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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. Careful 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
Conventional 2.5L PFI 6 spd Auto Gasoline	*Conventional* 1.4L DI Turbo 7 spd DCT Gasoline	*Conventional* 2.0L DI Turbo 6 spd DCT Diesel	*Hybrid Electric* 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 conjuncton 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].

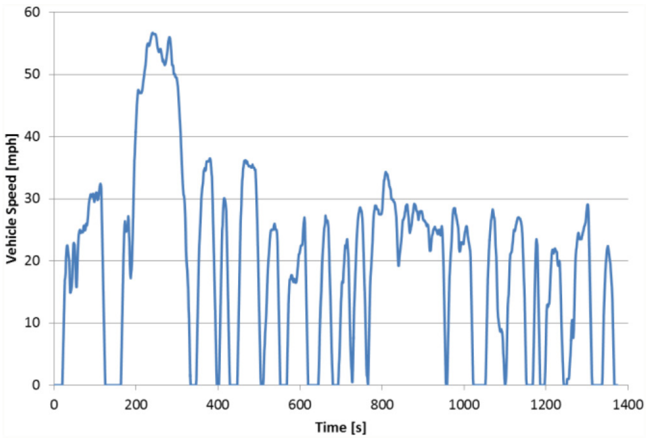

Figure 1. UDDS Driving Schedule

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].

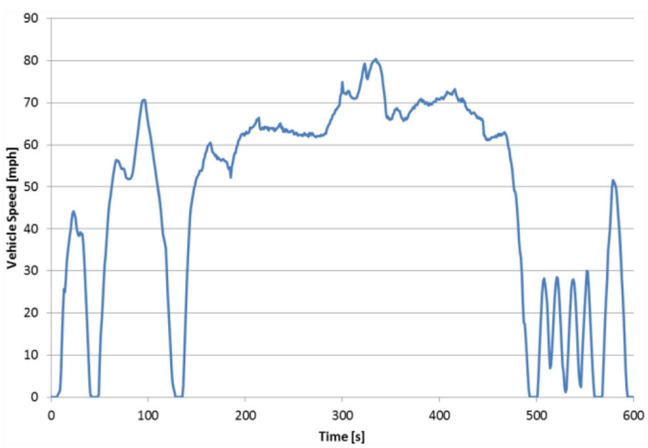

Figure 2. US06 Driving Schedule

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.

