

Vehicle Powertrain Thermal Management System Using Model Predictive Control

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ABSTRACT

An advanced powertrain cooling system with appropriate control strategy and active actuators allows greater flexibility in managing engine temperatures and operating near constraints. An organized controls development process is necessary to allow comparison of multiple configurations to select the best way forward. In this work, we formulate, calibrate and validate a Model Predictive Controller (MPC) for temperature regulation and constraint handling in an advanced cooling system. A model-based development process was followed; where the system model was used to develop and calibrate a gain scheduled linear MPC. The implementation of MPC for continuous systems and the modification related to implementing switching systems has been described.

Multiple hardware configurations were compared with their corresponding control system in simulations. The system level requirements were translated into MPC calibration parameters for consistent comparison between multiple configurations. Some of the configurations were then evaluated via hardware in the loop testing prior to evaluation in a vehicle. The paper works through key steps related to the development of MPC for system level evaluation of actuators for powertrain thermal management.

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INTRODUCTION

The use of advanced cooling system actuators and control for improving vehicle fuel efficiency has been gaining significant attention. Various switching actuators such as on/off valves to enable/disable flow paths in a cooling circuit have been studied and included for fast warmup. In addition to scheduling the actuators for fast powertrain warmup, the thermal management system can also contribute to improving the vehicle fuel efficiency by operating the powertrain system at elevated coolant temperatures to reduce friction and improve thermal efficiency. Operating at elevated temperatures, however, increases the risk of temperature constraint violation in presence of fast changing disturbances, such as changes in combustion heat load, vehicle speed or demanded cabin heat. An advanced cooling system with continuous actuators and an appropriate thermal management strategy can allow greater flexibility in managing engine temperatures and operating near constraints.

Vehicle driving is a significantly transient operation and driving conditions change the heat generation and heat rejection capabilities. Merely looking at steady state optimization of the system to evaluate the effectiveness of including the actuator is insufficient. It is also important to evaluate the challenges associated with coordination of different actuators and the benefit obtained by using a continuous actuator in place of a switching actuator. Thus, numerous actuator configurations of the cooling system need to be evaluated with appropriately calibrated control strategies.

The controls and calibration should be easily reconfigurable for small changes in hardware selection. Multiple people/skills are involved in the development and system level evaluation of the cooling system as shown in [Figure 1](#). The hardware designer designs the components and provides system level requirements. The controls developer tries to analyze requirements and system behavior to develop a control algorithm that meets the requirements provided by the hardware

design team. The calibrator evaluates the software in vehicle, optimizes the controller parameters and decides if the performance of the system is acceptable.

An efficient system level evaluation of multiple configurations requires a structured controls and calibration development process to determine if the system level requirements are satisfied with the given hardware characteristics. A potential way to expedite the evaluation process is a model-based development process that leverages phenomenological models built during the design and sizing process of the cooling system.

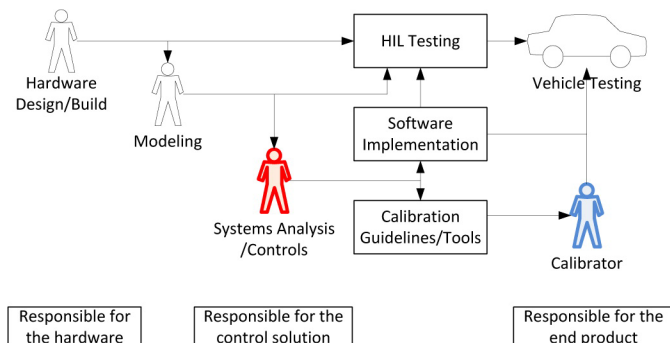


Figure 1. People (or groups) and key steps involved in the system development process.

These requirements are met by using Model Predictive Control (MPC), which is naturally suited for control problems requiring constraint management [1] [2]. A low fidelity system model is used to predict the system response to actuator commands. The actuator (control inputs) commands are chosen to optimize the system response and avoid constraint violations. Conceptually, the control design effort is then mainly focused on specifying the target temperature and constraints; and the calibration effort is mainly focused on calibrating the model and managing the trade-offs. In this work, a Model Predictive Controller was deployed using Honeywell's OnRAMP tool [3] [4], which handles controller design, tuning and deployment of MPC controllers.

