Improving Transient Torque Response for Boosted Engines with VCT and EGR

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Abstract

Modern gasoline engines have increased part-load fuel economy and specific power output through technologies such as downsizing, turbocharging, direct injection, and exhaust gas recirculation. These engines tend to have higher sensitivity to driving behavior because of the steady-state efficiency versus output characteristics (e.g., sweet spot at lower output) and the dynamic response characteristics (e.g., turbo lag). It has been observed that the technologies aimed at increased engine efficiency may improve fuel economy for less aggressive cycles and drivers while hurting fuel economy for more aggressive cycles and drivers. The higher degrees of freedom in these engines and the increased sensitivity make controls and calibration more complex and more important at the same time. The interactions between the dynamic response characteristics of the powertrain and the driver in mind, a dynamic control strategy for variable cam timing (VCT) and exhaust gas recirculation (EGR) is developed. The strategy allows actuator positions at steady-state optimal values when possible yet a fast response proportional to the driver request in transients. The aim is to strike a balance, which is tunable, between steady state efficiency and transient response. Most of the calibration process is algorithmic and based on standard engine mapping data. Experimental results for fuel economy on drive cycles and performance testing from powertrain and chassis dynamometers for two powertrain configurations are reported. Analysis shows improvements in terms of fuel economy and driver demand tracking on drive cycles as well as improved performance metrics. In particular, it is demonstrated that it is possible to simultaneously improve transient performance and fuel economy.

Introduction

New technologies are constantly being introduced for gasoline engines to improve fuel economy while satisfying increasingly stringent emissions requirements and maintaining or increasing peak power. Common today are variable cam timing (VCT) [1] as well as downsizing, boosting, and direct-injection [2]. Other promising technologies are low-pressure (LP) and high-pressure (HP) cooled exhaust gas recirculation (EGR) [3].

It has been observed that technologies, such as those mentioned above, which are aimed at increased engine efficiency sometimes improve fuel economy in steady-state and highway cycles while hurting fuel economy on more aggressive cycles, such as the US06 [4]. One contributor that has been identified is the interaction between the engine response and the driver. For a slow responding powertrain, a typical situation is a tip-in where the driver initially falls behind the desired acceleration and subsequently overcompensates, which leads to different and less efficient load-speed operation of the engine than if the initial request had been more closely followed. This is a potential issue for significantly downsized and boosted engines (with 20–25 bar BMEP). Boost builds slowly at first but then at an accelerating rate due to the positive feedback loop in which higher load and exhaust flow leads to more boost.

Processes and methods for modern high-degree of freedom engines have been proposed for determination of optimal actuator settings and their online implementation [5,6]. For naturally aspirated engines, scheduling the VCT for best fuel economy can be done without much consideration for transient performance because the charge density upstream of the throttle is constant and known and the cam actuators are relatively fast. For boosted engines, however, the conditions upstream of the throttle are significantly different at steady state than they are during a transient. During tip-in transients, only part of the load is delivered rapidly by opening the throttle while the rest relies on slower boost build-up [7,8]. Introducing external EGR has the potential of additional fuel efficiency improvements, but also leads to further increased lag and reduced response time [9]. There are thus opportunities to improve the transient torque response through actuator coordination that considers the air-path dynamics. Specifically, in this paper, a new method for dynamically scheduling VCT, EGR, and boost is developed to meet driver demand without compromising fuel economy. Experimental results show that it is possible, up to a point, to improve transient performance and fuel economy simultaneously.

Advanced centralized model-predictive air-path controllers have been proposed in literature (see, e.g., [10,11,12]) but have prohibitive computational complexity and are often difficult to calibrate for operation under the wide range of real-world operating conditions. The proposed scheduling method is aimed for current production air-path control systems, which are typically decentralized where VCT is controlled in a feed-forward way with respect to operating conditions and load demand. The existing, map-based, control system is seamlessly extended with a dynamic scheduling during transients that schedules VCT and EGR to deliver load when throttle authority is lost and while boost is being built. Moreover, the calibration is automated and based on standard engine mapping data.

The paper is organized as follows. The design, function, and calibration of the dynamic control strategy are first described. The experiments are then described and the results are discussed before concluding the work.
Dynamic Scheduling Method

The intended functionality of the dynamic scheduling method for VCT and EGR is to deliver the desired load during transients, while boost is being built, by modifying HP-EGR and VCT without compromising fuel economy. A central idea is scheduling in proportion to the shortfall ratio between driver demand and engine capability. This mechanism improves transient load delivery without compromising fuel economy by altering the schedule by the amount necessary to meet the demand and reducing the need for reserves (in volumetric efficiency and boost pressure) into the steady state scheduling points.