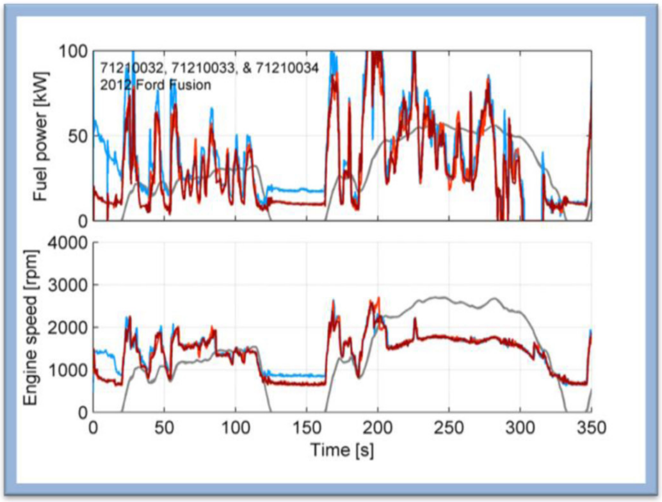

Figure 4. Ford Fusion UDDS Operation

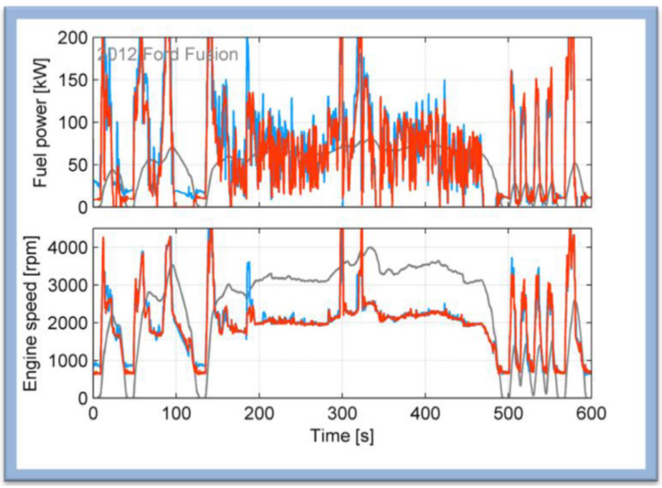

Figure 5. Ford Fusion US06 Operation

The second plot shown in Figure 5 shows the engine speed over the US06 cycles. In general, engine speeds are similar between the two cycles. During the aggressive acceleration event at 180 seconds, a spike in engine speed is evident. It appears as though the vehicle was initiating a change to a lower gear but aborted the maneuver. This was likely caused by driver variation and is not directly related to cold start behavior.

MY2010 Volkswagen Jetta TSI

The vehicle operation of the Jetta TSI over the UDDS cycles is depicted in Figure 6. As was the case with the Fusion, the Jetta exhibits increased fuel consumption during the first 350 seconds of the cold UDDS cycle. During the initial idle period following engine start, the rate at which fuel is consumed is more than eight times the amount required for a hot start test. During the second idle opportunity, this increase has been greatly reduced. Fuel rates synchronize completely around 1025 seconds into the cold start cycle. During cruising conditions, the cold start fuel rate increase is less noticeable than for other vehicles in this study. Engine speed does not change appreciably between the hot and cold start tests with the exception of the initial high idle speed.

