A Coordinated Approach for Throttle and Wastegate Control in Turbocharged Spark Ignition Engines

Patrick Gorzelic [1], Erik Hellström [1], Anna Stefanopoulou [1], Li Jiang [2], and Srinath Gopinath [1]
1. Department of Mechanical Engineering, University of Michigan, Ann Arbor, US
E-mail: pgoz@umich.edu
2. Robert Bosch LLC, Farmington Hills, US

Abstract: This paper presents a control approach for turbocharged spark ignition engines that coordinates the throttle and wastegate air path actuators in order to improve driveability without significant compromise in efficiency. The coordinated controller is based on a two-input single-output (TISO) architecture which can be tuned through classical frequency response techniques using linearizations of a nonlinear mean value engine model. A systematic tuning method for the TISO architecture based on prior work is recommended and explained. The controller is evaluated in simulation with a one-dimensional GT-Power model and its performance is compared to that of a controller that does not coordinate the throttle and wastegate.

Key Words: Turbocharged Engine Control, TISO Control, Mid-ranging Control, Master-Slave Control

1 INTRODUCTION

Exhaust gas turbocharging of internal combustion engines is a method to increase the cylinder air charge through use of exhaust gas energy. In stoichiometric combustion spark ignition (SI) engines where fuel is slaved to air, turbocharging is commonly used either to increase engine peak power, or reduce engine size while keeping the same peak power to provide better efficiency. A schematic of a turbocharged SI engine is shown in Figure 1. With the incorporation of a turbocharger into the SI engine air path, the control system is faced with an additional complexity involved with the turbine bypass valve, or wastegate, which must be used to regulate the cylinder air charge in addition to the standard throttle.

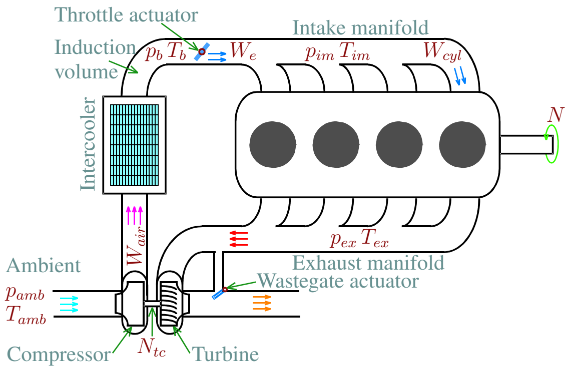

Figure 1: Schematic of a turbocharged SI engine. Reproduced from [1] with permission.

The goal of the turbocharged air path controller is to supply the appropriate amount of air to the cylinders to meet the driver torque demand using the throttle and wastegate, which are assumed here as fully controllable with electronic actuation. The reference variable in this control problem is typically taken to be the intake manifold pressure p_{im} (or, equivalently, the boost pressure in the event that the throttle is wide-open), since for a given engine speed this pressure largely determines the air flow. In the design of the air path controller, two major considerations are the response to the driver acceleration command and the fuel efficiency achieved. As derived by [2], the maximum efficiency will be achieved at a given operating point when the wastegate is kept as open as possible to fulfill the load demand at that operating point. This result makes intuitive sense because closing the wastegate causes the compressor to build boost pressure, forcing the engine to throttle more than if no boost was present at a given load. Thus keeping the wastegate open always minimizes the pumping losses. Applying this concept in a control system results in a split-ranged strategy wherein the wastegate is kept open at low and mid loads, and only when the load is high enough to cause wide-open throttle (WOT) does the wastegate start to close. Following the terminology in [2], this schedule will henceforth be referred to as *fuel-optimal*.

Such a strategy, however, introduces difficulties for torque management. The reason is that the air charge response to wastegate is much slower than that to throttle, as illustrated by simulation in Figure 2. In relying solely on the wastegate at high loads, the fuel-optimal approach is burdened with a slower torque response in this region.