The design process followed to choose between multiple actuator configurations has been elaborated in this paper. We start by building a model of the powertrain cooling system and then build four variants of the model by choosing different actuator combinations. Next, we develop MPCs for these model variants and evaluate the closed loop performance in terms of temperature regulation. This is described in the *Design of the Model Predictive Controller* section.

Once the closed loop simulation setup was available, the system performance in terms of fuel economy and temperature was evaluated for the different system variants by comparing the closed loop system responses under FTP and US06 test cycles. It is important to note that the response of critical temperatures to disturbances is faster than what the actuators can respond which requires the system to operate at lower operating temperatures to prevent constraint violations. A fair comparison is provided to all the configurations by following a consistent approach to controller tuning and adjustment of constraints for robustness. The fuel economy (FE) analysis including the impact of adjustment for robust constraint management is described in the

Simulation Results for Regulatory Cycles section. The simulation results show that the different system configurations provide similar fuel economy results for the criteria considered in this paper.

Managing the calibration challenges in implementing MPC for a nonlinear and switched system is critical for the success of this modern control method. As an example, the *Hardware in the Loop Evaluation* section compares two of the four configurations and highlights some of the design challenges associated with the valve and pump coordination. The *Vehicle Level Evaluation of the Controller* will be the scope for a future publication.

PROBLEM DESCRIPTION

Background

In [5], we discussed the development of a robust MPC for a thermal management system. A control oriented model was developed using energy balance and heat transfer equations. This control oriented model was calibrated using data generated from a high fidelity powertrain thermal system model that was previously developed for detailed system performance evaluation with existing passive actuators. The control oriented model was then modified to include active actuators, namely, an electric pump instead of a mechanical coolant pump and an electric 3-way valve instead of a passive thermostat.

A generic powertrain cooling system with engine and transmission as heat sources and the radiator and cabin air heat exchangers as heat sinks was used for the development of the MPC controller. The layout of the system is shown in Figure 2. The engine oil heat exchanger is placed in the path that bypasses the radiator. The solid blue lines indicate the cooling circuit that is applicable to this study, whereas the dashed gray lines indicate the paths which have been omitted from the study through the use of various valves typically used to aid system warmup. Their presence is treated as un-modeled disturbance and the controller is expected to be robust to these disturbances.

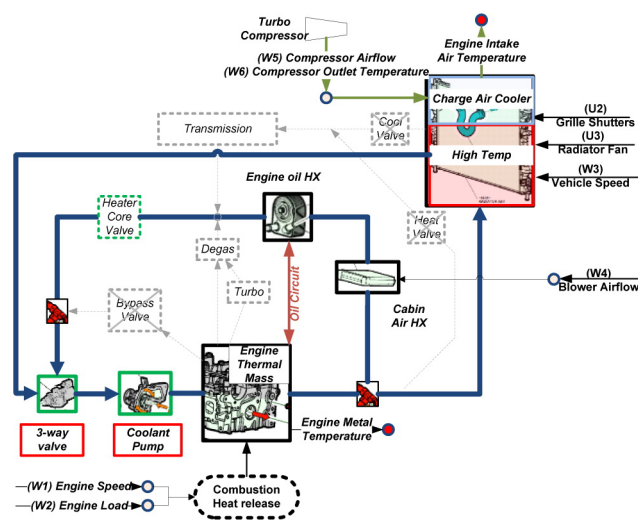


Figure 2. Schematic of the powertrain cooling system. The solid lines indicate the active circuit that has been modeled. The cross marks on the valves indicate that these paths have been shut-off by closing the valves.

In this paper, we extend the work in [5] by performing hardware tests to compare the compatibility of the active coolant pump and an active three way valve. With the main effort of model calibration complete, different configurations are evaluated in this paper. The MPC with robust constraint handling approach explained in [5] has now been used to develop the controllers for different configurations while maintaining consistent design and calibration criteria.

Control Problem

The active actuators for the cooling system are a three way valve, a coolant pump, radiator fan, and grill shutters. The focus of this work is to manage these actuators to control engine metal temperature and engine oil temperature.

The traditional thermostat is replaced by a three way valve. The three way valve was emulated using off-the-shelf valves, one in the engine bypass path and another in the path to the radiator. The opening of one valve was combined with the closing of the other valve, such that 0% command resulted in no flow to the radiator and 100% resulted in full flow to the radiator.

