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Opportunities in Automotive Powertrain Control Applications

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Abstract

The automotive industry faces substantial challenges to improve fuel economy and reduce emissions. New powertrain technologies use lean combustion, controlled aftertreatment and increasingly complex designs to wring-out additional efficiency from "conventional" reciprocating engines while actively managing the conversion of exhaust emissions. Model-based controls and systems engineering practice are the keys to achieving the benefits of these advanced combustion engine systems. This paper illustrates control applications for an advanced technology engine, and describes an engineering process that integrates model-based control design and strategy implementation in order to manage system and software complexity in an automotive environment. In lieu of conclusions, a few opportunities for research are highlighted that address some of today's challenges in automotive powertrain control.

1 Introduction

Automotive emissions regulations and the requirement for improved fuel economy have driven innovation in powertrain design and control for more than three decades. In Europe, "Stage I" emission standards were introduced in 1992; in the United States, the very first requirements on automotive pollution control date to the mid-1960's. Throughout the world, much has been accomplished in this important area: emissions from new vehicles in areas such as the United States and Western Europe are up to 98% lower than they were prior to the imposition of regulations. Nonetheless, the total amount of automotive emissions, while much lower, has not experienced as precipitous a decline, amounting to only about a 50% reduction from preregulatory levels due to increases in the number of cars on the road, the number of miles travelled and the emissions contributions of older vehicles [1]. Consequently, emissions mandates continue to challenge technology boundaries. In Europe, a 60% reduction in tailpipe emissions of oxides of nitrogen (NO_x) is required in the next decade to transition from the current "Stage III" to "Stage V" emission levels (and diesels will be as clean as gasoline vehicles). In the United States, a ten-fold reduction in NO_x is necessary over the same time period to achieve California's most stringent requirements. As for fuel economy, the European Automobile Manufacturers Association has committed to a reduction in carbon dioxide emissions (essentially, fuel consumption) for new passenger cars by over 25% to an average of 140 g/km by 2008. Corporate Average Fuel Economy (CAFE) regulations impose a minimum fleet average miles per gallon requirement in the U.S. Reductions in emissions and fuel consumption are societal obligations (regulated or not), but they cannot be accomplished with a disregard for performance: customers want vehicles that are fun to drive, responsive and achieve good fuel economy; they expect environmental stewardship.

These generally competing requirements of performance, fuel economy and emissions have fostered the development of advanced technology powertrains that are typically complex and control intensive: they incorporate new sensors and actuators, effect new methods of operation and are crucially dependent on the embedded control system to deliver the benefits of innovative powertrain hardware.

Although the control design problems for these advanced technology systems are in themselves difficult ones, achieving the required system performance is not the only challenge. The control systems for these complex powertrains must be developed at minimal cost and deployed in record time to meet the expectations of a competitive market. Today, the cost structure of the automotive industry imposes constraints on engineering resources, while rapid time-to-market pressures put the powertrain controller on the critical path of a vehicle's development schedule. Consequently, a systematic, model-based control development process that relies on modern Computer Aided Control Systems Design (CACSD) tools and methods is essential.

This paper is organized as follows: Section 2 describes some of the advances that have been made, and outlines challenges ahead with respect to controlling new powertrain systems. In Sections 3 through 5, a direct injection stratified charge engine and aftertreatment system serves as an example of a model-based, systems-driven control design that simultaneously achieves emissions and efficiency objectives. In Section 6, a systems engineering process for the automotive industry is described that supports model-based development of advanced technology powertrains in a production environment. Finally, a few research opportunities for control, based on the direct injection engine problem, are discussed in Section 7.

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2 Achievements and Challenges

There are only three things one can do to conventional reciprocating engines to achieve improved fuel economy: improve mechanical efficiency, improve thermal efficiency and reduce pumping losses. For the control engineer, these changes translate to additional sensors and actuators, multiple operating modes, interactive subsystems and new functionality. The challenge is to maximize fuel economy within the constraints imposed by the emission regulations. The approach is fundamentally multivariable and reliant on system and subsystem models for control synthesis, analysis, adaptation and optimization. Some of these "control intensive" systems include hybrid electric vehicles, already offered from some manufacturers and shortly to be available from most others, plus "everything variable" IC engines, many of which are on the road now. Some examples include:

- Variable geometry turbochargers [4, 5, 6, 7, 8]
- Variable cam timing [9, 10, 11, 12, 13]
- Variable displacement engines [14]
- Variable compression ratio
- Continuously variable transmissions [15]

The difficulty of the modeling and control problems posed by these systems is due to their complex physical nature, large scale and high number of independent actuators. Furthermore, system objectives are often in competition, such as simultaneously reducing oxides of nitrogen emissions and increasing fuel economy, while essentially "life of the vehicle" emissions requirements mean robustness and adaptation are always system design considerations. In the following sections, model development, some control design problems and system optimization will be reviewed for one such "control intensive" advanced technology powertrain.

3 A DISC Engine and its Multi-mode Operation

Sun *et al.* [2, 3] describe modeling and control of a direct injection stratified charge (DISC) gasoline engine, and discuss the fundamentally hybrid nature of the system. This model, plus a control-oriented representation of the exhaust aftertreatment, is the foundation of a systems approach that is essential to achieving fuel economy and emissions goals for this engine. The model is reviewed in the following paragraphs.