Despite its torque response difficulties at high loads, the fuel-optimal control approach is the most common found in literature. Besides fuel economy benefits, the fuel-optimal approach offers the advantage that only one actuator is active at a time, thereby reducing the two-input problem to two single-input problems. The more challenging problem in this case is control of the wastegate, again because it is a much slower actuator. A wide range of wastegate control methods with varying levels of complexity exist

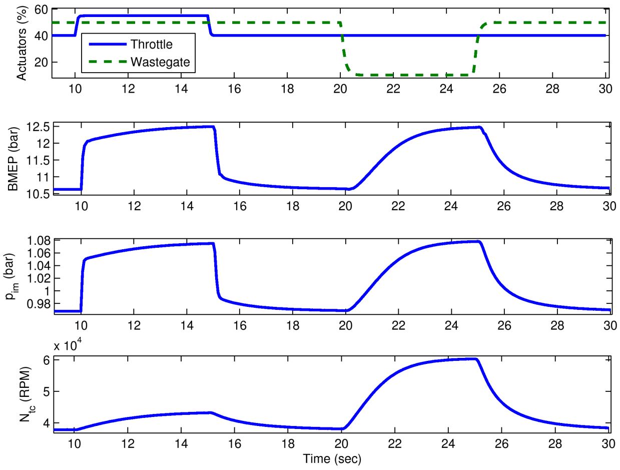

Figure 2: MVEM simulation of torque response to throttle and wastegate steps at a constant engine speed of 2000 RPM. Both inputs are characterized by the percentage of their full opening.

in literature, from more standard PID approaches [3], [4], to nonlinear feedforward and feedback linearization techniques [5], to neural network-based model predictive control [6]. However, these methods are all fundamentally limited by the slow torque response to the wastegate.

To improve the torque response at high loads while maintaining most of the efficiency benefits of the fuel-optimal schedule, this paper proposes a strategy that introduces a mid-region into the fuel-optimal schedule where the throttle and wastegate are both active, as depicted in Figure 3. The fuel-optimal schedule corresponds to the case where region 2 of Figure 3 is removed, so that only either the throttle or wastegate is active at one time. The mid-region of Figure 3 uses a two-input single-output controller (TISO) to coordinate throttle and wastegate so that the throttle may aid the wastegate for faster tracking of the torque demand.

Other works that deal with multivariable control of the throttle and wastegate exist in literature, e.g., [7], [8]. The controller of this paper differs from that in [7] in that this paper considers the tracking of a single output by two controllers that are tuned with classical frequency response methods, while the work in [7] considers a two-input two-output problem for which linear quadratic regulator techniques are employed to design a state-feedback controller and a subsequent reduced order approximation of the state-feedback controller which utilizes four classical controllers. [8] uses reference governors for throttle and wastegate control to enforce constraints for purposes such as preventing compressor surge.

The paper is organized as follows. Section 2 presents the proposed control scheme and summarizes the mean value engine model (MVEM) on which the control scheme is based. A tuning method based on [9] for the TISO controller utilized by the scheme is prescribed. Section 3 presents closed-loop simulation results on a GT-Power model with one-dimensional (1-D) fluid dynamics, and compares the torque response and efficiency characteristics of the proposed controller to a more standard design. Section 4 summarizes the work and draws conclusions.

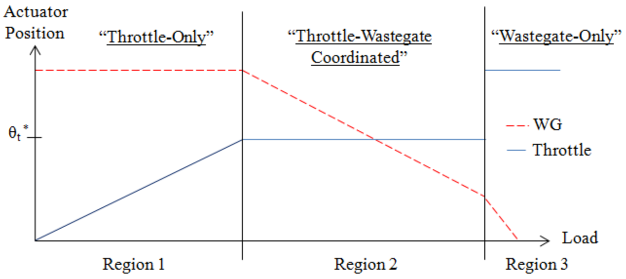

Figure 3: A representative actuator schedule utilizing the proposed coordinated approach.