A flow chart for the dynamic scheduling method is shown in Figure 1. Below, key terms are first summarized and then elaborated upon in a detailed description of the concept.

Core Parameters

Key terms in the Dynamic Scheduling concept are the following.

SSM – The steady state scheduling mode for VCT and EGR that would be used at current conditions if not in a transient.

TRM – The new transient scheduling mode that is used for delivering desired load in transients.

LSR – Load shortfall ratio, ratio of load request and what can be delivered in SSM with open throttle (OT) and no EGR. The request (numerator) comes from the driver demand. The capability (denominator) is calculated by re-using the available charge models in the engine management system. See Eq. (1) below.

SSM is the nominal schedule for VCT and EGR that is typically obtained by steady-state engine mapping with the purpose of finding the best fuel economy with constraints on combustion stability and emissions. This is typically also the best mode for mild driving. During a tip-in transient where the driver asks for increased load, the demand can be satisfied quickly if it does not exceed the throttle authority. In addition, if the increase in demand is not too fast, the turbocharger can fulfill it. In other words, if opening the throttle is enough there is no immediate need to do anything else. On the other hand, if the throttle authority is exhausted, there is an opportunity to move air-path actuators such as for VCT and EGR that are faster than the turbocharger. This is where the new transient mode, TRM, is enabled. When TRM is enabled, it is crucial to coordinate with the boosting system so that the mode is returned to SSM quickly and smoothly as to maximize fuel economy without inducing any drivability concerns.

The LSR is defined as the ratio

\[ \text{LSR} = \frac{\text{driver request}}{\text{capability @ (SSM, OT, No HP-EGR)}} \]  

between the driver requested load and what can be delivered in SSM with open throttle and no HP-EGR (LP-EGR at current value). For example, if this ratio is 1 that indicates that the authority of the fast throttle is exhausted and any additional request will require boost to build, which is a slower process. The driver requested load comes from translating the accelerator pedal input into a requested load. The capability comes from evaluating a charge model (available in the engine management system) with OT and no HP-EGR.

By anticipating the future value of LSR the responsiveness is further improved. The anticipated LSR (aLSR) can be obtained in various ways, e.g., with aid of preview information or simply a lead filter. Here, a lead filter is used

\[ X(k) = (1 - f) * X(k - 1) + f * \text{LSR}(k) \]

\[ a\text{LSR}(k) = (1 - r) * X(k) + r * \text{LSR}(k) \]

where \( k \) is time index, \( X(k) \) is an auxiliary variable, and \((f, r)\) are appropriately chosen parameters. The aggressiveness of the anticipation tunes how aggressively the actuators are scheduled to move away from the steady-state optimal values. Tuning the anticipation therefore balances between steady-state efficiency and transient performance.

Scheduling

The scheduling proceeds in the following manner (see also Figure 1). First, the fraction of HP-EGR is limited by \( (1 - \text{aLSR}) \). Thus, from Eq. (1), HP-EGR is limited just enough to deliver the request in SSM with OT (because the HP-EGR rate will proportionally reduce the load capability). Note that the scheduling only computes a clip for HP-EGR and that the desired rate may be less than \( (1 - \text{aLSR}) \). If the clip is not enough, i.e., if \( \text{aLSR} \) still exceeds a threshold (typically 1) then TRM is enabled. In TRM, the VCT is scheduled to increase the volumetric efficiency in proportion to \( \text{aLSR} \) (normally to precisely offset the shortfall). Note that with a threshold of 1 or larger, desired HP-EGR will be zero in TRM.

These actions will limit HP-EGR and move VCT just as far as is necessary to satisfy the driver demand, which avoids unnecessarily
aggressive and potentially fuel inefficient actions by the driver or the control system. The need for buffers in delivery capability associated with fuel economy penalties is also reduced. Moreover, while in TRM, coordination with the boost system is important. Specifically, the desired boost is not scheduled for the higher volumetric efficiency VCT but rather for the lower volumetric efficiency VCT corresponding to SSM (the same applies to HP-EGR). This action directs the boosting system to target the level necessary to sustain the SSM schedule thereby providing a fast and smooth transition out of TRM back to SSM. This would typically imply that the wastegate is more closed than if controlled based on the actual VCT positions and EGR levels during the transient.