A DISC engine, like a diesel, injects fuel directly into the combustion chamber, and offers substantially improved fuel economy through stratified combustion. This significantly extends the lean air-fuel ratio (A/F) operating limit and reduces pumping losses. The cost of improved fuel efficiency is increased system complexity and a critical dependence on control to deliver the benefits expected of the hardware. The direct injection engine is different from a typical port fuel-injected engine in several respects. Most importantly, the DISC engine can, depending on speed and load, operate in one of three combustion modes: homogeneous at air-fuel ratios that are stoichiometric (about 14.64) or rich, homogeneous lean (between stoichiometry and about 20:1) or stratified. A homogeneous A/F mixture is achieved by injecting fuel early in the intake stroke. Stratification is achieved by injecting late, during the compression stroke, forming a combustible mixture near the spark plug and a very lean mixture (air-fuel ratios around 40:1) throughout the rest of the cylinder. The torque and emission characteristics corresponding to homogeneous and stratified operation are so distinct that different control strategies are required to optimize performance in the two regimes. Note also that, in addition to the usual control variables such as throttle position, ignition timing, exhaust gas recirculation (EGR) and fueling rate, the DISC engine requires new inputs including injection timing, fuel rail pressure and swirl control, at a minimum (Table 1). Finally, the ultra-lean A/F operation of the direct injection engine mandates the use of a special, actively controlled catalytic converter called a lean NO_x trap (LNT) to manage oxides of nitrogen emissions. This device traps NO_x during lean operation, but needs to be periodically purged in the homogeneous combustion mode at an A/F rich of stoichiometry. Transitions between stratified and homogeneous operation must be accomplished rapidly to minimize fuel consumption, but with torque disturbances that are imperceptible to the driver. Importantly, DISC engine subsystems are highly interactive and cannot be decoupled without degrading system performance. Table 2 shows the coupling between control inputs and performance indices for conventional port fuel injection (PFI), and DISC engines. While the functional partitioning for actuators and I/O naturally follows from Table 2 for a PFI engine, the fundamentally multivariable nature of the DISC means that decentralized, "one SISO loop at a time" control development is not an option.

Table 1: Sensors and actuators for DISI control.

Actuators and actuations	Sensors
Electronic throttle	Throttle position sensor
Electronic EGR valve	MAP
Spark timing	Engine speed
Swirl control valve	MAF
Fuelrail pressure	Intake temperature
Fuel pulsewidth	UEGO and/or HEGOs
Fuel injection timing	LNT temperature

The DISC engine model is illustrated in Figure 1. On the surface, the model structure is not dissimilar to a conventional engine, consisting of the throttle, intake manifold dynamics, engine pumping, torque generation, rotational inertia and feedgas emissions. Because of the different characteristics for homogeneous and stratified operation, the model is, in fact, hybrid in the sense that most components are represented by two continuous-variable sub-models with a discrete switching mechanism to select the appropriate characterization based on injection timing. For example, the emis-

Table 2: Steady state input/output coupling for PFI and DISI engines.

	PFI			
	Torque	Emissions (AFR)	Feedgas NOx	Exhaust temp.
Throttle	●			
Fuel		●		
EGR			●	○
Spark	○		○	○
	DISI			
	Torque	HC/CO emissions	Feedgas NOx	Exhaust temp.
Throttle	●	●	●	○
Fuel	●	●	●	○
EGR	○	○	●	○
Spark	○	○	○	○

●: strong coupling, ○: weak or moderate coupling

sions characterization is substantially different between homogeneous and stratified operation as shown in Figure 3. Additionally, the injection-to-torque delay, fundamentally associated with the four stroke engine cycle (intake-compression-power-exhaust), becomes a function not only of engine speed, but also of the operating mode that dictates the relationship between the injection and combustion events. The mathematical structure of the DISC model is detailed in the appendix.

The purpose of developing the model is, of course, to synthesize a control system that will ultimately be implemented on the real engine. Some of the control elements that must be developed and integrated include air charge management, mode transition control with constraints on A/F and torque, EGR control, idle speed control and, crucially, management of the exhaust aftertreatment system. A supervisory controller [17, 18] establishes the combustion mode, and determines setpoints for lower level feedback control of fuel quantity and timing, spark, throttle and EGR valve position.

In [3, 16], the model forms the basis for the development of an adaptive cylinder charge and EGR controller that is robust to changes in the effective flow area of the EGR valve caused by soot deposits formed during stratified operation. It is shown that even a modest reduction in flow area results in a substantial penalty in feedgas NO_x emissions. The intake manifold pressure dynamics are described by

$$\dot{p}_m = c_m(W_{th} + \hat{W}_{egr} - \theta \cdot \hat{W}_{cyl}) \tag{1}$$

where $\hat{W}_{egr}$ is an estimate of the EGR flow; $\hat{W}_{cyl}$ is an estimate of the flow into the cylinders multiplied by an adaptive correction, θ; W_{th} is the measured flow through the throttle; and c_m depends on the manifold temperature, volume and gas constant. The EGR estimate is developed by an observer that uses the measured manifold pressure plus throttle and cylinder flows:

$$\begin{aligned} \dot{\varepsilon} &= -\alpha \cdot c_m \cdot (\varepsilon - W_{th} + \theta \hat{W}_{cyl} + \alpha p_m), \\ \hat{W}_{egr} &= \alpha p_m - \varepsilon \end{aligned} \tag{2}$$