2 CONTROL APPROACH

The MVEM on which the control design is based comes from that in [10]. The model is developed for a 4-cylinder, 2 liter engine equipped with a Borg-Warner type K04 turbocharger. The intake and exhaust manifolds and induction (i.e. compressor outlet) and turbine outlet volumes are modeled as isothermal control volumes with manifold filling dynamics. The resulting manifold state equations are given in, e.g., [11]. The throttle and wastegate actuator valves are modeled with the standard orifice equation, see, e.g., [11]. First-order lags are used to approximate the dynamics of these actuators; the throttle time constant is taken at 40 msec, and the wastegate time constant is taken at 125 msec, since the wastegate is typically a slower actuator than the throttle. Linearizations at multiple operating points show that these actuator dynamics substantially affect the bandwidth of the throttle to intake manifold pressure response, because the throttle directly affects the manifold filling dynamics, while the wastegate to intake manifold pressure response is only mildly affected because the wastegate is coupled to the manifold pressure through the slow dynamics of the turbocharger. The turbocharger compressor and turbine models are modified from those in [10] to include a compressor mass flow regression based on the Jensen and Kristensen method (see [12] or [13]) and a customized compressor efficiency regression that follows a power law in the difference between the current compressor mass flow rate and its value at the peak efficiency. Additionally, the turbine efficiency regression is changed from the standard quadratic polynomial in blade-speed ratio (see [12]) to a Gaussian function in blade-speed ratio, which extrapolates smoothly to lower blade-speed ratios where no data is available. The combustion model follows the same structure as that in [10], with the changes that the point of instantaneous combustion is chosen based on the logic set forth in [14], and the cylinder mass flow is obtained through a regression that follows the form in [1] instead of through an energy balance.

The control design is carried out assuming that combustion phasing is maintained at some prescribed set points, that the cylinder valve timings are fixed, and that the turbine outlet pressure is approximately constant at a given operating condition. The model is linearized about a grid of speed and load points and gains are tuned and scheduled at each point. Note that this gain scheduling approach can also capture the effects of variable-valve timing in scenarios where the valve timings are scheduled on engine speed and load as well. The reference intake manifold pressure to meet the driver torque demand is derived from an inversion of the MVEM's torque calculation assuming stoichiometry.

2.1 Actuator Schedule

As depicted in Figure 3, the proposed control approach introduces a coordinated control region into the standard fuel-optimal schedule in order to improve torque response at high load regions while retaining most of the efficiency benefits of the fuel-optimal schedule.

- Region 1: The throttle controls load with wastegate wide-open, as in the throttled region of the fuel-optimal schedule.
- Region 2: The throttle and wastegate are used simultaneously to control the load, with the throttle being maintained at the set point θ_t^* at steady-state.
- Region 3: The wastegate controls load with throttle wide-open, as in the unthrottled region of the fuel-optimal schedule.

The reasoning behind this schedule is as follows; at low and mid loads, the throttle is sufficient to supply air flow necessary to meet the driver torque demand. Thus, the wastegate should be left open at low and mid loads to attain the best efficiency (minimal pumping) possible, while maintaining a fast torque response from actuation via the throttle. However, instead of persisting with this scheme until the throttle is wide-open, the throttle is kept slightly below WOT, at a pre-determined value θ_t^*. As a result, when the driver requests an acceleration in this region, the throttle will be able to supply a quick burst of torque. Additionally, because θ_t^* is near the wide-open position, pumping losses will be nearly as low as in the fuel-optimal control case. θ_t^* then takes the role of a tuning variable that can be used to weight the emphasis that the controller places on the high load torque response versus efficiency. Specifically, a higher θ_t^* value maintains the throttle closer to wide-open during coordinated operation, giving better efficiency but reducing the throttle authority and therefore the torque response speed. θ_t^* is scheduled based on engine speed and is intuitive to tune from knowledge of the throttle's wide-open position at each scheduled engine speed. Lastly, at very high loads, the throttle is placed wide-open and the wastegate controls load alone; the reason for this decision is that once load is very high, there will normally be a large amount of exhaust enthalpy, which gives the wastegate more authority to spool up the turbocharger and manage the air charge response on its own.

As stated in Section 1, the wastegate is taken to be electronic, so that it can be positioned freely and the actuator schedule of Figure 3 can implemented directly. In traditional engines with a pneumatically actuated wastegate, the wastegate remains closed at low loads where the turbocharger has not built significant boost, and so the configuration in region 1 cannot be implemented exactly as shown. However, the overall idea of the strategy, to leave the wastegate open as far as possible at low at mid loads, coordinate the throttle and wastegate at high loads, and switch to wastegate only at very high loads, can still be applied in these engines.

2.2 Controller Structure

As stated in Section 1, the most common turbocharged air path control methodology in literature is the fuel-optimal approach, which utilizes throttle and wastegate separately. As a consequence, many techniques exist in literature for designing the single input throttle and wastegate controllers in regions 1 and 3 of Figure 3, see, e.g., [15], [4] for throttle control, and [5], [4] for wastegate control. A throttle controller similar to that in [15] is used here, with a feedforward command obtained from inversion of the throttle's governing equation, and a proportional + integral (PI) controller generating the feedback command. For the wastegate, the load is controlled solely through a PI controller.