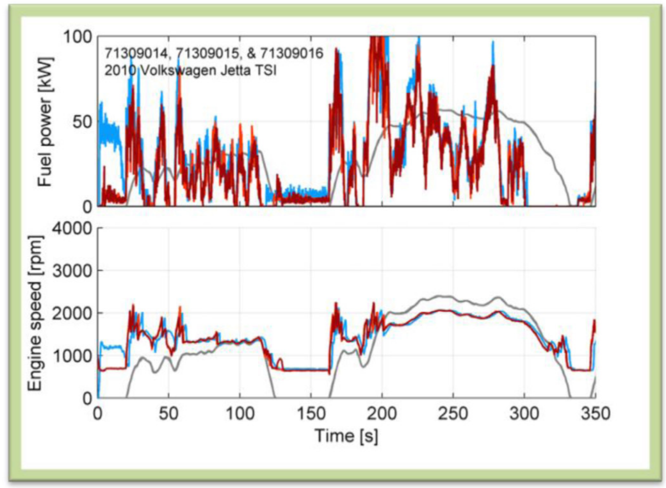

Figure 6. Jetta TSI UDDS Operation

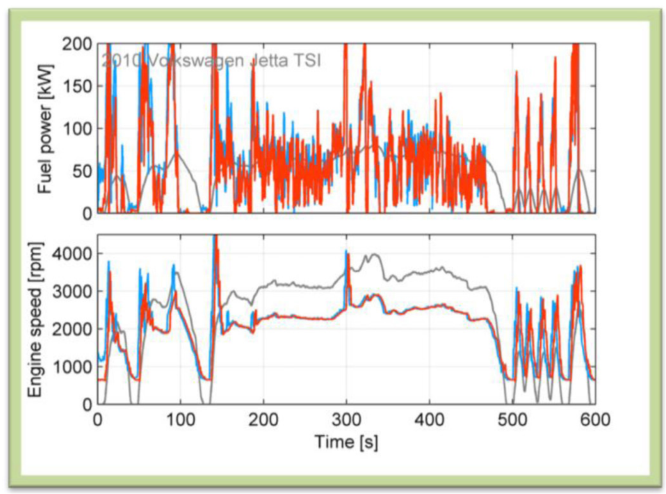

Figure 7. Jetta TSI US06 Operation

The Jetta TSI's operating characteristics over the US06 cycles can be found in Figure 7. As is the case in the UDDS cold start cycle, the US06 cold start cycle shows increased fueling demand. Because there is little idle opportunity during this cycle, this effect is best observed during the acceleration events early in the test. As the vehicle warms, this effect diminishes until the fuel rates synchronize 505 seconds into the drive cycle. Engine speed is very similar between the two cycles during cruise, but it can be seen at the 50 and 90 second marks that the TSI utilizes a lower gear ratio during hard accelerations when cold.

MY2009 Volkswagen Jetta TDI

The Jetta TDI was subjected to the same set of three UDDS cycles as the other test vehicles in order to investigate its cold start behavior. Figure 8 depicts the rate of fuel consumption and engine speed for the vehicle.

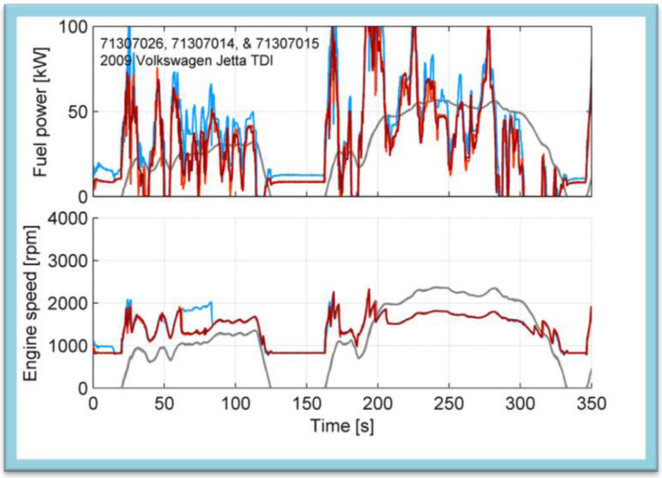

Figure 8. Jetta TDI UDDS Operation

It can be seen in Figure 8 that the Jetta TDI exhibits a larger fueling demand during the early parts of the cold start UDDS cycle. The magnitude of the increase during cruising conditions is especially significant for this vehicle. Though fueling rates during the idle period directly following engine start are also larger during cold start conditions, the increase is smaller than that seen for the gasoline fueled vehicles. Larger fueling rates persist at noticeable magnitudes for the first 1020 seconds of the UDDS test. The increased fuel flow may be used to bring the exhaust aftertreatment system up to operating temperature.

Engine speed behavior for the TDI is similar during cold and hot start tests, with the exception of one interesting phenomenon. Observation of the engine speed graph at the 60 second mark shows that during the cold start test, the Jetta TDI holds a lower transmission gear for an additional twelve seconds before upshifting. This phenomenon can be seen several times during the first third of the cold start UDDS cycle. It is the opinion of the authors that this strategy may be adopted to minimize engine speed and load transients that can contribute to increased emissions levels.

Figure 9 shows the TDI's behavior over the more aggressive US06 cycles. Here the fueling demand increases again for the cold start cycle, but the duration of the effect is considerably shorter. Fuel rates synchronize around 460 seconds into the cycle. The first two acceleration events in the cycle show higher peak engine speeds for the cold start test as the TDI upshifts later in the engine speed range than when at full operating temperature. During accelerations taking place later in the cycle no change is noticeable. This is likely due both to the relatively quick warming behavior as well as the robust torque curve provided by the turbodiesel engine.