Although the EGR observer does not depend on valve parameters, it does involve an estimate of the cylinder flow, which may also be corrupted by the effects of soot deposits. Consequently, when the EGR valve is closed and the engine is operating at steady state, the cylinder charge estimate is updated by

$$\dot{\theta} = -\gamma \cdot \hat{W}_{cyl} \cdot (p_m - \hat{p}_m) \tag{3}$$

where γ is an adaptation gain and $\hat{p}_m$ is a manifold pressure estimate based on the current estimate of cylinder flow.

The supervising controller interprets driver demand plus accessory loads to generate a torque requirement that is met by coordinated control of cylinder charge, fuel and ignition by minimizing the cost function [3]

$$\begin{aligned} J &= \{(\tau - \tau^d)^2 + \gamma_1(W_{cyl} - \lambda^d W_f)^2 \\ &+ \gamma_2(\delta - \delta^d)^2 + \gamma_3(F_{bg} - F^d{}_{bg})^2\} \end{aligned} \tag{4}$$

where τ is engine torque; W_f is fuel flow; λ is air-fuel ratio; δ is spark timing and F_{bg} is the burned gas fraction of the EGR flow, keeping in mind that in a DISC engine operating in homogeneous lean or stratified mode, the EGR flow contains a significant portion of combustible air. τ^d, λ^d, δ^d and $F^d{}_{bg}$ are setpoint values. The multipliers γ_1 through γ_3 are relative weighting factors that depend on operating condition. For example,

- $\gamma_1 \gg 1$ when λ^d = stoichiometry and A/F control is the highest priority objective.
- $\gamma_2 \gg \gamma_1$ for stratified or lean homogeneous operation. In this case, the A/F requirement is relaxed, but spark must be carefully managed within a limited range for combustion stability.

Other constraints on the minimization include manifold pressure (sufficient vacuum must be maintained to operate vacuum controlled devices such as the power brake booster), the limits of authority of the throttle and EGR valve, and allowable spark timing and A/F. Figure 2 shows experimental A/F and torque traces on a small DISC engine for constant torque combustion mode transitions. In the case of a transition from homogeneous to stratified, the transient A/F requirement is relaxed, giving the fuel actuator substantial authority to maintain constant torque during the mode shift. On the other hand, the transition from stratified to homogeneous operation at stoichiometry requires tight control on A/F for good emissions. Consequently, γ_1 is large, requiring torque management via limited authority spark and slower throttle actuator resulting in slightly deteriorated control.

A system model is key to attacking the DISC idle speed control problem. In [19], a controller is designed to regulate speed, A/F, EGR and spark whenever all setpoint objectives are simultaneously achievable. In [20], the overall control objective is to idle the engine in the presence of disturbances while minimizing

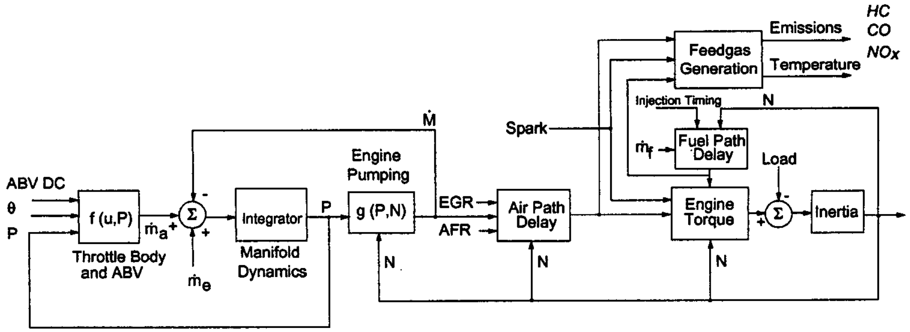

Figure 1: Block diagram of DISC engine model

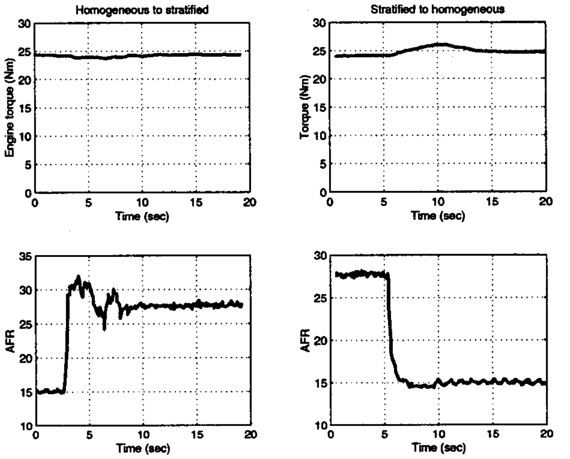

Figure 2: Constant torque DISC engine mode transition. Homogeneous to stratified transition (left) prioritizes torque control; stratified to homogeneous transition (right) relaxes the torque objective to ensure A/F control at stoichiometry

fuel consumption and emissions. Two control topologies are developed with speed or A/F regulation being dominant objectives, and a supervisory control system switches between the two to exploit the multiple operating modes of the engine. When the engine is operating in the homogeneous lean or stratified mode, A/F may vary over a relatively wide range, and engine speed is assigned the highest priority. In this case, the fastest actuator, fuel, is used to maintain idle speed while the throttle manages A/F to achieve a setpoint established by the supervisor for best emissions-constrained fuel economy. If the supervisor has commanded stoichiometric or rich operation, during LNT purge, for example, or before the trap has reached an efficient operating temperature, then the highest priority is A/F regulation. The fuel actuator is then assigned this task, while the throttle regulates engine speed. The idle speed control topologies are illustrated in Figure 4. Robustness to torque disturbances and LNT mode transitions is demonstrated on the simulation model.