The controller of region 2 in Figure 3 employs the mid-ranging strategy [16] to achieve the depicted actuator coordination. Mid-ranging has found other applications in the automotive sector regarding HCCI combustion control [17]. Mid-ranging is a technique originating in the process control sector that is used in scenarios where a trim actuator and a coarse actuator control a single output. The trim actuator has high bandwidth and resolution, but saturates easily, while the coarse actuator can change the output by large amounts, but has a lower bandwidth and resolution. As shown in Figure 4, the mid-ranging controller uses the trim actuator u_1 to track the output y to the reference r, and uses the coarse actuator u_2 to maintain the trim actuator at the set point u_1^* so that u_1 does not saturate. This specific architecture is referred to as a valve position controller (VPC) in the mid-ranging literature. At conditions near WOT, the turbocharged air path falls into this scenario, with the throttle angle θ_t taking the role of u_1 and the wastegate position θ_w taking the role of u_2, and both actuators tracking the manifold pressure as the output y. For this reason, the trim and coarse controller and plant transfer functions have been given the subscript t and w, respectively. Applying the mid-ranging strategy gives the actuator behavior shown in region 2 of Figure 3.

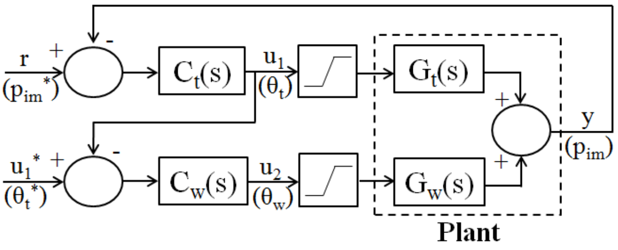

Figure 4: Mid-ranging valve position control architecture. Turbocharged air path variable names shown below their corresponding general variable names.

Since many methods have been developed for single input throttle and wastegate control as stated above, the main issue to be addressed in the proposed control method is the design of the coordinated controller. The structure of the mid-ranging controller is chosen so that the throttle controller C_t is a proportional (P) controller, and the wastegate controller C_w is a PI controller. This decision is motivated by the form of the closed-loop transfer function from the reference to output, which can be derived from the block diagram in Figure 4 (neglecting the saturation blocks) as

$$\frac{y(s)}{r(s)} = \frac{L(s)}{L(s)+1}, \quad L(s) = C_t(s)(G_t(s) - G_w(s)C_w(s)) \tag{1}$$

which takes the standard unity feedback loop form. Simplification of the equivalent open-loop transfer function L reveals that the open-loop poles are the union of the plant poles and both controller poles, and that the loop gain is determined by the gain of C_t. Thus, C_t is chosen as a simple gain for the purposes of tuning the loop gain, and C_w is given an integrator because this ensures steady-state of both the output to the reference and the throttle to θ_t^*. That the throttle is tracked to θ_t^* by this integrator is obvious from Figure 4, while the output to reference tracking stems from the fact that the poles of L include the poles of both controllers, so an integrator in either controller is sufficient. The zero in C_w is used to add phase lead at low frequencies.

2.3 Coordinated Controller Tuning

To tune the gains of the throttle-wastegate coordinated controller, some methods have been proposed in the mid-ranging literature [18], [19]. However, these tuning methods assume that the coarse actuator can be considered stationary while the trim actuator acts, and hence the cross coupling between the actuators can be ignored. To discern a tuning method which takes into account the actuator cross coupling to give better coordination, note that the response of y to r in Figure 4 can be considered separately from the response of y to u_1^* by way of the superposition principle. Setting $u_1^* = 0$ to tune the y to r response, the mid-ranging architecture in Figure 4 reduces to the so-called master-slave architecture, for which a number of tuning methods have been proposed by the hard disk drive sector. Analysis of the block diagram in Figure 4 shows that the closed-loop poles from y to u_1^* are the same as those from y to r, which means that stabilization of the y to r response implies stabilization of the y to u_1^* response. Thus, the controller can be tuned by applying master-slave techniques to the y to r system, viewing u_1^* as a disturbance whose effect is inherently stabilized.

