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MINIMUM BACKPRESSURE WASTEGATE CONTROL FOR A BOOSTED GASOLINE ENGINE WITH LOW PRESSURE EXTERNAL EGR

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ABSTRACT

Turbocharging and downsizing (TRBDS) a gasoline direct injection (GDI) engine can reduce fuel consumption but with increased drivability challenges compared to larger displacement engines. This tradeoff between efficiency and drivability is influenced by the throttle-wastegate control strategy. A more severe tradeoff between efficiency and drivability is shown with the introduction of Low-Pressure Exhaust Gas Recirculation (LP-EGR). This paper investigates and quantifies these tradeoffs by designing and implementing in a one-dimensional (1D) engine simulation two prototypical throttle-wastegate strategies that bound the achievable engine performance with respect to efficiency and torque response. Specifically, a closed-wastegate (WGC) strategy for the fastest achievable response and a throttle-wastegate strategy that minimizes engine backpressure (MBWG) for the best fuel efficiency, are evaluated and compared based on closed loop response. The simulation of an aggressive tip-in (the driver's request for torque increase) shows that the wastegate strategy can negotiate a 0.8% efficiency gain at the expense of 160 ms slower torque response both with and without LP-EGR. The LP-EGR strategy, however offers a substantial 5% efficiency improvement followed by an undesirable 1 second increase in torque time response, clarifying the opportunities and challenges associated with LP-EGR.

INTRODUCTION

Market trends and fuel economy regulations are pushing manufacturers to develop more efficient spark-ignited (SI) internal combustion engines. While engine downsizing and boosting is one well known approach for improving fuel economy, the slower air path dynamics associated with turbocharger lag can negatively impact the drivability of these engines.

The best drivability is achieved with wastegate control strategies [1] that keep the wastegate closed at part load to maintain the highest possible turbocharger speed when the engine is partially throttled. The elevated turbocharger speed and rapid intake filling during throttle opening enable fast torque response during tip-in. However, this approach sacrifices fuel economy for performance. Turbo-lag becomes even more severe when a minimum backpressure strategy is used for wastegate control. This strategy, which is also known as optimal fuel economy wastegate control [1], regulates the wastegate position to minimize the turbine inlet pressure, and improves fuel economy as a result of reduced pumping losses. Transient response unfortunately degrades with this approach as the throttle must be kept as open as possible because of the diminished boost pressure.

Many different controllers have been introduced for wastegate control to improve turbocharged engine response. For example, Moulin et al. [2] use a non-linear control strategy based on feedback linearization and constrained motion planning. Thomasson et al. [3] model a pneumatic wastegate and develop a controller consisting of a feedforward loop and a feedback PID loop. A multivariable throttle and wastegate controller targeting intake manifold and boost pressures is introduced by Karnik et al. [4], while a nonlinear controller adopting a minimum backpressure wastegate control strategy is presented by

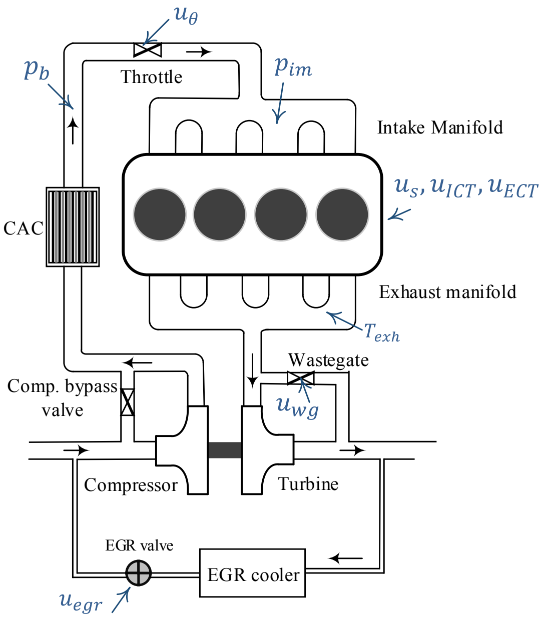

FIGURE 1. Schematic of turbocharged SIDI engine with low pressure loop EGR

Khiar et al. [5]. Finally, internal model controllers (IMC) are employed in [6] and [7] to control wastegate position in turbocharged SI engines. Note that operating point selection is very important for both fuel efficiency and actuators authority, and hence the closed loop dynamics, independently of the control methodology applied. Recognizing this fact, Gorzelic et al. [8] propose a control design that changes the controller structure depending on the operating points. Specifically, the design switches from a throttle-control/wastegate-open strategy at low load, to a coordinated mid-ranging strategy at part load, and finally switches again at high load to a strategy with throttle-open/wastegate-control.