Clearly, a very important element of the DISC systems problem is the interaction of the engine with the lean NO_x trap. In the next sections, a LNT model will be described, along with a dynamic programming optimization methodology that is used to define aftertreatment system requirements and a control policy for the DISC powertrain.

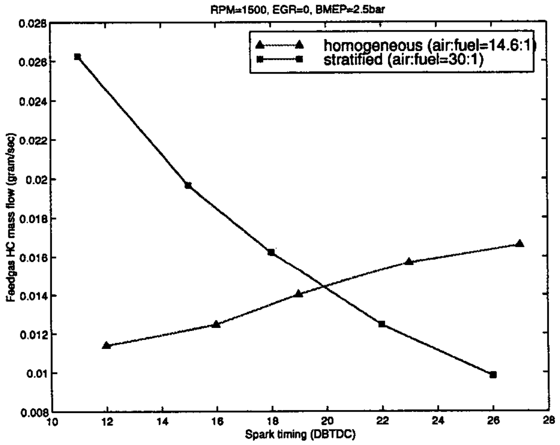

Figure 3: Behavior of feedgas HC emissions as a function of spark timing for a DISC engine.

4 Aftertreatment Modeling for DISC Engines

The typical three-way catalytic converter (TWC) used to minimize exhaust emissions during homogeneous charge, stoichiometric operation is ineffective in reducing oxides of nitrogen in the lean and stratified charge regimes that provide the fuel economy benefits of the DISC engine. A lean NO_x trap incorporates a storage element (typically barium) to trap NO_x during lean operation. The trap must be periodically purged by operating rich of stoichiometry, where the retained NO_x is reduced to N_2 by association with CO and HC in the exhaust.

The operation of the LNT is detailed by the following reactions: under lean conditions, NO_x is oxidized to NO_2 and stored as barium nitrate.

$$\begin{aligned} NO + (1/2)O_2 &\Leftrightarrow NO_2 \\ BaCO_3 + 2NO_2 &\Leftrightarrow Ba(NO_3)_2 \end{aligned}$$

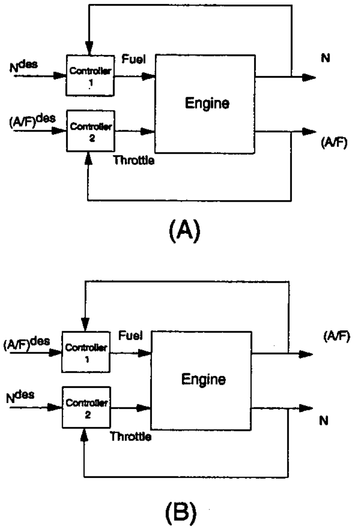

Figure 4: Idle speed controller topologies: in (A), speed regulation is the dominant control objective, and is associated with the fast fuel actuator. In topology (B), A/F regulation is the dominant objective, so the actuators are switched.

Under rich conditions, the barium nitrate releases NO_2 which, in the presence of CO and HC over the catalyst, is converted to nitrogen, restoring the original barium carbonate trapping constituent.

$$\begin{aligned} Ba(NO_3)_2 &\Leftrightarrow BaO + 2NO_2 \\ 2NO_2 + 2CO &\Rightarrow N_2 + 2CO_2 \\ BaO + CO_2 &\Rightarrow BaCO_3 \end{aligned}$$

Obviously, a crucial trade-off exists between low emissions (frequent trap purging) and high fuel economy (maximum lean operation), and thus the purge control policy must be carefully optimized to meet these conflicting goals. Wang *et al.* [21] develop a phenomenological model of the LNT to undertake this trade-off study. The model represents the storage mechanism as

$$\dot{x} = \frac{W_{NO_x}}{C}\left(1 - \frac{x}{r(T)}\right) \tag{5}$$

and purge operation as

$$\dot{x} = f(W_{HC}, W_{CO}) \tag{6}$$

where x is the mass of NO_x stored, T is the LNT temperature, $r(T)$ is the available storage capacity at a given temperature and W_{NO_x}, W_{HC}, W_{CO} are the flow rates of the constituent exhaust emissions. To fully represent the DISC aftertreatment system, the LNT model must be augmented with a conventional TWC model [22] that manages emissions during stoichiometric operation, and affects the oxygen and temperature dynamics ahead of the trap. The available LNT capacity depends strongly on the amount of NO_x already stored and the LNT temperature. Since the instantaneous trap capacity is not measurable, an accurate estimate must be developed on-line to predict the LNT state and initiate or terminate the purge operation. In [23], a method is developed to identify and adapt the parameters of the LNT model to mitigate effects of uncertainty and variations with operating condition and age.