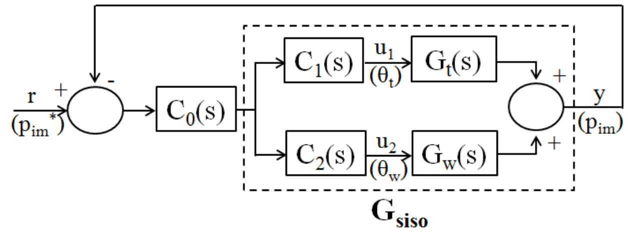

Figure 5: Block diagram considered by the PQ tuning method. Turbocharged air path variable names shown below their corresponding general variable names.

A master-slave method that is straightforward to tune and considers actuator interaction is the PQ method [9], which is used here for tuning the TISO air path controller. The PQ method considers the generalized block diagram shown in Figure 5. Notice that $G_{siso} = C_1G_t + C_2G_w$ plays the role of the plant of a unity feedback loop with controller C_0, and hence stabilization of the zeros of G_{siso} rules out non-minimum phase behavior. Setting $G_{siso} = 0$ and rearranging gives

$$1 + \frac{C_2(s)G_w(s)}{C_1(s)G_t(s)} = 0 = 1 + PQ, \tag{2}$$

$$P = \frac{G_w(s)}{G_t(s)}, \quad Q = \frac{C_2(s)}{C_1(s)}$$

This takes the form of the closed-loop characteristic equation a unity feedback loop with open-loop transfer function PQ. In addition, notice that the gain of PQ is the ratio of the coarse to trim actuator gains, and the phase of PQ is the phase lag between the actuators,

$$|PQ| = \frac{|C_2(s)G_w(s)|}{|C_1(s)G_t(s)|}, \tag{3}$$

$$\angle PQ = \angle C_1(s)G_w(s) - \angle C_1(s)G_t(s)$$

As a consequence, the gain crossover frequency of PQ determines where the actuators switch dominance, and the phase of PQ at the gain crossover frequency (i.e. the phase margin) determines how out of phase the actuators are where their effects on the output are equal and hence may destructively interfere. Thus, Q can be tuned not only to ensure minimum phase behavior, but also to give desirable actuator interaction characteristics.

Once Q is determined, if it is realizable then its constituent controllers can be obtained simply by setting $C_1 = 1$ and $C_2 = Q$, which is the approach taken in this paper. C_0 is then tuned as a standard unity feedback loop treating G_{siso} as the plant. When all the controllers are obtained, the VPC architecture is reverted to simply by setting $C_t = C_0$ and $C_w = C_2$. For more details on the PQ method, see [9].

To illustrate the tuning procedure, an example tuning of the coordinated air path controller is given here for a linearization point at 2000 RPM with the throttle and wastegate set points at 43% and 70%, respectively. Beginning with the first step of the PQ method, the controller Q is tuned taking P as the plant of a unity feedback loop. Figure 6 (A) shows the frequency response of P for the linearized system. Note that since it is known that $Q = C_2 = C_w$, the integrator pole of the C_w PI controller is included in the frequency response of P, so that its effects may be considered in the tuning. The tuning is carried out by placing the PI zero at low frequencies ($s = -0.4$) to add phase lead in this region and achieve a better phase margin. To confidently avoid interference between the actuators, a phase margin of 90 ° is targeted. The PI gain is then tuned to bring the gain cross-over frequency near the -6 dB bandwidth of G_w without violating the phase margin target, in order to make the actuators switch dominance at frequencies where the wastegate can no longer adequately affect the output. The resulting PQ frequency response is shown in Figure 6 (A). With Q determined, the PQ method is proceeds to its second step by tuning C_0, treating G_{siso} as the plant of a unity