**Calibration Process**

The central calibration item is the function for scheduling VCT in response to a given load shortfall ratio. The calibration process is analytical and based on the data obtained during standard engine mapping. In essence, the required VCT position to offset a given shortfall is calculated based on the mapping data. Other calibration parameters, such as thresholds, are obtained by post-processing data.

**Test Results**

The concept has been implemented for several powertrain configurations and tested in simulation, on the road, in powertrain dynamometer, and in chassis dynamometers at sea level and at altitude. Compared to the baselines, the results typically show better fuel economy with transient performance improvements with no effects on emissions. To illustrate the results, samples of the data sets are discussed in this section.

**Experimental Setup**

The results reported here come from two vehicles equipped with, respectively, a 2.0L GTDI (gasoline turbocharged direct-injection) I4 and a 2.7L GTDI V6. These tests are performed in powertrain dynamometer and chassis dynamometers at sea level and at altitude. Compared to the baselines, the results typically show better fuel economy with transient performance improvements with no effects on emissions. To illustrate the results, samples of the data sets are discussed in this section.

**Fuel Economy and Demand Tracking**

The fuel economy (FE) is calculated from PCM (powertrain control module) estimates of fuel flow and vehicle speed. The demand tracking is quantified by the root mean-square error (RMSE) between desired and actual engine load (normalized air charge).

FE and tracking error for the drive cycles are shown in Figure 2 through Figure 4. All values are offset with the average for the baseline for the respective cycle as to present the change (Δ) in FE and tracking error. Improvements relative to the baseline are indicated if Δ for FE is positive (an increase) and if Δ for tracking error is negative (a decrease). 95% confidence intervals for the average values are computed using the normal approximation.

For LA4 (bag 2–3), HWFET (bag 4), and US06 (bag 5) average FE and tracking error are both improved with Dynamic Scheduling without anticipation compared to baseline. FE increased 0.3–0.6% and tracking error reduced 3.5–8.0%. For US06, which is the most aggressive cycle, Dynamic Scheduling was also evaluated with anticipation (through lead filtering). With anticipation, tracking error on US06 is reduced even further. The average FE also improves but the benefit is roughly halved with the lead filter compared to without. This is likely a price paid for the further improvements of tracking the desired load through more responsive scheduling with the lead filter. As can be expected, the Dynamic Scheduling has a larger effect on US06 than the milder cycles LA4 and HWFET.
Dynamic Scheduling compared to baseline (FE increase and tracking error decrease).

![Graph](image)

Figure 4. US06 FE (top plot) and load tracking RMSE (bottom plot) for baseline (Base), Dynamic Scheduling (Dyn), and Dynamic Scheduling with anticipation (Dyn w/ lead) (2.0L GTDI). Error bars show 95% confidence intervals. The metrics improve with Dynamic Scheduling without anticipation compared to baseline (fuel economy increase and tracking error decrease). With lead, the tracking error is further decreased while the average FE improvement relative to baseline diminishes.

Statistics for the differences in FE and tracking error for the drive cycles are estimated by assuming independent samples and applying the normal approximation. The results, in terms of average and 95% confidence intervals are shown in Figure 5. Without anticipation, the confidence level for significant FE improvements are high for HWFET (94%) and US06 (96%) and less for LA4 (85%). On US06 with anticipation, the average indicates an improvement with low confidence. The load tracking improvements for all cases are significant above 95%.

![Graph](image)

Figure 5. Statistics for the differences on the drive cycles comparing Dynamic Scheduling with baseline (2.0L GTDI). Anticipation is not enabled in the Dynamic Scheduling except for one case (US06, lead). The change in FE is plotted versus the change in load tracking error with 95% confidence intervals. The average values are all contained in the second quadrant, which means improvements in both metrics. The results for US06, comparing baseline and Dynamic Scheduling without anticipation, are significant at 95% confidence level.

**Performance and Driveability**

The Ford internal metrics for performance and driveability were similar or improved with the Dynamic Scheduling method compared to the baselines. A few illustrative examples are shown here to demonstrate the effect on the transient engine response.

