

A Comparison of Cold-Start Behavior and its Impact on Fuel Economy for Advanced Technology Vehicles

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ABSTRACT

Vehicle operation during cold-start powertrain conditions can have a significant impact on drivability, fuel economy and tailpipe emissions in modern passenger vehicles. As efforts continue to maximize fuel economy in passenger vehicles, considerable engineering resources are being spent in order to reduce the consumption penalties incurred shortly after engine start and during powertrain warmup while maintaining suitably low levels of tailpipe emissions. Engine downsizing, advanced transmissions and hybrid-electric architecture can each have an appreciable effect on cold-start strategy and its impact on fuel economy.

This work seeks to explore the cold-start strategy of several passenger vehicles with different powertrain architectures and to understand the resulting fuel economy impact relative to warm powertrain operation. To this end, four vehicles were chosen with different powertrain architectures. These include a modern conventional vehicle with a 6-speed automatic transmission equipped with a torque converter, a downsized and turbocharged GDI vehicle with a 7-speed dual-clutch transmission, a modern turbo-diesel with a 6-speed dual-clutch transmission, and a gasoline-electric hybrid with a power split transmission. The vehicles were operated on a chassis dynamometer with instrumentation in place to determine real-time fuel consumption and tailpipe emissions while observing powertrain behavior.

The test vehicles were subjected to hot and cold start iterations of the EPA Urban Dynamometer Driving Schedule (UDDS) and US06 drive cycles at 72°F ambient test cell temperature. The vehicles were found to exhibit increased fueling rates, mild changes in shifting behavior, larger levels of tailpipe emissions, and changes to secondary operating strategies such as deceleration fuel cutoff. The duration of cold start behavior varied between the vehicles, and was directly affected by the aggressiveness of the drive cycle. The severity of the cold start penalty was found to vary with vehicle architecture and drive cycle, but was generally smaller for more aggressive vehicle operation. Cold start penalties ranged from a low of 10.5% on the US06 drive cycle to a maximum of 21.8% on the UDDS cycle.

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BACKGROUND

INTRODUCTION

Efforts to maximize fuel economy and minimize emissions have led to significant vehicle optimization efforts throughout the industry. As technology has improved, engineers are forced to turn to increasingly creative places in order to realize further improvements.

One area that still presents opportunity for improvement is vehicle behavior during cold start operating conditions. During the period directly following initial engine start, the powertrain is subjected to increased losses resulting from cold lubricants, tires and engine surfaces. At the same time, emissions-reduction strategies often dictate retarded combustion timing and increased fueling rates to elevate exhaust catalyst temperatures. Both of these effects result in decreased vehicle efficiency and increased fuel consumption.

management of vehicle behavior during this period can help to minimize the fuel economy and emissions penalties associated with cold start operation while providing proper drivability.

In order to investigate recent cold start strategies, several modern vehicles were evaluated on a chassis dynamometer over hot and cold start versions of the EPA UDDS and US06 drive cycles. The test vehicles were chosen to represent diverse powertrain configurations including conventional gasoline, downsized gasoline, turbodiesel, and hybrid-electric architectures.

Chassis dynamometer testing efforts for this research endeavor were undertaken at the Argonne National Laboratory Advanced Powertrain Research Facility in Lemont, IL.

Selected Research Vehicles

Cold start fuel consumption penalties are a difficulty faced by all vehicle architectures, but different configurations can employ varied techniques to minimize these effects. In order to investigate this, a selection of vehicles was chosen to represent some of the modern architectures that make up the current passenger vehicle market.

In order to provide a modern benchmark, a MY2012 Ford Fusion was included in the study. This vehicle is equipped with a 2.5L gasoline-fueled, port-fuel-injected four cylinder engine mated to a 6-speed torque converter automatic transmission.

The second vehicle chosen for the study was a MY2010 Volkswagen Jetta TSI. The TSI is also of conventional architecture, but is equipped with a downsized, turbocharged 1.4L gasoline engine with direct fuel injection. The engine is coupled to a 7-speed dual-clutch transmission.