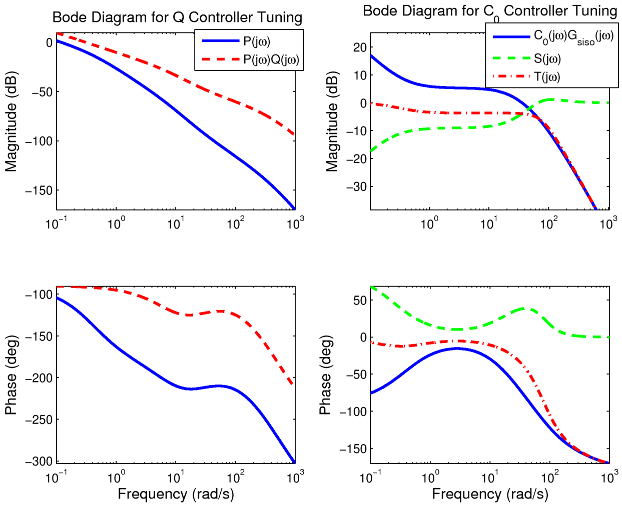

Figure 6: Bode plots for example coordinated controller tuning with PQ method. Column (A): Bode plots of P and PQ involved with tuning of Q. Column (B): Bode plots of full system open-loop and sensitivity transfer functions involved with tuning of C_0.

feedback loop. Note that since it is known that $C_0 = C_t$ and C_t is a P controller, this involves only the tuning of the loop gain. The frequency response of G_{siso} displays excellent gain and phase margins, so as a first approach the the C_0 gain is chosen to achieve as high a bandwidth as possible for the complementary sensitivity function $T(j\omega)$ while keeping the peak in the sensitivity function $S(j\omega)$ to an acceptable limit. In practical implementation, the C_0 gain may be reduced to limit the response to disturbances such as pressure waves or perturbations in the driver load command. Care must also be taken to avoid tuning the C_0 gain so high that when the controller enters a region with a further closed throttle (e.g., on a load step down), the controller gain is too high for the increased throttle authority in these regions, which increases the plant gain and can threaten stability margins. The resulting open-loop transfer function, sensitivity function, and complementary sensitivity function after tuning C_0 are shown in Figure 6 (B).

3 SIMULATION RESULTS

To evaluate the effectiveness of the proposed control approach, the controller is discretized at an assumed sample frequency 100 Hz and applied to a 1-D GT-Power model to track load commands at constant speed. Before viewing the closed-loop simulations, an open-loop simulation of a transient throttle step is presented to compare the accuracy of the MVEM and GT-Power model against transient data. The response of several air path outputs is shown in Figure 7. Both the MVEM and GT-Power model agree with the transient simulation within an acceptable error margin. Note that some GT-Power outputs are moving average filtered for visibility, and so they appear to be slightly slower.

Figure 8 shows the coordinated controller tracking of torque step commands, characterized by the brake mean effective pressure (BMEP), at 2000 RPM. For comparison, the same step commands are plotted when tracked by a controller that utilizes only the wastegate, as would be done in the fuel-optimal control case. The wastegate-only controller is a PI controller that is tuned to be very aggressive, to show the torque response speed with a separated throttle and wastegate controller in an extreme case. Note that the slight offset in the BMEP tracking is due to mismatch between the MVEM and the GT-Power model, since the MVEM is used to derive the manifold pressure reference.

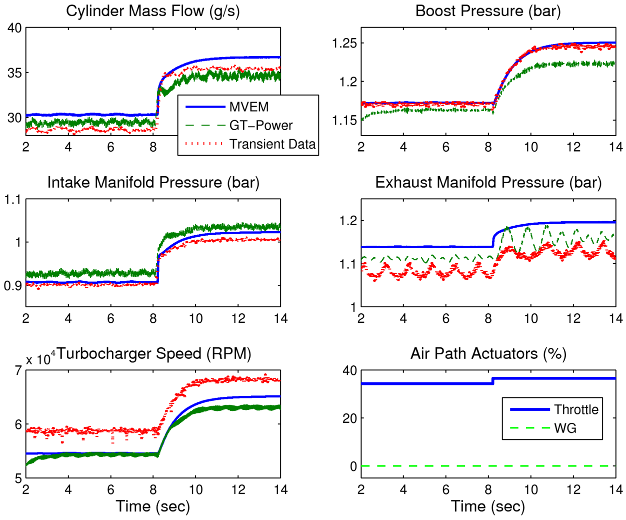

Figure 7: Open-loop simulation of MVEM and GT-Power model for comparison with transient data.