A major challenge with down sized boosted SI engines is high load end-gas knock. While combustion can be retarded for knock mitigation, the late combustion phasing will increase fuel consumption [9–17]. The introduction of cooled external EGR (eEGR) reduces end of compression temperature (hence knock tendency), allowing for spark to advance towards the Maximum Brake Torque (MBT) timing [9–17] . Using eEGR also lowers heat transfer losses through cylinder walls (because of lower burned gas temperatures) and increases the ratio of specific heats during expansion, which increases work extraction from the charge. All of these effects improve engine fuel efficiency. External EGR also lowers turbine inlet temperature, reducing the need for high load fuel enrichment necessary for turbine protection that comes at the expense of increased high load fuel consumption. Finally, low-pressure (LP) EGR (where the recirculated exhaust is introduced upstream of the compressor as shown in the engine schematic in Fig. 1) reduces the need for throttling the intake manifold to guarantee sufficient EGR flow. Hence it can be coupled with a minimum engine-backpressure strategy that reduces overall engine pumping losses.

However, EGR in the intake system also influences the open loop system dynamics and can slow the tip-in response. The throttle-wastegate control strategy needs to negotiate higher flow rates given the additional EGR and warrants the investigation presented in this paper. Namely, a simple control strategy is designed for a minimum engine-backpressure strategy in an engine with and without EGR and the associated tradeoff between the drivability and fuel consumption is investigated using a thermodynamic, 1-dimensional flow model [18] to allow a realistic evaluation of the fuel consumption and the slow tip-in response caused by EGR.

SYSTEM AND MODEL DESCRIPTION

The studied engine is a 1.6 liter, 4 cylinder four-stroke turbocharged gasoline fueled spark ignition direct injection engine. Figure1 shows the schematic of the engine and its air path including major components such as: The engine, intake and exhaust manifolds, turbocharger, charge air cooler (CAC) and EGR intercooler. Various actuator inputs are also represented on the figure including: spark timing (u_s), intake and exhaust cam timing (u_{ICT} and u_{ECT}), throttle (u_θ), wastegate (u_{wg}) and EGR valve (u_{egr}) position. Intake manifold residual fraction is estimated with a fast O2 sensor, making it possible to use this variable as a controller input.

The GT-power model used in this study captures 1-D manifold gas dynamics, valve lift and port flow behavior, fuel injection and vaporization, heat transfer, turbocharger performance and other details necessary to predict engine performance. Heat release is modeled with a Wiebe function, while an Arrhenius auto-ignition delay integral [19] based on the ignition delay expression of Hoepke et al. [20] is used to model knock. The knock model is tuned to data from a downsized boosted SI engine detailed in [21].

STEADY STATE STRATEGY

The fuel economy impact of eEGR with the minimum backpressure wastegate control strategy is evaluated for a range of engine loads at 2000 rpm. For each level of eEGR, the spark timing that minimizes Brake Specific Fuel Consumption (BSFC) is found for each operating condition.

Figure 2 shows predicted BSFC variation versus spark advance at 2000 rpm and 90%, 60% and 30% of full load respectively. Two different wastegate control strategies were used in developing these results:

- The first, a wasegate closed strategy,“WGC”, keeps wastegate closed for fast engine response to a torque demand.
- The second, a minimum back pressure strategy, “MBWG”, minimizes the engine back pressure for higher fuel economy.

The presented BSFC and spark timing values are changes relative to a reference operating condition, which is the condition at 10% of full load without eEGR and WGC strategy. A positive ΔBSFC stands for an increase in BSFC (which is an undesirable direction) and vice versa. A positive Δspark timing means retarding the spark and a negative value of this parameter means advancing the spark. This is also shown on the figure.

The red line shows the ΔBSFC for different Δspark timing with 0% eEGR and fast response wastegate control. The green, blue and black lines respectively show ΔBSFC versus Δspark timing for 5%, 10% and 15% eEGR with minimum backpressure wastegate control. Red circles on the plots mark the spark advance where knock onset was predicted. Knock was not observed at 30% of full load, allowing MBT spark calibration, which is evidently where the ΔBSFC is a minimum for each curve. For medium to high loads, increasing eEGR advances the spark timing of knock onset, allowing further BSFC improvement due to more optimal combustion phasing.