A comparison for a pedal crowd from steady driving with the 2.0L GTDI engine is shown in Figure 6. This test was performed in powertrain dynamometer. The load response is improved by an earlier VCT movement with Dynamic Scheduling, which recognizes the load shortfall. The anticipation provided by the lead filter almost completely removes the flat spot around 0.9s.

![Graph](image)

Figure 6. Comparison of engine load response during pedal crowd from steady driving (2.0L GTDI). Dynamic Scheduling with lead filter (solid lines) and without (dotted lines) are compared with baseline (dashed lines). The pedal, driving the load demand, is practically the same for all three cases but the response is improved with Dynamic Scheduling by recognizing the load shortfall and moving the VCT earlier than the baseline. With anticipation, the VCT movement is more aggressive and the load tracking improves further.

Figure 7 shows a comparison for a pedal crowd from steady driving with the 2.7L GTDI engine performed on a test track. The clip on desired EGR (in proportion to the load shortfall ratio) leads to about 300ms earlier reduction in EGR rate. Dynamic Scheduling also gives a slight overdrive of the intake cam timing. The result is better load tracking compared to the baseline.
Figure 7. Comparison of engine load response during pedal crowd from steady driving (2.7L GTDI). Dynamic Scheduling (solid lines) is compared with baseline (dashed lines). Dynamic Scheduling gives earlier reduction in desired EGR rate and an intake cam overdrive, which gives better load tracking.

Time to torque tests with prescribed pedal ramp rates were performed with transmission locked in gear and the chassis dynamometer in speed control mode. The torque responses with the 2.7L GTDI engine, based on measured dynamometer torque, are shown in Figure 8. For the first 0.6s there are small improvements without the lead filter and noticeable improvements with the lead filter.

A driving idea behind Dynamic Scheduling was that improving transient response might lead to fuel economy improvements on aggressive drive cycles for modern downsized engines because of interactions with the driver if demand is not delivered. Tests tend to show fuel economy improvements and with similar or improved response rate metrics. Test results are reported here from two GTDI powertrain configurations.

Drive cycle tests were performed in a highly repeatable powertrain dynamometer with robot driver. The results on bag 2–5 show fuel economy improvements of 0.3–0.6% for the 2.0L GTDI powertrain with Dynamic Scheduling compared to the baseline. The larger effects are obtained on the most aggressive US06 (bag 5) cycle. It should be noted that changes in fuel economy on the order observed, less than 1%, are relatively small compared to test uncertainties and are challenging to determine accurately. For the tests performed statistical significant (above 94%) FE improvements were achieved on US06 and HWFET. Load tracking RMSE was reduced (with statistical significance at 95%) on all drive cycles. The lower load tracking errors indicate better drivability in terms of following the driver demand.

The transient response is further improved through anticipation, which was implemented by a lead filter. With lead action, the load shortfall is anticipated and Dynamic Scheduling is more aggressive. Results on US06 with the 2.0L GTDI powertrain showed that response and tracking could be improved at the expense of the fuel economy improvement obtained without anticipation.

Conclusions

A method for dynamic scheduling of VCT and EGR in proportion to load shortfall ratio was developed. The calibration process is mostly algorithmic to facilitate desktop calibration in a short amount of time.

References


**Definitions/Abbreviations**

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<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>aLSR</td>
<td>Anticipated load shortfall ratio</td>
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<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
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<td>FE</td>
<td>Fuel economy</td>
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<tr>
<td>GTDI</td>
<td>Gasoline turbocharged direct-injected</td>
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<td>HP</td>
<td>High pressure</td>
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<td>HWFET</td>
<td>EPA highway fuel economy driving schedule</td>
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<tr>
<td>IVO</td>
<td>Intake valve opening</td>
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<td>MPG</td>
<td>Miles per gallon</td>
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<td>LA4</td>
<td>EPA urban dynamometer driving schedule</td>
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<tr>
<td>LP</td>
<td>Low pressure</td>
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<tr>
<td>LSR</td>
<td>Load shortfall ratio</td>
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<td>OT</td>
<td>Open throttle</td>
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<td>PCM</td>
<td>Powertrain control module</td>
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<td>RMSE</td>
<td>Root mean-square error</td>
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<td>RON</td>
<td>Research octane number</td>
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<td>SSM</td>
<td>Steady state scheduling mode</td>
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<td>Transient scheduling mode</td>
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<td>EPA supplemental FTP driving schedule</td>
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<td>Variable cam timing</td>
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