A MY2009 Volkswagen Jetta TDI was the third vehicle included in the study. The TDI is also a conventional vehicle, incorporating a modern 2.0L four cylinder turbocharged diesel engine with a common-rail fuel system. The transmission is a 6-speed dual-clutch unit.

Finally, a MY2010 Toyota Prius was chosen in order to investigate cold start penalties for hybrid electric vehicles. The Prius is powered by a 1.8L four cylinder gasoline engine utilizing delayed intake valve closure to facilitate Atkinson cycle operation. It is also equipped with a pair of motor/generators and a power split transmission.

Table 1 catalogues the test vehicles and their relevant characteristics. To promote clarity, plots corresponding to each vehicle are color-coded to match the table throughout this paper.

Table 1. Test Vehicle Architecture

2012 Fusion	2010 TSI	2009 TDI	2010 Prius
<i>Conventional</i> 2.5L PFI 6 spd Auto Gasoline	<i>Conventional</i> 1.4L DI Turbo 7 spd DCT Gasoline	<i>Conventional</i> 2.0L DI Turbo 6 spd DCT Diesel	<i>Hybrid Electric</i> 1.8L PFI Power Split 60 kW Primary Motor
			

Test Facilities & Instrumentation

The work discussed in this paper was performed as part of the ongoing APRF effort to benchmark advanced technology vehicles for the U.S. Department of Energy (DOE). Test vehicle purchases are funded by the DOE, and the vehicles are instrumented at the APRF to facilitate proper data collection. The test vehicles included in this study were instrumented to varying degrees, but a basic minimum set of measurements were maintained to facilitate cold start analysis.

Engine speed was measured for each of the vehicles using either vehicle communication bus decoding or physical measurement of the stock engine position sensor suite.

The fuel consumption of the gasoline vehicles was measured directly with an inline positive-displacement fuel meter. In the case of the diesel vehicle, fuel consumption was measured via decoding of the vehicle's communication bus and verified using a carbon balance with measurements facilitated by a Semtech portable emissions measurement device. This alternative method was necessary due to the difficulties of directly measuring fuel consumption quantities in a fuel tank return-based fuel system such as that of the TDI.

Tailpipe emissions were collected for all vehicles using a Sensors, Inc. Semtech portable emissions analyzer in conjunction with an AVL Direct Volume Exhaust measurement device.

All vehicles were operated on a Burke E. Porter 2WD chassis dynamometer providing emulation of chosen cycles while returning signals such as tractive effort and vehicle speed. Each vehicle was evaluated with the hood up with cooling airflow provided by a single speed fan.

Test Plan

Each of the vehicles included in this study were subjected to cold start and hot start iterations of the EPA UDDS and US06 drive cycles. In order to ensure the vehicles were operating without thermal residuals from previous testing, the vehicles were allowed to soak for a minimum of twelve hours in the test cell which was maintained at 72°F before the cold start tests were run.

The UDDS cycle is typically used to represent city driving, and involves relatively low power demands and low vehicle speeds. In order to ensure full vehicle warmup, three consecutive UDDS cycles are provided for each vehicle. In some cases the powertrain fluids are still warming during the second cycle. For this reason, the third iteration of the cycle should be considered representative of the vehicle's behavior at full operating temperature. A single UDDS cycle is pictured in Figure 1 [1].