The dashed magenta line corresponds to the case with 15% eEGR and the fast response wastegate control method. Comparing this line to the black line makes it possible to estimate the improvement resulting from the minimum backpressure wastegate control strategy at 15% eEGR. These lines essentially coincide, showing that MBWG control does not significantly affect backpressure relative to the WGC approach, because the wastegate has to be almost closed at this load to provide the necessary boost. A maximum eEGR level of 15% is chosen given the close proximity to the maximum eEGR rate (17%) achievable with the existing turbocharger at this load with closed wastegate -even higher EGR rates resulted in power drop. Knock limited spark advance is affected by approximately 1 degree CA. The improvement in fuel economy relative to the fast response case at this load was 5.4% with 15% eEGR and 6.3% with 15% eEGR and the minimum backpressure wastegate control approach. Considering that turbine inlet temperature limits were not applied, the predictions with eEGR likely under predict BSFC improvement given that fuel enrichment was not used, in particular for the fast response case without eEGR. Considering this approach, fuel economy improvements will be even greater with eEGR at this load.

For the 60% and 30% of full load cases, the effect of MBWG control is more noticeable. The simulations predict at least 2.0% BSFC reductions can be achieved using both MBWG control and 5% eEGR. Applying the MBWG control decreases BSFC by 0.8% - 0.9% for the investigated conditions. Even greater BSFC reductions can be achieved with higher eEGR rates. For 60% load case, the BSFC improvement was 3.0% with 15% eEGR and 3.8% with 15% eEGR and MBWG control strategy. Similar improvements were achieved for 30% load case, including a 2.8% BSFC reduction with the fast response wastegate strategy at 15% eEGR and a 3.6% reduction with 15% eEGR and MBWG control method.

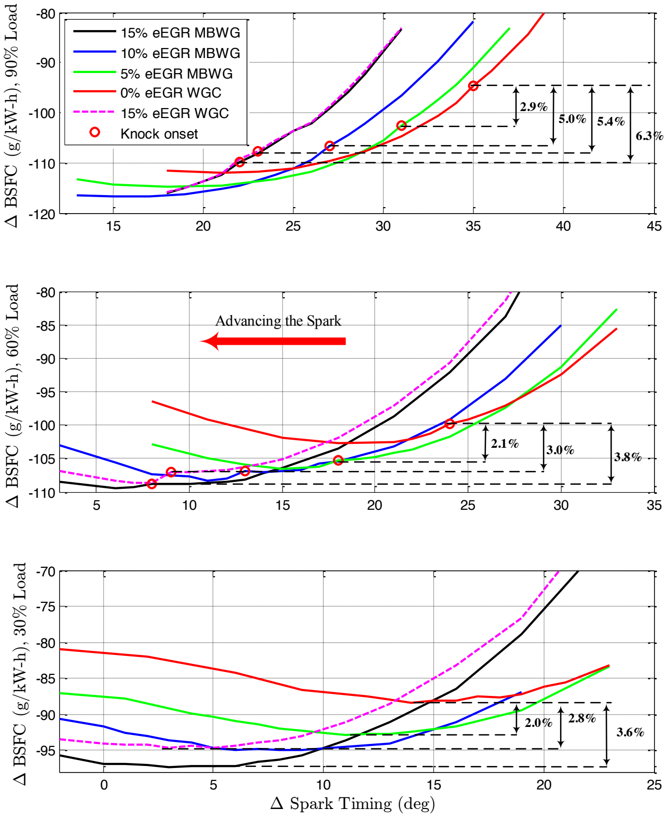

FIGURE 2. Spark sweep results for 2000 rpm engine speed

CONTROL STRATEGY

In the turbocharged power train architecture, there are several actuators complicating the turbocharged engine control strategies. These actuators include spark timing, intake and exhaust cam timing, low pressure EGR valve, throttle and wastegate positions. Figure 3 illustrates the schematic of engine controller developed for the current work. The main goals of this controller are to apply a minimum backpressure wastegate control strategy while providing a fast and proper response.