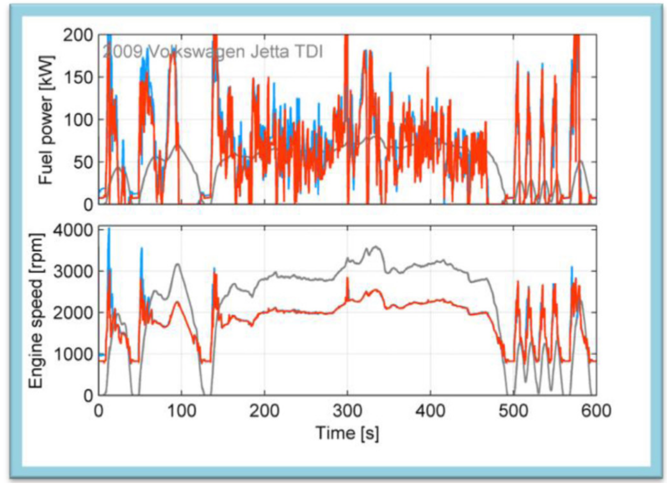

Figure 9. Jetta TDI US06 Operation

MY2010 Toyota Prius

The 2010 Prius was chosen to participate in this comparative study because of its hybrid architecture. The hybrid system provides the Prius with the ability to operate the engine independently of the wheels at low speed, adding an additional degree of freedom to the vehicle's warmup strategy.

Figure 10 depicts the Prius' fuel flow requirements and engine speed over three UDDS cycles, in addition to the power provided by the high voltage battery pack. It should be noted that the convention for this signal is such that positive values denote energy leaving the battery, while negative values represent battery charging.

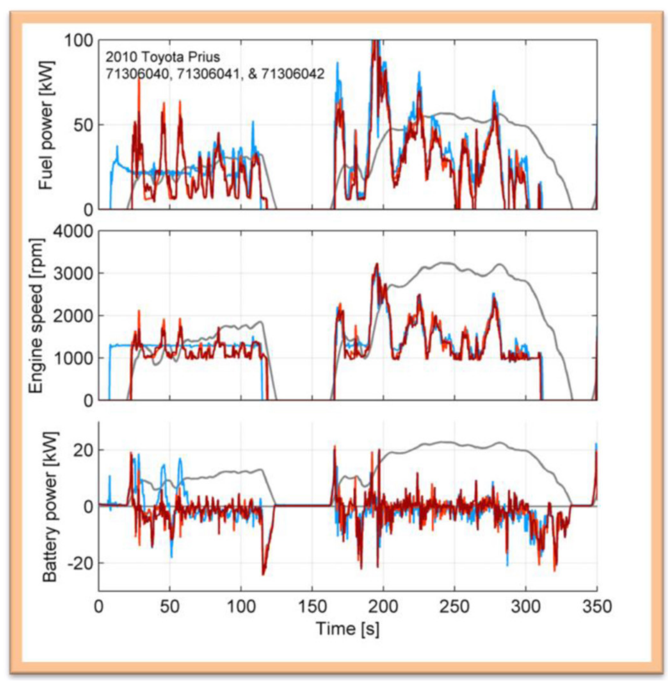

Figure 10. Toyota Prius UDDS Operation

Several interesting behaviors can be found in Figure 10 that set the Prius HEV apart from the conventional vehicles featured in this paper. During the first 'hill' of the UDDS cycle (the driving period between 20 and 120 seconds), the vehicle operates its gasoline engine at a fixed speed. For the first 60 seconds of operation, the rate of fuel consumption is held very steady, and the tractive effort demands of the vehicle are met by spikes in positive battery power that correspond to the acceleration events. Operating the gasoline engine independently of the wheels allows the Prius to maintain steady control of engine speed and torque, minimizing transients that can contribute to increased emissions levels and optimizing operation to warm the catalysts as quickly as possible.

During the deceleration event at the end of the first 'hill', the engine cycles off for all three of the UDDS cycles. The fuel required during the second hill of the cold start UDDS cycle is greater than that required for the latter two cycles. This is due to a combination of increased frictional losses due to cold start conditions as well as a need to recharge the high voltage battery pack to replenish the energy used to generate motive force during the initial warmup cycle. During the cold start cycle, the Prius also exhibits eight additional engine start events not found during the second and third cycles. This change in motive power strategy is again partly due to the need to replenish battery energy depleted during the initial warming period. Though the specialized cold start engine operating strategy is finished roughly 60 seconds into the test, the Prius' fueling rates for the cold and hot start iterations do not fully converge until almost 1300 seconds into the cold start cycle.