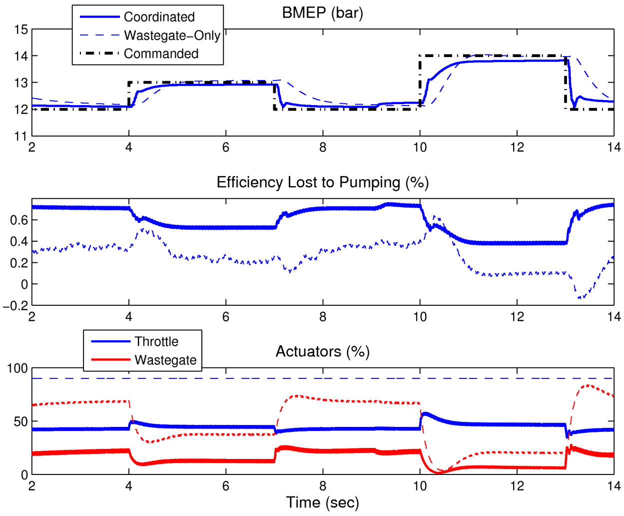

Figure 8: Load command step tracking at 2000 RPM. The performance of the coordinated controller (solid line) is compared with a controller that uses only the wastegate, i.e. the fuel-optimal case (dashed line). The coordinated controller has $\theta_t^* = 43\%$. The wastegate-only controller is PI with $k_P = -500$, $k_I = -800$.

Observing the plots, it is clear that the coordinated controller out-performs the wastegate-only controller in terms of torque response, quickly adjusting the torque at the onset of load commands and giving a faster rise time overall. Also plotted is the percentage of the gross cycle work lost to pumping, so that the efficiency level of the two strategies can be compared. The coordinated controller incurs only an additional .2 to .4 % efficiency loss beyond the fuel-optimal case, showing that the coordinated controller may achieve a faster torque response in return for a small trade-off in efficiency.

To display the controller's tracking performance across all three of the regions in Figure 3, Figure 9 plots the closed-loop response to a step command series that causes the system to transition between each of these regions. The controller maintains its performance throughout each of the transitions, with the only noticeable excursion being the overshoot on the step down from coordinated to throttle-only operation, which is minor in terms of percentage of the full load step (11%). Notice that the intake manifold pressure reference is rate-limited (at 0.9 bar/sec) during the transition from wastegate-only to coordinated operation. The rate limit was imposed because the sharp transient caused by the throttle set-point moving from wide-open to θ_t^* was sometimes observed to cause the throttle and wastegate actuators to oscillate with one another before settling down to the reference manifold pressure. Rate limiting the reference during the transition is a simple heuristic approach that slows down the throttle movement and avoid the oscillatory behavior in exchange for a slightly more sluggish torque response. Note that this issue was not experienced during the transition from wastegate-only directly to throttle-only, because in the throttle-only region the wastegate does not follow the throttle and therefore cannot amplify oscillations.

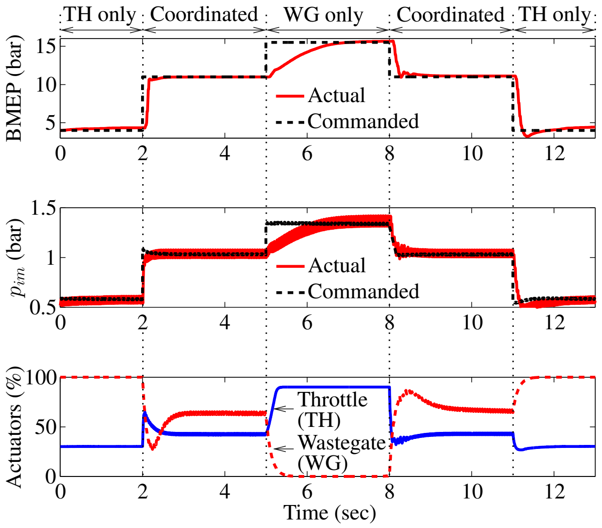

Figure 9: Tracking of load command steps over all three regions of the proposed control approach at 2000 RPM .

4 CONCLUSION

This paper presented a control approach for the air path of turbocharged SI engines that integrates a coordinated throttle and wastegate control scheme into the standard method of separating the throttle- and wastegate-active regions. The approach is based on classical control methods, and can be extended over the entire engine operating range via gain scheduling. A systematic tuning method for the coordinated controller of the proposed approach based on frequency response techniques was prescribed following the work in [9]. The coordinated controller was shown to improve torque response at high loads while retaining most of the efficiency benefits inherent in the separated throttle and wastegate control policy. This illustrates that the proposed approach allows for a faster high load torque response to be achieved in return for a small penalty in efficiency.