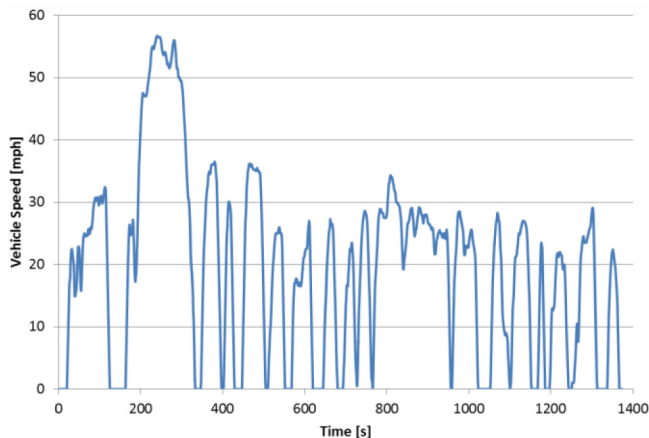


Figure 1. UDDS Driving Schedule

The US06 cycle was chosen for its aggressive acceleration requirements to examine the change in duration of noticeable cold start effects. The US06 was performed in sets of two consecutive cycles. In the cold start case, the first cycle conducted after a twelve hour soak period is of interest. For hot start tests, a set of two cycles is again conducted. In this case, the vehicle starts the first cycle near operating temperature, and the second of the two cycles is considered for analysis. A single US06 cycle is pictured in Figure 2 [1].

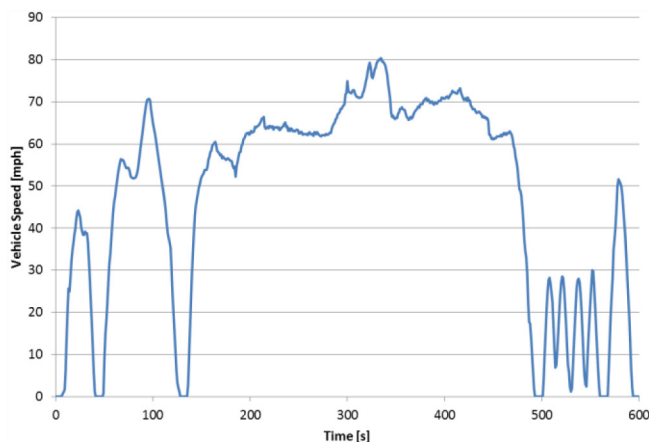


Figure 2. US06 Driving Schedule

TEST RESULTS

Vehicle Behavior

To evaluate cold start behavior and the resulting effects on fuel economy and emissions, each of the test vehicles was operated over hot start and cold start iterations of the UDDS

and US06 drive cycles. The vehicle behavior plots found in this section are repeated at several points for the different test vehicles and drive cycles. To refrain from obscuring the data in the plots, the legends are supplied in Figure 3. These apply to all time series plots. Vehicle speed traces are supplied in grey.



Figure 3. Time Series Plot Legends

MY2012 Ford Fusion

Figure 4 depicts the vehicle operation of the Fusion during the first 350 seconds of the UDDS cycles. The first plot shows the rate at which fuel energy was supplied to the Fusion's engine. It can be seen that the cold start fuel consumption varies significantly from the hot start iterations of the same test. The fuel demand during cold start is significantly higher throughout the first 350 seconds of the cycle. This can be seen clearly during the initial idle period from 0 to 30 seconds, and again during the idle period from 125 to 160 seconds. During the second idle period, idle fuel consumption is increased by 80% with respect to the hot start tests. As the test proceeds, the additional fuel demand for the cold start test decreases until fueling rates converge around 955 seconds. Fuel consumption behavior for the second and third UDDS cycles is very similar, indicating that the cold start effect is largely confined to the first cycle.

Examining the second plot in Figure 4 shows that cold start operation also has an effect on the Fusion's engine speed. This effect is noticeable at idle, where the vehicle exhibits a higher idle engine speed during the first and second idle periods. This strategy may be adopted to help warm the aftertreatment catalyst and engine coolant and oil. When the vehicle is moving, engine speed varies only slightly from the hot start tests. The engine meets the additional cold start power requirements with greater throttle openings, while transmission ratio selection is unchanged.

Figure 5 shows the Fusion's behavior on the US06 hot and cold start cycles. It can again be seen that the vehicle's fuel demand increases during the cold start cycle. This is partly a result of higher idle speed during the first 150 seconds of the test, but it can also be seen that the demand is generally higher during all conditions for the majority of the test. Fuel rates between the hot and cold start tests synchronize around 500 seconds into the test. An additional cold start effect seen here is the reduction of deceleration fuel cutoff. During the cold start test fuel is supplied to the engine during the long deceleration event between 100 and 120 seconds. Conversely, the fueling rate is cut significantly for the hot start cycle.