Figure 11 depicts the Prius' operation on the more aggressive US06 cycle. Because of the more aggressive tractive effort demands, the Prius is unable to provide the required acceleration while utilizing the electric powertrain alone and must also employ the gasoline engine during the first acceleration events in the cycle. When acceleration demands lessen, the Prius reverts to the same warmup strategy seen in the UDDS cold start cycle.

The extra battery energy depleted during this time is replenished later in the cycle. This is visible as increased negative battery power throughout much of the middle section of the test caused by more aggressive regenerative braking. The engine is also fueled during the deceleration events at 510 and 520 seconds into the cold start US06 test. The increased negative battery power during this time shows that the engine is actively charging the battery pack.

Though the Prius employs noticeably greater regenerative braking throughout the cold start US06 cycle, the majority of this behavior is not directly attributable to cold start behavior. Due to the aggressive nature of this test, the temperature of the Prius' high voltage battery pack increases significantly. Once the pack temperature is elevated, the vehicle manages the heat load in part by limiting the available battery power.

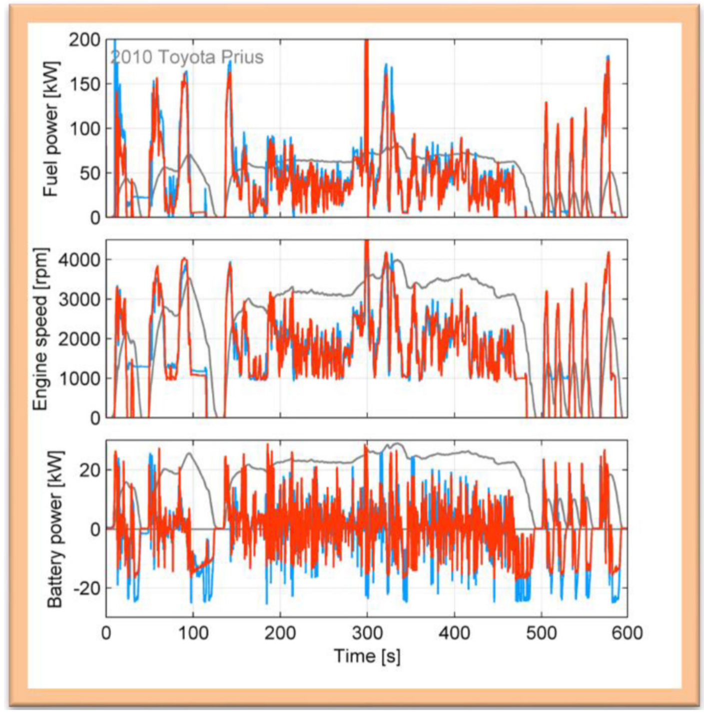

Figure 11. Toyota Prius US06 Operation

Duration of Cold Start Behavior

As shown in the previous section, the duration of noticeable cold start behavior differs for each of the test vehicles. Cold start duration can be defined in several ways depending on whether fuel consumption, emissions behavior, or operational strategy is of particular interest. For the purposes of this study, we define cold start duration as the period of time during which deviation in engine fueling behavior is evident. Figure 12 catalogues the duration results of the UDDS and US06 cycles for each test vehicle.