The spark timing is controlled in a feedback manner in the form of a look up table for different instantaneous engine speed’s (N), Brake Mean Effective Pressures (BMEP’s) and EGR levels in the intake manifold. This look up table is formed with the results of the spark sweep simulations from the previous section.

$$u_s = f_1(N, BMEP, EGR) \qquad (1)$$

In order to avoid knock and combustion misfire, it is necessary to calibrate the spark timing based on the dynamic prediction of in-cylinder residuals, including the effect of instantaneous eEGR. The internal residuals depend on intake and exhaust valve timing which are scheduled against BMEP and engine speed. The effect of internal residuals is therefore implicitly included in the spark timing calibration.

The EGR valve controller is a feedforward controller calibrated for a desired engine speed and load ($BMEP^*$) and desired eEGR ($eEGR^*$) level.

$$u_{egr} = f_2(N, BMEP^*, eEGR^*) \qquad (2)$$

The dynamic behavior of the EGR valve is modeled as a first order transfer function with a time constant of 50 ms.

$$\tau \dot{u}_{egr}^{act} + u_{egr}^{act} = u_{egr} \qquad (3)$$

where u_{egr}^{act} is the actuator position and u_{egr} is the actuator command.

The desired intake manifold pressure (p_{im}^*) is determined based on desired BMEP, engine speed and desired eEGR level. The throttle controller is used to regulate the intake manifold pressure, p_{im}. It consists of PI feedback and model based feedforward parts. The advantage of this controller over PID controllers is that it does not need to be tuned since it is model based.

$$u_\theta = k_{p,\theta}(p_{im} - p_{im}^*) + k_{i,\theta}\int_{t_0}^{t}(p_{im} - p_{im}^*)dt + u_\theta^{ff} \qquad (4)$$

$k_{p,\theta}$ and $k_{i,\theta}$ are the proportional and integral feedback gains and u_θ^{ff} is the feedforward portion and is the calculated throttle opening based on the target intake manifold pressure and parameters such as engine speed, engine size, throttle size and intake manifold volume. The wastegate controls the boost pressure, p_b. In order to achieve the minimum backpressure wastegate control strategy, the desired boost pressure (p_b^*) is determined with the following:

$$p_b^* = \begin{cases} p_{im}^* & if\ p_{im}^* \geq p_{ambient}, \\ p_{ambient} & if\ \ p_{im}^* < p_{ambient} \end{cases} \qquad (5)$$

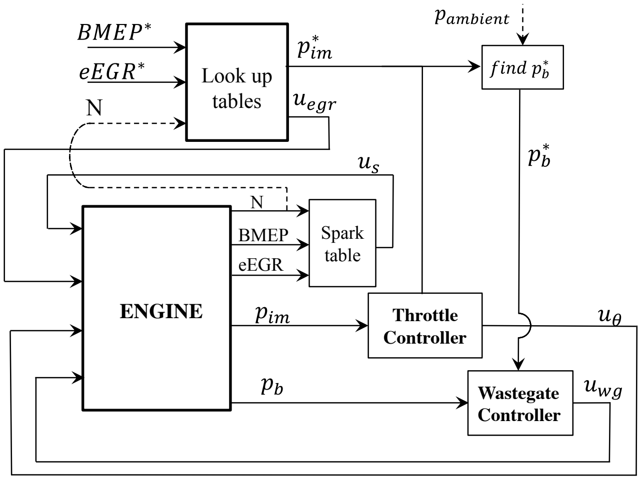

FIGURE 3. Controller schematic

As shown in Eqn.(5), the desired boost pressure is the smallest required value. At medium to high loads, the required intake manifold pressure is higher than ambient and the wastegate targets zero pressure drop across the throttle. Note that although the target values of intake manifold pressure and boost pressure are equal in this situation and they are closely coupled through the throttle valve, they are not the same parameters. Therefore the throttle and wastegate are actuating based on different variables. The wastegate controller opens the wastegate to the highest value possible, this way minimizing engine backpressure.

The wastegate controller is a PI controller as following:

$$u_{wg}^{MBWG} = k_{p,wg}(p_b - p_b^*) + k_{i,wg}\int_{t_0}^{t}(p_b - p_b^*)dt \qquad (6)$$

where $k_{p,wg}$ is the proportional gain and $k_{i,wg}$ is the integral gain.

For the cases with the fast response wastegate control method, the wastegate is kept closed ($u_{wg}^{WGC} = 0$) independently of p_{im}^* and the throttle controls the intake manifold pressure.