5 Model-based Systems Development

In this section, the DISC and aftertreatment models are combined, and a dynamic programming-based systems engineering method is described in which fuel economy and emissions trade-offs can be evaluated as a function of physical design parameters and controller structure.

The lean NO_x trap component of the DISC powertrain system leads to a dynamic optimal control problem because fuel consumption and emissions, evaluated over a specified driving cycle, are not simply functions of the instantaneous speed-load point, but of the operating history of the engine. Kang *et al.* [24, 25] introduce a method that dramatically reduces the computational burden of dynamic programming to make model-based design decisions for the lean burn DISC powertrain, and present results showing the sensitivity of the fuel economy performance objective at European Stage IV emission standards with respect to physical aftertreatment parameters, including the amount of oxygen storage in the TWC and the capacity of the lean NO_x trap. These results are illustrated in Figures 5 and 6. In another trade-off study, control complexity was evaluated with respect to emissions benefit. Specifically, the lean homogeneous combustion mode was eliminated, and the optimal fuel economy calculated constrained by Stage III and Stage IV requirements. It was determined, as illustrated in Figure 7, that as NO_x emission requirements become more stringent, the benefits of operating the engine in the homogeneous lean mode become less appreciable, up to a point where the incremental benefits may not be enough to justify the additional complexity.

The most important contributions of [24, 25] are methodological. In particular, the computationally intense dynamic programming algorithm is rendered tractable by model simplification, state descretization, an analysis-based restriction on the search trajectories (called "calibrations") and careful treatment of computational details. The dynamic programming problem for a two-state system (TWC plus LNT) over a an emissions drive-cycle was reduced to 40 minutes from 60 hours, while still achieving a near-optimal solution as shown in Figure 8.

6 Automotive Powertrain Controller Development using CACSD

We have presented the technical challenges facing automotive powertrain control developers, and described a DISC case study that relies on model-based control design and system optimization to robustly achieve fuel economy and emission goals. The story, however, does not end there. The ultimate realization of the control system is embedded, distributed soft-

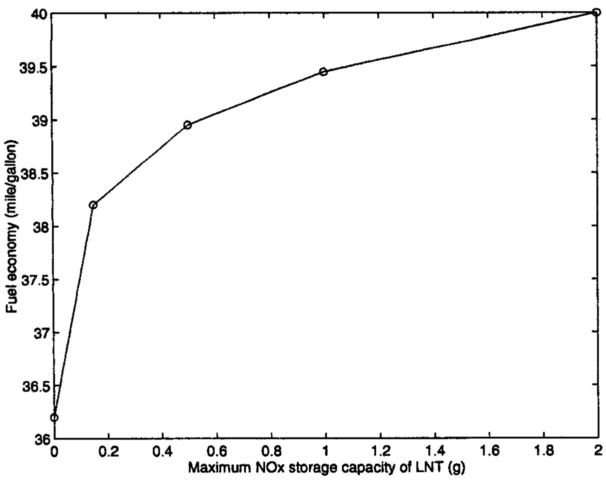

Figure 5: Fuel economy satisfying Stage IV NO_x Emission Standard of Euro-cycle with various maximum trap capacity of LNT.

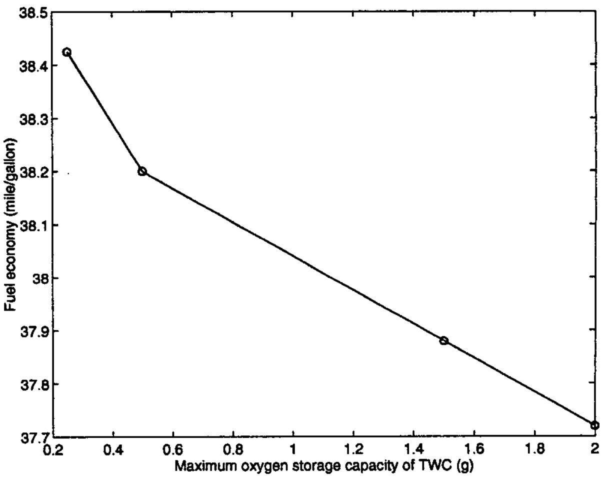

Figure 6: Fuel economy satisfying Stage IV NO_x Emission Standard of Euro-cycle with various maximum oxygen storage capacity of TWC.

ware and hardware incorporating design detail significantly beyond the control architecture. The software instantiation of the control law must seamlessly integrate with legacy powertrain code, be reusable across multiple powertrain families, and incorporate diagnostics, failure management, and well-defined start-up and shut-down procedures. It must, moreover, be maintainable, and generated within a process that supports increasingly shorter product development time at reduced cost, and with high quality.

