

Calibration and Demonstration of Vehicle Powertrain Thermal Management Using Model Predictive Control

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ABSTRACT

Control of vehicle powertrain thermal management systems is becoming more challenging as the number of components is growing, and as a result, advanced control methods are being investigated. Model predictive control (MPC) is particularly interesting in this application because it provides a suitable framework to manage actuator and temperature constraints, and can potentially leverage preview information if available in the future. In previous SAE publications (2015-01-0336 and 2016-01-0215), a robust MPC control formulation was proposed, and both simulation and powertrain thermal lab test results were provided. In this work, we discuss the controller deployment in a vehicle; where controller validation is done through road driving and on a wind tunnel chassis dynamometer. This paper discusses challenges of linear MPC implementation related to nonlinearities in this over-actuated thermal system. Specifically, the fan and grill shutter actuators have a nonlinear influence on the individual airflows through the charge air cooler and radiator heat exchangers, and the design choices in dealing with these nonlinearities affects the control performance and controller memory requirements. The memory requirements of the resulting controller are also analyzed and compared to other MPC controllers.

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INTRODUCTION

The traditional engine cooling system, with only a mechanical water pump, wax thermostat and high temperature radiator, is becoming less common due to the increased cooling demands of advanced powertrains and the pressure to increase efficiency in every subsystem on a vehicle. The new or additional cooling hardware is likely to be actively controlled in order to achieve state of the art performance and efficiency; posing a growing controls challenge to manage this complexity.

The automotive industry is aware of the challenges that come from increasing complexity and is actively working to improve not only the performance and efficiency of the components in thermal management systems, but also the control [1]. Increasingly precise control of powertrain component temperatures, especially the engine, is needed to maximize efficiencies and also to protect against failure. Actuator power consumption must also be aggressively managed in order to maximize efficiency. Many times these are competing demands, which provides the motivation behind applying advanced control methods to manage these requirements.

Ford has been working with Honeywell to apply model predictive control (MPC) [2] [3] as a potential solution to manage the growing complexity in thermal systems as well as improve the control. MPC

naturally handles MIMO systems with coupled dynamics, while more traditional approaches, such as PID controllers, can become difficult to design as the system complexity grows. MPC also offers the benefit of constraint management, which is particularly useful for handling component temperature limits. Furthermore, the ability of MPC to use disturbance preview information, if available from a connected or autonomous vehicle for example, could enable even more efficiency improvements.

In earlier publications [4] [5], an advanced thermal system was introduced and the efficiency benefits from optimal temperature control were presented. Once the system characteristics were understood, a control framework for robust MPC was evaluated in simulation. Simulation results were then followed by testing in the thermal lab; where the controller was reconfigured to match hardware changes. Now, in this publication, the controller has been applied to a thermal system in a test vehicle for verification both in real world driving and on a chassis dynamometer in a wind tunnel. This paper discusses the system analysis, controller calibration, and controller validation that were part of the vehicle implementation.

In addition to the controller calibration, when deploying a controller on a powertrain control module, care must be taken to understand the memory footprint and processor computations required. The choice to

use a linear MPC can reduce computation loads by pre-defining linear models offline. However, the nonlinearities in the system may require storage of multiple linear models which increases the memory footprint. This is reviewed in the last section in the paper.

PROBLEM DESCRIPTION

Background

The vehicle thermal system used for our controls development includes a traditional high temperature radiator, oil cooler, heater core (cabin air heat exchanger), and mechanical water pump. A continuous three-way valve is used instead of the conventional wax pellet thermostat to allow for active control of the ratio between the radiator coolant flow and the bypass flow.

The vehicle uses a turbocharged engine with an air-to-air charge air cooler (CAC), which is used to cool the compressor outlet air. The airflows over both the radiator and the CAC are controlled by grill shutters and an electric cooling fan (both continuous). A schematic of the system is shown in Figure 1.