TRANSIENT SIMULATION RESULTS

BMEP Response

In this section the transient response of the two wastegate control strategies (fast response and minimum backpressure wastegate control) are evaluated at two eEGR rates (0% and 15%) for an extreme tip-in (10% to 90% of full load) at constant engine speed (2000 rpm). Figure 4 compares the step response for four different cases including:

- The turbocharged engine with 0% eEGR and fully closed wastegate for the fastest possible response (black line).
- The turbocharged engine with 0% eEGR and minimum backpressure wastegate (MBWG) control strategy (dashed

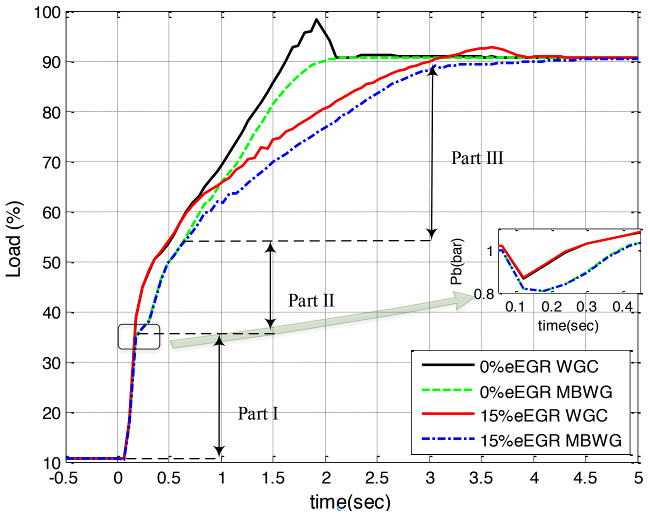

FIGURE 4. Transient response comparison for turbocharged engine with and without eEGR and with different wastegate control strategies at 2000 rpm

green line).

- The turbocharged engine with 15% eEGR and fully closed wastegate (red line).
- The turbocharged engine with 15% eEGR and MBWG control approach (dash-dot blue line).

As expected, turbocharged engine with closed wastegate control strategy and without eEGR has the shortest response time (10-90%), equal to 1.28 sec. If the minimum backpressure wastegate control strategy is employed, this response time increases to 1.44 sec. In the case with 15% eEGR, even with closed wastegate during tip-in, the response time is 2.00 sec, which is much longer than that of the fastest response case. If minimum backpressure wastegate control is applied with 15% eEGR, then the situation will be much worse, with a response time of 2.30 sec.

Different features are evident in the slope of the load response, and are marked on the figure for the 15% eEGR case with MBWG control.

- Part I, which has the largest slope, is almost instantaneous -jump in load is due to throttle opening. This jump is larger for the two cases with fast response wastegate control strategy (red and black lines). The additional available boost pressure allows more air to rapidly flow into the engine, resulting in a faster produced power increase.
- Part II, in which the slope is almost the same for all four cases, is due to turbo-lag. In this time interval the throttle is open, the wastegate is closed and the turbocharger is speeding up to produce the necessary boost pressure for load acceptance. The external residual level in intake manifold for the cases with 15% eEGR level is still not high (the transient is started without eEGR, see Fig.5).
  The small kink in the cases with minimum backpressure wastegate control at the beginning of Part II (marked with rounded rectangles) results from flow rushing into the intake manifold at throttle opening. Due to its momentum, the flow continues to fill the manifold while the turbocharger speed is insufficient to feed the required charge, and for a small time interval the boost pressure drops to less than ambient. This is shown in the small plot on the right, which presents all four boost pressures during this time interval. This effect is more sever in the cases with the MBWG controller, since the turbocharger speed is lower at the beginning of transient, this causes the slow response at the beginning of Part II.
- In Part III, which has the smallest slope and exists just for the cases with 15% eEGR level (red and blue lines), the level of external residuals within the intake manifold have now increased, and the slower response is due to this effect. Comparing the slope of red line to black line and the slope of blue line to green line after their separation clarifies the eEGR effect on load response.

It should be noted that in the cases where the wastegate actuator is not used, there is an overshoot in the load response. The reason for this is that at wide-open throttle (see Fig.6) the throttle actuator has limited authority due to its nonlinear behavior. Hence the throttle controller is not capable of mitigating the response overshoot -a more complex throttle controller can remedy this behavior. Since the aim of this study is to compare the turbolag of different systems, the overshoot and associated controller design is left for future studies.