Butts *et al.* [26] describe a model-based engineering process and CACSD toolset that emphasizes three critical elements of the software development process: (1) verification and validation to ensure faithful implementation of functional requirements, (2) feedback to previously executed development stages and (3) engineering analysis throughout. The vision behind the process illustrated in Figure 9 is that control law designs are validated through simulation and rapid prototyping (RP), and result in an executable software specification (an algorithm model) against which hand-generated code may be verified or from which code may be automatically generated. The embedded implementation of the control system is verified by hardware-in-the-loop (HIL) simulation before ultimate vehicle implementation and calibration. Also key is the concept that models developed for control design may be re-used throughout the process for RP development, autocode generation and HIL system verification [27]. As one might expect, current practice when compared with this vision of a seamless flow of model-based information from requirements generation and control design through embedded implementation and calibration comes up somewhat short, with the result that there are a number of important systems engineering research opportunities such as:

- Multiple view modeling
- Model composition
- Dynamical analysis of hybrid systems
- Automatic code generation, analysis and functional allocation

Multiple view modeling refers to the ability to exchange domain-specific views of the system model throughout the development process from requirements capture to embedded software implementation. It is closely related to meta-modeling for the purpose of model information exchange among analysis tools appropriate to distinct elements of the embedded product development process. Magner *et al.* [28] describe model transformation requirements to support architecture definition, software synthesis, strategy development and embedded implementation.

Model composition refers to a development environment that facilitates the automatic composition of system models from archived, reusable components [29]. This research is motivated by the fact that models are usually developed for a specific purpose, and rarely reused beyond the original application because of the time-consuming modifications often required to resurrect and interface them for a new design. Automatic composability ("plug and play") requires interface definition among models in three areas: signals, execution criteria and calibration parameters. Signal composability consists of connectivity, type resolution (data type, units, dimension) and name ambiguity. Execution composibility refers to compatibility of simulation methods between subsystems. Calibration composability refers to methods of handling large sets of parameters that define multiple instantiations or calibrations of the same model structure.

Hybrid systems analysis in the sense of embedded software design refers to the fact that the embedded controller is substantially made up of discrete valued states describing the mode of operation, while the physical plant contains continuous-valued states plus, in the

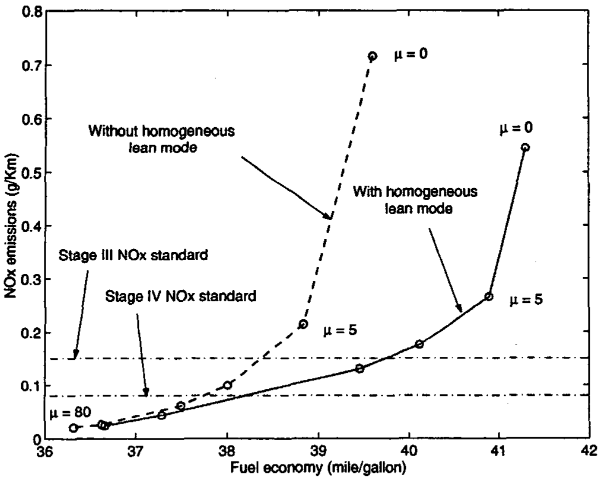

Figure 7: Fuel economy and NO_x emissions over Euro-cycle with, and without homogeneous lean mode.

DISC case, hybrid dynamics. Currently, system validation is achieved by extensive simulation. Exhaustive simulation is impossible, however, even for moderately complex systems. Analysis requirements include verifying state and path achievability, mode transition integrity (cyclic behavior) and scenario evaluation (determination of whether there exists a condition under which a specified, undesirable state might be achieved). An assessment of the current status of algorithmic approaches to the verification of hybrid systems is given in [30].

Automatic software generation from executable models is a reality. Nonetheless, research continues to increase the efficiency and flexibility of the generated code. Automatic unit test vector generation, scheduling analysis and allocation of model-based functional requirements in a distributed computing environment are remaining challenges.

7 Opportunities in Automotive Powertrain Control Applications

In this paper, we have briefly described the fuel economy and emission challenges facing the automotive industry, and described a model-based systems development process essential to the application of "control critical" advanced technology powertrains. An example of a direct injection stratified charge (DISC) engine and aftertreatment system was discussed in which an optimal control policy and multivariable control design rest on a foundation of phenomenological model development. Many research opportunities remain with direct application to powertrain control, and we conclude by enumerating a few of the most interesting ones:

7.1 Data-driven Model Development for Complex Systems

Phenomenological models combine a structure based on first principles with identified parameters to provide a representation that incorporates the essential dynamics and behaviors required for control design. For powertrain control, mapping the system behavior (torque, emissions, fuel consumption, ...) over the engine operating range for each of the control inputs (spark advance, A/F, ...) typically provides the parameterization.

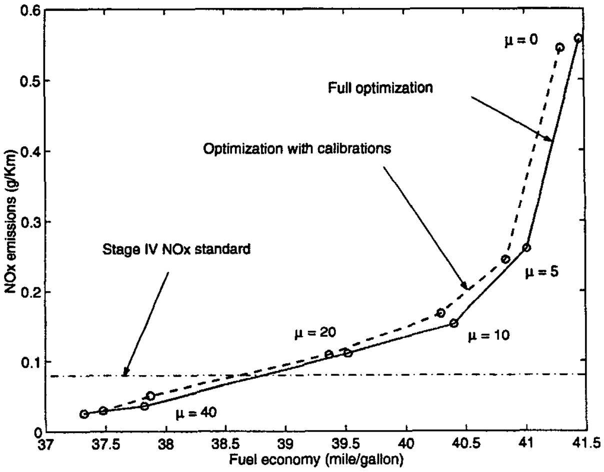

Figure 8: Fuel economy versus NO_x emissions of optimal policy with calibrations and from full optimization, over the Euro-cycle. The DISI engine, TWC models are quasi-static. The LNT NO_x filling and emptying is dynamically updated.