The coolant pump capacity is selected to meet the flow requirements at extreme cooling conditions, such as, a low vehicle speed with high engine load, in high ambient temperatures. Two variations of the coolant pump are considered, namely a mechanical pump and an electrical pump. The mechanical coolant pump speed is proportional to engine speed, whereas the electric pump follows the commanded pump speed with a first order response with 2sec time constant. The mechanical and electrical coolant pumps are chosen to have the same capacity and characteristics with respect to pump speed.

With this setup, four different configurations (see Table 1) were evaluated, with configuration “A” being the least expensive and Configuration “D” being the most expensive. A reliable continuous three way valve is significantly more expensive than having a switching (On/Off) valve, therefore a study needs to be conducted to quantify the benefit of these continuous actuators. The use of switching actuators imposes additional control design challenges and will be described later in the *Design of the Model Predictive Controller* section.

Table 1. System Configurations.

Config	3WV	Coolant Pump	RadiatorFan	GrillShutter
A	Switching	Mechanical	Continuous	Continuous
B	Continuous	Mechanical	Continuous	Continuous
C	Switching	Electrical	Continuous	Continuous
D	Continuous	Electrical	Continuous	Continuous

Although the main focus of this problem is the high temperature cooling circuit, Figure 2 also includes the charge air cooler circuit (low temperature region) because the cooling airflow to the charge air cooler is affected by the grill shutters and radiator fan. When using these actuators to manipulate engine temperature, it is important to consider the effect of these actuators on the intake air temperature leaving the charge air cooler. The charge air cooler is placed after the

compressor of a turbocharged engine to reduce the charge air temperature prior to entering the engine intake. While the intake air temperature has a weak impact on fuel economy, excessive temperature can limit the performance of the engine. It is therefore important to maintain the intake temperature within its limits.

High Level System Requirements & Metrics for Evaluation

The various high level requirements for what the system should achieve are summarized as follows:

1. The measured metal temperature should not exceed its limits, T_{metal}^{max} . The expected location of this temperature measurement is near the exhaust port. This is chosen such that the critical metal temperatures in the cylinder stay within acceptable limits.
2. Oil temperature should not exceed oil temperature limits T_{oil}^{max} for proper system functioning and durability of oil.
3. Operate the oil temperature as high as possible for optimal fuel economy. For the given setup the oil temperature is typically near the metal temperature, therefore operate the oil temperature above the metal temperature.
4. Avoid extended intake manifold air temperature excursions beyond 55degC.
5. Minimize the pump and radiator fan speeds for reduced power consumption.
6. Whenever possible, minimize the AGS opening to reduce aerodynamic drag.

The controllers are also evaluated on the resulting engine fuel consumption. For a detailed analysis, all the different components shown in Figure 3 would need to be included. For the demonstration in this paper, only the engine pumping, engine friction and combustion phasing impact on fuel consumption have been used. The details related to the fuel consumption term are provided in [5].

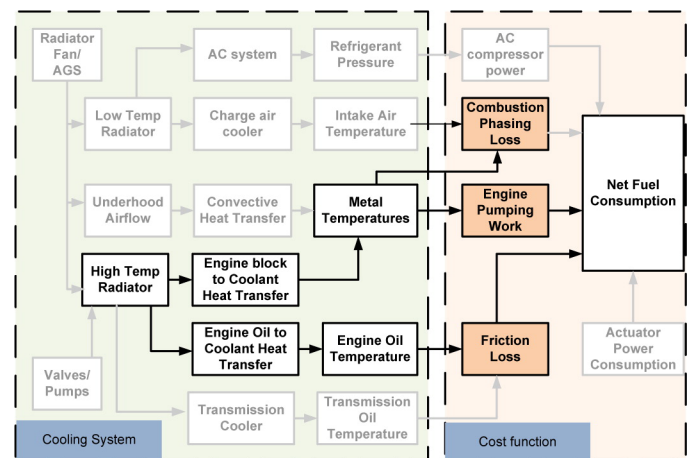


Figure 3. Fuel Consumption loss for a generic vehicle thermal management system. In this paper, only a subsection of the system is considered.

The test scenarios include an FTP75 and US06 drive cycle. The US06 is more aggressive and has frequent changes in the operating conditions compared to the FTP75 drive cycle (see Figure 1). The optimal fuel consumption for the two tests is calculated assuming that