The clear result of these simulations is that applying the MBWG control method and adding eEGR will slow the transient response of the engine to a torque demand. In the case of adding eEGR, which has a more significant effect on fuel economy, the response time will slow even more considerably. It should be noted that even the fastest model with closed wastegate is much slower than a naturally aspirated engine, which has a response time of around 250 ms - such differences will noticeably affect vehicle drivability.

Performance Parameters

Figure 5 illustrates the relative changes in BSFC and turbine inlet temperature (relative to the reference operating condition described in STEADY STATE STRATEGY section). Also shown is the residual fraction within the intake manifold during the tip-in. A segment of BSFC plot after the tip-in, when the response has almost reached steady state, is magnified to more clearly show the differences in fuel consumption between the different cases. The minimum BSFC is achieved for the dash-dot blue line, which represents the case with 15% eEGR and MBWG control.The fuel consumption subsequently worsens for the red line, where just eEGR is used, the dashed green line, which is the

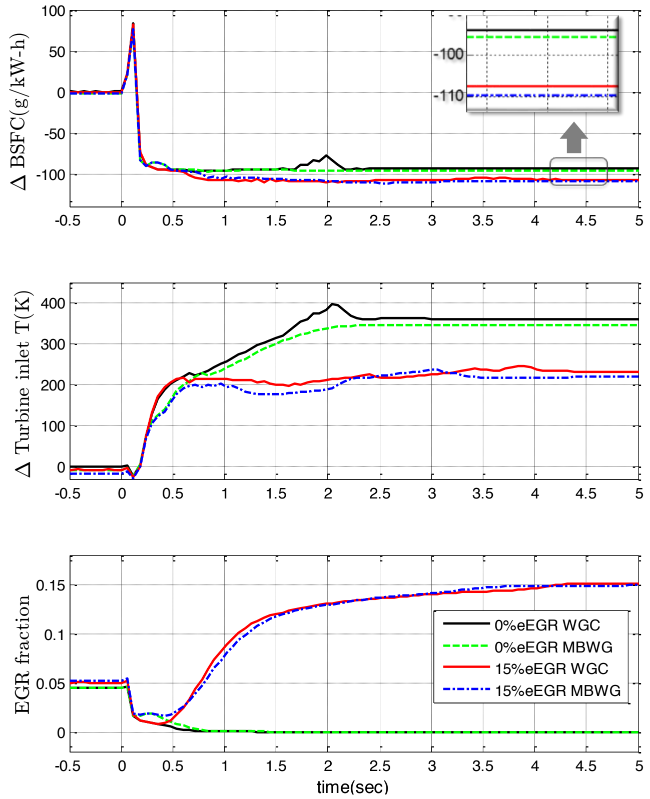

FIGURE 5. Fuel economy, turbine inlet temperature and intake manifold residuals for 10% to 90% of full load tip-in at 2000 rpm

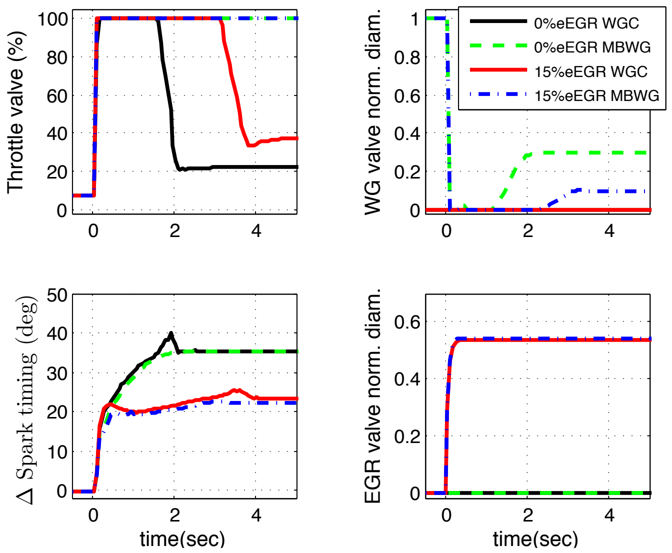

FIGURE 6. Actuators movement for 10% to 90% of full load tip-in at 2000 rpm

case without eEGR but with MBWG control and finally the baseline model, where no external EGR was used and the wastegate was kept closed for performance.

The second plot compares relative change in turbine inlet temperature for the different cases (refer to Fig.1 for T_{exh}). These plots show that adding 15% eEGR significantly decreases turbine inlet temperature, up 140°C for MBWG control compared to the baseline. The wastegate control strategy also contributes to changes in the turbine inlet temperature, perhaps because of the impact on engine backpressure, however this effect is around 10°C.