Acknowledgments

This material is based upon work supported by the Department of Energy (National Energy Technology Laboratory) under award number DE-EE0003533. This work is performed as a part of the ACCESS project consortium (Robert Bosch LLC, AVL Inc., Emitec Inc.) under the direction of PI Hakan Yilmaz, Robert Bosch, LLC

References

[1] D.H. Lee, L. Jiang, H. Yilmaz, A. Stefanopoulou, Air Charge Control for Turbocharged Spark Ignition Engines with Internal Exhaust Gas Recirculation, Proceedings of the ACC, 1471-6, 2010.

[2] L. Eriksson, S. Frei, C. Onder, L. Guzzella, Control and optimization of turbocharged spark ignited engines, Proceedings of the IFAC 15th Triennial World Congress, 2002.

[3] A. Thomasson, L. Eriksson, O. Leufven, P. Andersson, Wastegate Actuator Modeling and Model-Based Boost Pressure Control, IFAC Workshop on Engine and Powertrain Contol, 87-94, 2009.

[4] G. Colin, Y. Chamaillard, B. Bellicaud, Robust control for the air path of a downsized engine, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 930-43, 2011.

[5] P. Moulin, J. Chauvin, and B. Youssef, Modeling and control of the air system of a turbocharged gasoline engine, Control Engineering Practice 19, 287-297, 2011

[6] G. Colin, Y. Chamaillard, G. Bloch, G. Corde, Neural control of fast nonlinear systems - application to a turbocharged SI engine with VCT, IEEE Trans. on Neural Networks, 18(4), 1101-1114, 2007.

[7] A. Karnik, J. Buckland, J. Freundenberg, Electronic throttle and wastegate control for turbocharged gasoline engines. Proceedings of the ACC, 4434-4439, 2005.

[8] U. Kalabić, I. Kolmanovsky, J. Buckland, E. Gilbert, Reference and Extended Command Governors for Control of Turbocharged Gasoline Engines Based on Linear Models, Proceedings of the IEEE Conference on Control Applications, 319-25, 2011.

[9] S. Schroeck and W. Messner, On Controller Design for Linear Time-Invariant Dual-Input Single-Output Systems. Proceedings of the ACC, 4122-26, 1999.

[10] L. Jiang, A. Stefanopoulou, J. Vanier, H. Yilmaz, Parameterization and simulation for a turbocharged spark ignition direct injection engine with variable valve timing, SAE Technical Paper, no. 2009-01-0680, 2009.

[11] L. Eriksson, Modeling and Control of Turbocharged SI and DI Engines, Oil & Gas Science and Technology-Rev. IFP, Vol. 62, no. 4, 523-538, 2007

[12] P. Moraal and I. Kolmonovsky, Turbocharger modeling for automotive control applications, SAE Technical Paper 1999-01-0908, 1999.

[13] J.P. Jensen, A.F. Kristensen, S.C. Sorenson, N. Houbak, E. Hendricks, Mean value modeling of a small turbocharged diesel engine, SAE 910070.

[14] L. Eriksson and I. Andersson, An Analytic Model for Cylinder Pressure in a Four Stroke SI Engine, SAE Technical Paper 2002-01-0371, 2002.

[15] G. Le Solliec, F. Le Berr, G. Colin, G. Corde, Y. Chamaillard, Engine Control of a Downsized Spark Ignited Engine: From Simulation to Vehicle, Oil & Gas Science and Technology-Rev. IFP, Vol. 62, no. 4, 555-572, 2007

[16] B. Allison and A. Isaksson, Design and performance of mid-ranging controllers, J. Process Control, vol. 8, 469-74, 1998

[17] N. Ravi, H. Liao, A. Jungkunz, J. Gerdes, Mid-ranging control of a multi-cylinder HCCI engine using split fuel injection and valve timings, 6th IFAC Symposium Advances in Automotive Control, p 797-802, 2010

[18] B. Allison and S. Ogawa. Design and tuning of valve position controllers with industrial applications, Transactions of the Institute of Measurement and Control, 25, 3-16, 2003.

[19] S. Gayadeen and W. Heath., An Internal Model Control Approach to Mid-Ranging Control, IFAC Advanced Control of Chemical Processes,vol. 7, part 1, 2009