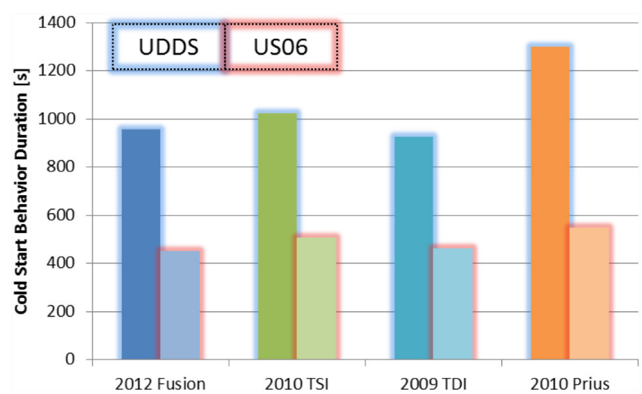

Figure 12. Cold Start Behavior Duration

Examining Figure 12 shows that the duration of noticeable cold start effects is shorter for the conventional vehicles in this study. Effect duration for the conventional vehicles is relatively similar, falling between 924 and 1023 seconds for the UDDS cycle and between 450 and 505 seconds for the US06 cycle. Cold start effects are visible for a greater time period for the Prius, largely because of the additional time used to recapture battery energy spent during the beginning of the cold start tests. In the case of the UDDS cold start cycle, the effect duration shown by the Prius is 275 seconds longer than that shown by the Jetta TSI.

The relative vehicle to vehicle effect durations are consistent for both cycles; for example, the TDI exhibits the shortest effect duration for both the UDDS and US06 cycles. The effect duration for the US06 cycles is on average 53% shorter than that found on the urban cycle for the four vehicles, indicating that cycle aggressiveness is a significant factor determining the length of the cold start effect. The Prius exhibits the greatest change in cold start effect duration between the two cycles, largely due to the significant opportunity for engine-off operation during the UDDS cycle.

Cold Start Emissions Behavior

Curtailing tailpipe emissions of oxides of nitrogen (NOx) and total hydrocarbons (THC) during cold start conditions is an important goal that is in part responsible for general cold start drive cycle behavior. The normalized NOx emissions of the four vehicles during the cold start UDDS cycle are displayed in Figure 13. Figure 14 shows THC behavior for the same cycle. All values are normalized using the maximum modal generation rate for each vehicle.

It was found that the most significant emissions of NOx and THC occur during the initial 100 seconds after engine start for the gasoline powered vehicles. The Prius generates its peak emissions rates slightly later in the cycle than the Fusion and TSI; this is because the Prius starts its engine several seconds later during the cycle. After the first 100 second period, the gasoline vehicles' aftertreatment catalysts have reached operating temperature and tailpipe emissions levels are drastically reduced.

The Prius produces two additional noticeable NOx emissions beginning 300 seconds into the test, both spurred by transient acceleration events. The second, more significant event occurs after a long engine-off deceleration which may have resulted in a catalyst temperature drop. The same behavior is not present in the hot start test.

The Jetta TSI was found to exhibit noticeable hydrocarbon emissions on the second hill. This behavior is also present during hot start conditions.

With the exception of these events, emissions for the gasoline-powered vehicles are extremely low after the initial catalyst heating period.

The diesel-powered Jetta TDI exhibits markedly different emissions behavior than that seen for the gasoline vehicles. The TDI generates its highest rate of NOx and THC formation during the second hill of the UDDS cycle. This may indicate that the diesel's aftertreatment equipment takes longer to reach operating temperature. Though the vehicle's highest levels of NOx and THC are found during the second hill, it also exhibits significant levels of these pollutants shortly after initial engine start.

While the gasoline powered vehicles emissions after the intial part of the cycle are largely negligible, the TDI continues to produce measurable levels of THC, usually caused during transient engine speed operation such as downshifts.

For all vehicles, the large emissions rates found early in the cold start UDDS cycle are largely absent when the same test is performed under hot start conditions. Emissions behavior on the cold and hot start US06 cycles shows similar trends, with greater overall emissions levels due to the aggressive nature of US06 operation.