The third plot shows the residual fraction within the intake manifold during the tip-in. The baseline engine maintains low load in-cylinder internal residuals as high as 20% through the valve events. To avoid combustion instability and misfire, it is not possible to include eEGR at these loads, which is why the EGR valve is kept closed before the tip-in. Even though eEGR is not used at low load, up to 5% residual fraction is present in the intake manifold for all cases. This results from internal residuals entering the intake manifold from the cylinders during valve overlap. After the tip-in, the decrease in valve overlap stops internal residuals from entering the intake manifold. The EGR valve remains closed for the cases without eEGR, which have no residuals in the intake manifold at high load. In cases where eEGR is targeted at high load, the EGR valve opens after the tip-in, however, there is a lag before the eEGR fills the intake manifold. This causes the undershoot and slow increase of residual fraction within the intake manifold for these cases.

Actuator Movement

Figure 6 illustrates the response of the main actuators during the transient beginning with the throttle valve percent in the top left plot. After applying the load step the throttle fully opens for all cases. It remains wide-open for the cases where MBWG control is used (dash-dot blue and dashed green lines), since the required intake manifold pressure is higher than ambient pressure at 90% of full load. However throttle eventually closes at high load for the other two cases. The throttle starts closing sooner for the case without eEGR (black line) because the target manifold air pressure and the target load are achieved faster for this case. However, since the throttle authority is very limited at the fully open position, it cannot regulate the intake manifold pressure fast enough to avoid the response overshoot. The final value of throttle opening is higher for the case with eEGR compared to the previous case, because the required intake manifold air pressure is higher for this case due to the partial pressure of the residuals in the intake manifold.

The top plot on right shows the wastegate actuator normalized effective diameter during the time span of interest. The normalized diameter is computed as the ratio of wastegate effective diameter to the maximum wastegate effective diameter. As explained before, the two cases employing fast response wastegate control keep the wastegate closed during the simulation for quick turbocharger response. In the MBWG control cases, the wastegate is fully open at low load as expected. After the tip-in is applied the wastegate closes at first in order to help with turbocharger speed-up and then opens later to avoid producing unnecessary boost pressure. In the case without eEGR, the wastegate opens sooner and to a higher value. The reason in this case is that the target boost pressure is lower and is achieved faster than the case with eEGR due to lack of residuals within the intake manifold.

The bottom left plot shows the relative change in spark timing in degrees during the transient. As explained above, the spark timing is calibrated for different engine speed, engine load and intake manifold residual levels. At low load, the spark timing is the same for all cases due to similar operating condition. During the transient response the spark timing is different for the different cases because of the variations in both BMEP response and intake manifold residual fraction response. At high load the spark is advanced for the cases with eEGR, as expected.

Finally the last plot shows the EGR valve normalized effective diameter. The EGR valve is closed at low load for all cases and remains closed after the tip-in for the cases without eEGR. For the other two cases, the EGR valve opens to its desired valued. The cam timing values are not included in the results because they are similar for all four cases.

CONCLUSIONS

This paper quantified the general understanding that a minimum backpressure WG strategy and the introduction of LP-EGR would improve the engine efficiency at the expense of drivability (torque response). Two WG strategies, namely a closed wastegate (WGC) and a minimum backpressure (MBWG), are compared in a turbocharged GDI engine with and without LP-EGR, based on a high fidelity simulation. Although the metrics reported in this paper are for an aggressive tip-in maneuver at 2000 rpm, the same trends were found for other, more moderate, tip-in maneuvers.

The two prototypical WG strategies investigated in this paper affect similarly the efficiency and torque time response for 0% and 15% LP-EGR. Specifically in both cases, with and without LP-EGR, the closed wastegate response is atleast 160 ms faster and has 0.8% higher fuel consumption than the minimum backpressure watsegate strategy.

Although every drop of fuel counts for meeting the stringent 2025 US fuel economy standards, the tradeoff between efficiency and drivability with the two prototypical WG strategies seem manageable, and not as exciting as the tradeoff associated with the LP-EGR quantified in this paper. Indeed, the LP-EGR strategy is proven to have a substantial impact in the engine efficiency and response. Specifically, LP-EGR is shown to decrease in fuel consumption by more than 5% but slows-down the time response by an entire second. These results point to the need for innovative methods to speed-up the response time in the presence of LP-EGR.

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