmission upshifts. During an upshift, the rotational inertia of the engine, torque converter and other components connected to the transmission input shaft must be decelerated to match the angular velocity of the new gear ratio. This transfers angular momentum through the powertrain providing a momentary acceleration, which can lead to rough shift feel if not mitigated by powertrain torque management.

The engines and transmission can coordinate torque output during shifting to smooth out the bump in torque through changes in spark timing. Figure 4 contains data showing this shift smoothing behavior, as recorded from the Chevrolet Silverado. Fuel flow was calculated using the captured engine torque and speed with the steady-state map ($\dot{m}_{f,ss}$) and using the measured injector timing and calibration ($\dot{m}_{f,cal}$). The two calculations align close enough to provide an indication that the steady-state map in general provides an accurate reflection of fuel flow rate. During transmission upshifts, however, there is a

significant deviation between the two quantities. The measured fuel flow is reasonably consistent through the gear shift while the steady-state map output shows a significant reduction attributable to the reduction in engine torque production. The lower chart in Figure 4 shows the source of the reduction in torque, a retarded spark timing during the shift events, a transient phenomenon that is not reflected in the steady-state engine maps.

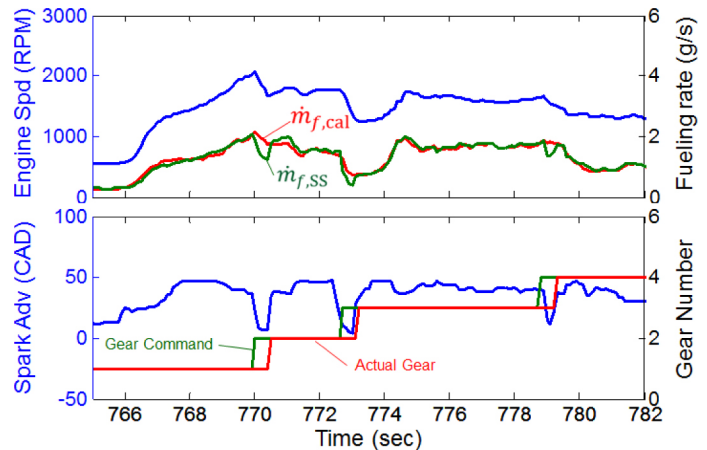


Figure 4. Fueling rates during a series of shift events from the Chevrolet Silverado. The fuel rate $\dot{m}_{f,cal}$ is calculated from measured injector duration using the injection calibration data, and $\dot{m}_{f,ss}$ is calculated using measured engine speed and load on the quasi-steady engine map.

The ALPHA engine model does not simulate engine operation at the spark timing level, but these deviations in timing do have an effect on fuel consumption. To account for the observed behavior during upshifts, a separate torque path was constructed to reduce output torque during these events. For transmission upshifts, the quantity of the torque reduction was calculated from the engine rotational inertia and rate of deceleration. This torque adjustment is applied to the engine output, but the unadjusted torque is used when interpolating the steady-state fuel map. This application is synonymous with the fast path torque used in engine controls, reducing torque by shifting spark timing away from maximum brake torque (MBT).

Engine torque reductions for transmission coordination in ALPHA are activated during transmission upshifts or torque converter lockup. Torque reductions can be disabled or reduced during situations of high driver demand such as a zero to sixty acceleration test when the additional shift harshness may be acceptable.

Currently ALPHA only utilizes this fast path torque for transmission upshifting and torque converter lockup. Other events where short duration rapid torque reduction events may be encountered, such as stability control, could be included as well but are not necessary for most fuel economy simulations.

Fuel Adjustments for Changes in Engine Power

Complete modeling of all interactions and dynamics associated with engine combustion and torque generation would be complex, time and resource intensive, and not practical for EPA's GHG simulation