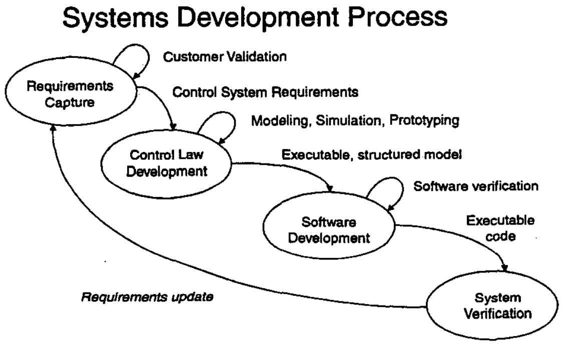

Figure 9: Model-based development process for embedded software

Complexity increases exponentially with the number of degrees of freedom of the system, and the time required to develop data-driven models of engine systems with many inputs and modes is simply not available. For example, adding independently variable intake and exhaust cam timing to a conventional engine increases the number of mapping data points by a factor of about thirty. An area for research: how do we build models from sparse data sets, while retaining sufficient accuracy and the domain knowledge so important to engineering decision making and automatic control design?

7.2 Hybrid Systems Analysis

Just as it was previously argued that hybrid systems analysis methods must replace simulation for functional verification of embedded systems and software, effective control analysis and design methods are required for multi-mode plants. For example, the DISC idle speed problem of [20] has neither a formal stability proof nor performance guarantee, except as illustrated by simulation. Hybrid systems analysis is a well-established research area; the DISC idle speed problem is recommended as a practical test bed for the theory being developed.

7.3 System Optimization

Optimization and trade-off studies such as those described in [24] have proven invaluable in defining the aftertreatment configuration and control law objectives for the DISC engine. Great effort, however, was expended in making the multi-objective, dynamic optimization problem computationally tractable for a two-state (TWC and LNT) system. Another research opportunity: development of optimal control law computation methods for realistic systems on the order of five or more states.

7.4 Fault Isolation and Accomodation

Although redundant hardware (and software) is common for critical applications (electronic throttle control, for example), cost considerations require fault accomodation, in general, to be realized through control reconfiguration for many automotive systems. For example, LNT failure must be detected and DISC engine operation restricted to stoichiometry for emissions management using only the conventional TWC. Similarly, sensor and actuator failures must be accomodated, while maintaining safe vehicle operation, with as little sacrifice to fuel economy, emissions and driving performance as possible. Research opportunities: fault detection, fault tolerant and reconfigurable control with stability and performance guarantees in the presence of sensor and actuator failures.

7.5 Model-based Systems Engineering Tools

We have stated that complex data-driven powertrain models are challenging to develop, but essential to achieving control objectives. We hope that, through the DISC engine example, a flavor of the powertrain control challenge has been imparted. We have perhaps hinted at automotive development cycles distinguished by ever-changing hardware, short timelines and hard-to-capture requirements ("driveability"), and we have suggested some research opportunities to address these issues. The final research opportunity is to put it all together: creating a model-based *environment* for automotive powertrain systems development, facilitating requirements capture, model composition, system optimization (trade-off and sensitivity analysis) and embedded implementation for personal mobility that achieves environmental goals and remains fun to drive.

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8 Appendix DISC Engine Model

8.1 Intake Manifold Dynamics and Volumetric Efficiency

The intake manifold dynamics are derived from the ideal gas law:

$$\dot{P}_i = K_i(W_a + W_{egr} - W_{cyl}) \tag{7}$$

where K_i depends on the intake manifold volume and temperature, W_a, W_{egr} are the mass flow rates through the throttle body and the EGR valve, respectively; W_{cyl} is the mean value of the charge inducted into the cylinders over an engine cycle. The flows through the throttle body and EGR valve are represented by a standard orifice equation:

$$W_a = \frac{A_{th}P_i}{\sqrt{T_a}}\phi\left(\frac{P_i}{P_a}\right), \quad W_{egr} = \frac{A_{egr}P_e}{\sqrt{T_e}}\phi\left(\frac{P_i}{P_e}\right) \tag{8}$$

where A_{th}, A_{egr} are the effective flow areas for the throttle body and EGR valve respectively; P_i, P_e, and P_a are intake manifold, exhaust manifold and ambient pressures; T_a and T_e are the ambient and exhaust temperatures. The function ϕ represents the effects of the pressure ratio across the valve in the sub-sonic flow region:

$$\phi(x) = \begin{cases} \gamma^{\frac{1}{2}}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} & \text{if } x \leq \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \\ x^{\frac{1}{\gamma}}\left\{\frac{2\gamma}{\gamma-1}\left[1 - x^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} & \text{if } x > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \end{cases} \tag{9}$$

where γ is the ratio of specific heats which takes different value for W_a and W_{egr}.

