<u>Combined Torque and Emission Control for a Turbocharged Gasoline Engine</u>

Key words: *turbocharged engine, model-based control, torque control, emission control*

Background: To reduce the environmental impact of spark-ignited gasoline engines, it is critical to minimize harmful exhaust emissions such as NOx, CO, and unburned hydrocarbons. A competing goal is to effectively control the crankshaft torque, which is directly related to the performance and safety of the vehicle. For example, during the gear shifting phase in a vehicle with an automatic transmission, the engine must produce a certain torque trajectory over some fixed period of time to minimize frictional losses and to avoid passenger discomfort [1]. Although it is common in the automotive industry to achieve low emissions by varying the intake valve timing [2], it is still rare to combine emission control and torque control into one cohesive strategy. The two are traditionally run in separate control loops, and torque response is often sacrificed in favor of meeting strict emissions requirements [3].

Furthermore, many automotive companies are embracing the trend of downsizing (reducing volume) and turbocharging gasoline engines – a technique which has been shown to improve fuel efficiency while preserving acceleration performance desired by drivers [4]. This approach benefits from lower manufacturing, maintenance, and disposal costs compared to a gas-electric hybrid approach, thus providing a more economical option for lower-income households. However, the nonlinear dynamics of a turbocharged engine present a challenge for control, especially if multiple goals must be accomplished. In particular, the nonlinear coupling between the intake and exhaust gas dynamics may result in the emission control loop degrading the torque response more than it would in a naturally aspirated engine. A solution is to explicitly utilize knowledge of the nonlinear and coupled behavior during the control design, using model-based techniques.

Model-based control involves analyzing a model of the system, which facilitates the design of a sophisticated controller. An additional benefit is that the controller may be tested in simulation before actual implementation, thus allowing the control design to be done in parallel with the mechanical design and relieving the efforts needed to re-tune control gains in the event of a mechanical design change. For these reasons, many engine manufacturers are moving toward model-based control. The goal of this research is to optimally combine the torque and emission control loops using a model-based technique that is easy to adopt in industry.

Hypothesis: Model-based techniques will (1) facilitate the analysis of interactions between torque and emission behavior, (2) enable the combination of torque and emission control, and (3) provide better torque tracking performance than traditional engine control methods while maintaining low emissions.

Research Plan: <u>*Strategy*</u>: Thanks to my education at UC Berkeley, I have become well-acquainted with a variety of advanced model-based control schemes, including multivariable robust control, linear parameter-varying control, iterative learning control, model predictive control, and nonlinear sliding control. I am also familiar with innovative new approaches to control, such as apprenticeship learning and other artificial intelligence methods. Drawing from this theoretical background, I will synthesize an advanced controller appropriate for the turbocharged engine. I will have access to the world-class controls faculty at UC Berkeley to assist me in this process, and I will also have regular meetings with a senior control engineer at Toyota to ensure that the results are practical to implement on a production vehicle.

<u>*Methodology*</u>: The combined torque and emission control will be validated on a 2.3L turbocharged, gasoline direct-injection Mazda engine. This engine, provided by Tula Technology, is equipped with a full data acquisition system, including a cylinder pressure transducer which will be used for torque estimation [5]. It is currently installed on a dynamometer with motoring

capabilities, meaning that non-steady load tests are viable. Since it is difficult to access or modify the code in the factory engine control unit, I plan to install a LabVIEW/FPGA-based control unit to adjust the actuation signals as necessary. Engineers from Tula have agreed to provide technical support for any issues. One or two undergraduate researchers will also be available to assist me with the work on the experimental setup, while I introduce them to advanced control theory and practice beyond their in-class material.

As described in my Previous Research Experience essay, I have already formulated a control-oriented model of a turbocharged engine system, and preliminary simulations of the model reflect the typical behavior of a turbocharged engine. The remaining milestones for this project are planned as follows:

Spring 2012: Install LabVIEW/FPGA-based control unit, and obtain system identification results of the Mazda engine to match with the derived model.

2012-2013 year: Obtain performance results using traditional (i.e. separated) torque and emission control. Also, analyze the interactions between torque and emission behavior using the turbocharged engine model.

2013-2014 year: Formulate an advanced control scheme and test in simulation. Implement the controller on the Mazda engine and compare its performance with that of the traditional control.

Anticipated Results and Intellectual Merit: My research will *advance understanding* about the interactions between the torque and emission behavior of a turbocharged engine. By integrating torque control with emission control, my study's *potentially transformative* results will offer engine manufacturers an effective method of achieving the two control objectives simultaneously, therefore providing better torque tracking and acceleration performance with no hardware modifications. This control scheme will be easy to adopt, and perhaps even possible to implement on cars already on the road. With the engine test bench available for use, as well as my connections to automotive control engineers at Toyota and Tula in addition to the UC Berkeley faculty, I feel that I have *sufficient access to resources* to carry out this research.

Broader Impact: Development of an integrated torque and emission control will *benefit society* by taking advantage of variable valve timing technology to minimize harmful emissions while improving torque and acceleration performance. Furthermore, the application to turbocharged engines will encourage the downsizing approach for reducing fuel consumption, an economical alternative to gas-electric hybrids. Through partnerships with Toyota and Tula Technology, my work will *enhance the infrastructure for research* among the academic community, a major automotive manufacturer, and a startup company focused on fuel efficient technologies. This research will *advance discovery* while also *training* undergraduate researchers to *learn* more about automotive technology and controls. Moreover, I hope to *broaden the participation of underrepresented groups* by inspiring other women to pursue higher degrees in mechanical engineering. Finally, I plan to *disseminate my research results broadly* through publications in conferences and peer-reviewed journals.

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