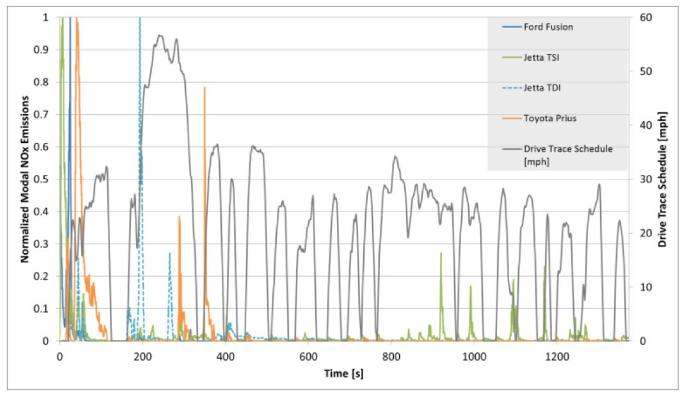

Figure 13. Modal NOx Emissions, Cold Start UDDS Cycle

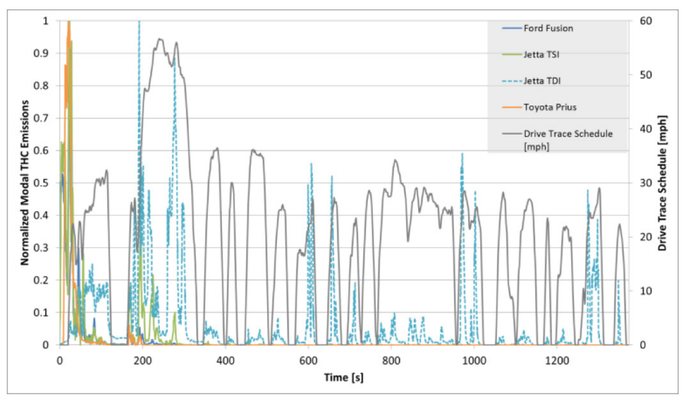

Figure 14. Modal THC Emissions, Cold Start UDDS Cycle

Cold Start Fuel Consumption Penalty

The end result of the operational changes exhibited during cold start conditions is a measurable fuel consumption penalty for each vehicle. The fuel consumption results for the test vehicles are shown in Table 2.

Table 2. Fuel Economy Results

		2012 Fusion	2010 Jetta TSI	2009 Jetta TDI	2010 Prius
UDDS CS	[mpg]	23.9	35.4	32.5	59.2
UDDS #2	[mpg]	26.4	39.0	36.8	70.2
UDDS #3	[mpg]	26.5	39.0	36.8	72.0
US06 CS	[mpg]	23.6	28.2	31.9	38.8
US06 HS	[mpg]	26.1	31.6	35.5	43.7

Though the fuel consumption performance of the test vehicles varies widely, it can be seen that each vehicle consumes additional fuel on the cold start iteration of both the UDDS and US06 drive cycles. In the case of the UDDS cycle, the Fusion and Prius each perform slightly better on the third iteration of the test, suggesting that some small remainder of the cold start effect carries over to the second cycle. The difference in consumption between the second and third cycle is on the order of 0.3% to 2.5%, and may be due to still warming driveline lubricants and tires.

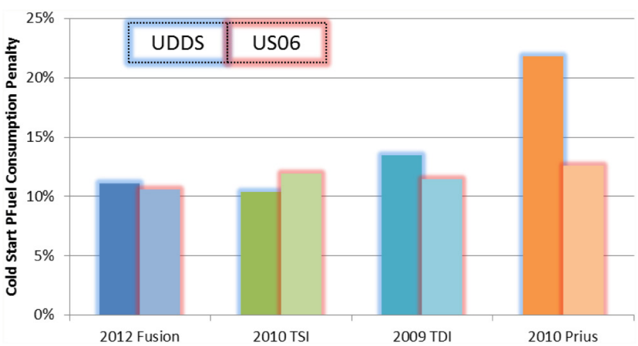

Figure 15. Cold Start Fuel Consumption Penalty

Figure 15 shows the fuel consumption penalty associated with cold start operation for each of the test vehicles. It should be noted that the UDDS penalty is expressed with respect to the observed fuel consumption on the third iteration of the UDDS cycle.