The following static regression equation is used to represent the engine pumping rate:

$$W_{cyl} = (f_0^1 + f_1^1 N + f_2^1 T_i + f_3^1 P_i + f_4^1 N P_i + f_5^1 T_i P_i)N, \tag{10}$$

where $f_i^1, i = 0, \cdots, 5$ are coefficients which can be determined by regressing the test data using curve fitting techniques. The intake manifold temperature depends on the air mass flow and EGR as determined by the function:

$$T_i = f_0^2 + f_1^2 E + f_2^2 W_a + f_3^2 E^2 + f_4^2 E W_a + f_5^2 W_a^2 \tag{11}$$

with E being the mass percentage of EGR in the intake manifild defined as

$$E = \frac{W_{egr}}{W_a} \times 100.$$

The volumetric efficiency for the engine can be then calculated as:

$$\eta_e = \frac{120 W_{cyl}}{\rho_{a,i} V_d N},$$

where $\rho_{a,i}$ is the air density in either the ambient (in which case η_e defines the breathing efficiency of the entire intake system, including throttle, intake ports and valves) or intake manifold (η_e then reflects the efficiency of the intake ports and valves), V_d is the engine displacement volume.

8.2 Engine Rotational Dynamics and Torque Generation

Engine rotational dynamics follow the equation:

$$\frac{\pi}{30} J_e \dot{N} = \mathcal{T}_b - \mathcal{T}_l \tag{12}$$

where $\mathcal{T}_b, \mathcal{T}_l$ are the engine brake and load torque in Nm, respectively, and the factor $\pi/30$ is due to the unit conversion of engine speed (from rpm to rad/sec). The engine brake torque, $\mathcal{T}_b$, is the net torque available on the crankshaft to drive the rest of powertrain, and can be decomposed into:

$$\mathcal{T}_b = \mathcal{T}_i - \mathcal{T}_f, \tag{13}$$

where $\mathcal{T}_i$ is the indicated torque, a measure of the total torque delivered to the piston by burning the fuel, $\mathcal{T}_f$ is the total friction which the engine has to overcome when delivering the torque to the crankshaft.

Engine pumping losses and rubbing friction. The friction torque includes the pumping losses during the intake and exhaust strokes, and the mechanical rubbing friction to overcome the resistance due to the moving parts of the engine.

$$\mathcal{T}_f = f_0^p + f_1^p P_i + f_2^p N + f_3^p P_i N + f_4^p N^2, \tag{14}$$

Indicated torque The indicated torque is a measure of thermal efficiency in converting the fuel chemical energy into work at the piston during the combustion process.

$$\mathcal{T}_i = (a_t + b_t(\delta - \delta_M)^2) W_f, \tag{15}$$

where W_f is the fueling rate (in g/s), $\delta - \delta_M$ is the spark timing deviation from the maximum efficiency setting δ_M, and a_t, b_t are the coefficients for the torque model represented by the following functions:

$$a_t(N, r_c) = f_0^{a_t} + f_1^{a_t} N + \frac{f_2^{a_t}}{N} + f_3^{a_t} r_c, \tag{16}$$

$$b_t(N, r_c, F_c) = f_0^{b_t} + f_1^{b_t} r_c + f_2^{b_t} F_c + f_3^{b_t} N + \frac{f_4^{b_t}}{N} + f_5^{b_t} F_c N. \tag{17}$$

8.3 Feedgas Emission Models

The following functions are used to regress dynamometer emission data:

$$W_{HC} = \begin{cases} (a_{hch} + b_{hch}(\delta - \delta_M)) W_f & \text{stratified} \\ (a_{hcs} + b_{hcs}(\delta - \delta_M))(W_f + W_a) & \text{homogeneous} \end{cases} \tag{18}$$

$$W_{nox} = (a_{nox} + b_{nox}(\delta - \delta_M)) W_f \tag{19}$$

where W_f is the fueling rate. The $a's$ and $b's$ in the emission model depend on $(P, N, r_c, F_c, t_{inj})$. The CO emissions for homogeneous operation resemble those of a typical PFI engine and are primarily a function of air-fuel ratio and exhaust mass flow:

$$W_{co} = f(r_c)(W_a + W_f). \tag{20}$$

For stratified operation, other than the similar dependency of the CO emissions on air-fuel ratio and exhaust flow rate, the engine speed and spark timing also have some influence on the feedgas emissions, especially when the air-fuel ratio is relative rich (less than 28:1). The HC and CO emissions are higher than in the homogeneous case because of the local rich mixture. Therefore, we used the following function to represent the CO emissions for the stratified operation:

$$W_{co} = f(r_c) g(N, \delta)(W_a + W_f) \tag{21}$$

where r_c is incorporated in the function g to account for the fact that the dependency of CO on N and δ is significant only when r_c is relatively rich in the stratified operation.

8.4 Exhaust Temperature

The static exhaust temperature is represented by two polynomial functions with different inputs for stratified and homogeneous operation, i.e.,

$$T_e = \begin{cases} T_s(F_f, N, P_i) & \text{stratified} \\ T_h(\delta, N, \mathcal{T}_b) & \text{homogeneous,} \end{cases} \tag{22}$$

where $F_f = W_f/(W_f + W_a + W_{egr})$ is the fraction of fuel in the total exhaust gas. The functions T_s and T_h are second order polynomial functions.

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