The four test vehicles consumed an average of 11.6% additional fuel on the US06 cold start cycle, with consumption penalties ranging from 10.5 to 12.5%. The aggressive nature of this cycle forces each vehicle to expend large amounts of fuel energy, rapidly heating the powertrains and exhaust aftertreatment systems. In all cases except that of the TSI, the consumption penalty is smaller for the US06 cycle than for the UDDS cycle.

On the UDDS cycles, the vehicles exhibited a wider variance in consumption penalties. In the case of the conventional vehicles, between 10.4% and 13.4% additional fuel was consumed during the cold start cycle. These penalties are very close to the behavior observed for these vehicles over the US06 cycles.

A 1994 paper submitted to SAE investigated a large selection of cold and hot start data to illustrate the cold start fuel consumption penalty over the urban cycle for passenger vehicles and light trucks. The authors found a strong correlation between cold and hot start fuel economy, and found the cold start penalty to be on the order of 6-7% on the UDDS cycle [2]. This figure is smaller than the penalties exhibited by the conventional vehicles in this work. The larger cold start penalty of modern vehicles is most likely due to more aggressive emissions control strategies and better optimized hot start fuel economy.

Among the vehicles in this study, the Toyota Prius showed the most significant UDDS cold start penalty, consuming 21.8% more fuel under cold start conditions. It is shown in Figure 10 that during the 60-second period following initial engine start, the Prius does not increase fuel energy to the engine to charge its battery pack. Instead, all fuel energy spent during these conditions serves only to warm the engine and emissions system. In the hot start cycle no fuel is consumed at this point. Though the duration of this effect is short, it represents a significant additional fuel demand when compared to the hot start cycle. This strategy, in conjunction with the need to recharge the battery later in the cycle, gives rise to the Prius' relatively large UDDS cold start consumption penalty.

The Jetta TSI is unique in that it is the only vehicle in the test to show a more significant fuel consumption penalty for the UDDS cycle than for the US06 cycle. It is worth noting that the rated power of the TSI's engine is a relatively low 90 kW. The vehicle's small displacement turbocharged engine is forced to operate under high load more often than its larger counterpart in the Fusion, helping to reduce throttling losses and improve efficiency. In the case of the cold start US06 cycle, the TSI's engine is sometimes loaded heavily enough to be forced to retard spark timing and richen the fuel mixture, sacrificing efficiency to produce adequate power. Under these conditions, this engine design performs less economically.

SUMMARY

Four advanced technology vehicles of different architectures were tested on a vehicle chassis dynamometer at 72°F ambient temperature to determine the effects of cold start operation on vehicle behavior, fuel consumption, and tailpipe emissions.

It was found that each vehicle behaves differently when operated in cold start conditions. The vehicles exhibited increased fueling rates, mild changes in shifting behavior, increased levels of tailpipe emissions, and changes to secondary operating strategies such as deceleration fuel cutoff. The duration of cold start behavior was found to vary between the vehicles, and was directly affected by the aggressiveness of the cycle over which the vehicle was operated.

Cold start conditions resulted in significantly elevated rates of NOx and THC production early in the cycle for all vehicles. Once the vehicles begin to warm up and the aftertreatment systems reach operating temperature, emissions levels are very similar to hot start conditions for a given cycle.

The severity of the cold start penalty was found to be a function of vehicle architecture. In the majority of cases, the consumption penalty is less for more aggressive operation. Cold start penalties ranged from a low of 10.5% on the US06 drive cycle to 21.8% on the UDDS cycle. These penalties are a direct result of the changes in operating behavior observed early during the cold start cycles.

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Definitions/Abbreviations

APRF - Advanced Powertrain Research Facility

NOx - Oxides of Nitrogen

THC - Total Hydrocarbons