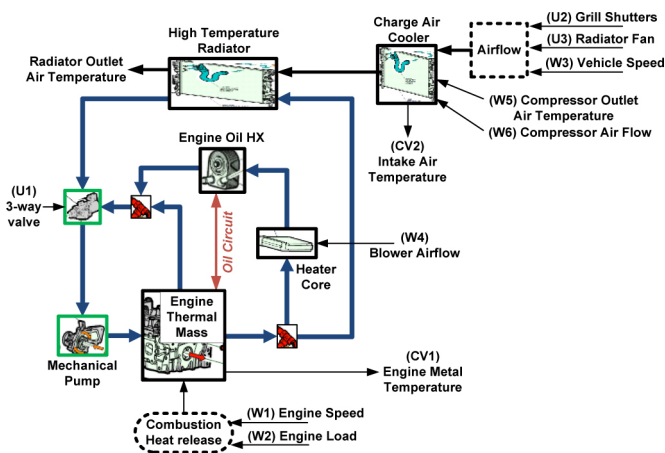


Figure 1. Powertrain cooling system schematic

Combustion heat is added to the system through the engine block and is then transferred to the coolant flowing through the engine. The amount of heat added depends on the engine load and speed. The coolant flow is governed by a mechanical pump at the engine inlet and the pump speed is coupled to the engine speed. Coolant flow from the engine can be cooled through the radiator, used to warm the passenger compartment through the heater core, or control oil temperature through the engine oil heat exchanger. When flow is allowed to bypass the radiator, depending on the three-way valve position, the heater core and engine oil heat exchanger branch share the flow with a bypass branch which is used to directly recirculate the coolant back to the engine. The flow split between these two branches is determined by the flow resistances in the system and cannot be actively controlled.

Airflow through the vehicle grill allows both the CAC to cool the compressed intake air from the turbocharger outlet and the radiator to cool the coolant. The cooling airflow to the CAC and radiator are a function of the same inputs: vehicle speed, grill shutter position, and

radiator fan speed. Since the CAC is in front of part of the radiator, the heat rejected through the CAC affects the temperature of the air entering the radiator. This paper focuses on the interactions and nonlinearities of the CAC and the radiator airflows.

Interferences such as turbocharger cooling and transmission oil heating/cooling were present, but not included in the system diagram or control problem formulation. These are considered to be unmeasured and un-modeled disturbances, which the controller must reject robustly.

CAC and Radiator Airflow Characteristics

In the previous thermal lab work [5], the radiator airflow was controlled solely by the fan, since the radiator (and thermal system) was stationary. Additionally, a heat source was used to emulate the heat transferred to the coolant from the engine block and there was no CAC since there was no engine air to be cooled. As a result, in this current work the CAC and radiator airflows in response to the grill shutters, fan, and vehicle speed inputs, had to be understood and modeled. The controller was configured to control both the CAC and radiator airflows using the grill shutters and radiator fan. This further increased the complexity compared to the system used in the previous work.

The behavior of the CAC and radiator airflows was evaluated using CFD simulations and the results, shown in Figure 2, illustrate some interesting differences. The authority of the radiator fan to increase airflow diminishes as the vehicle speed increases (fan on/off shown by comparing the dashed lines to the solid lines). Note that at 70mph a radiator fan input can cause almost no change in airflow through either heat exchanger. Notice also that the airflow to the CAC reduces with increasing grill shutter position above about 33% and this effect is more pronounced at higher vehicle speeds. The radiator airflow however, always increases with increasing grill shutter position.

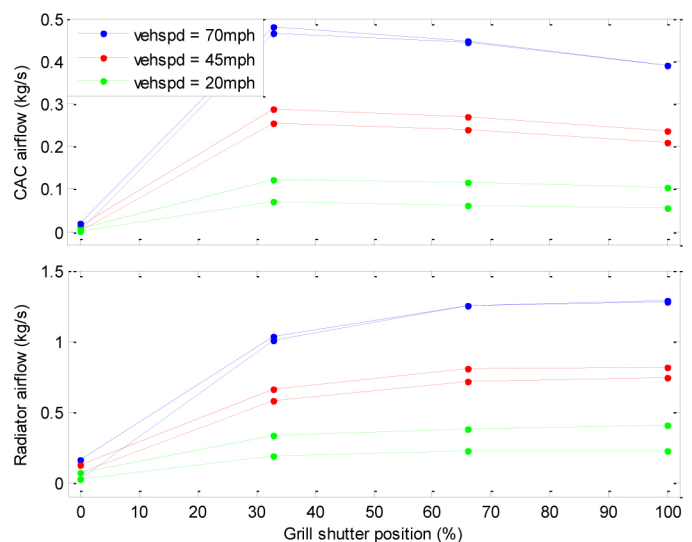


Figure 2. Airflows through the CAC and radiator as a function of grill shutter position, radiator fan speed and vehicle speed. The colors correspond to various vehicle speeds, and the solid versus dashed lines represent when the fan is off or on, respectively.

The differences in the behaviors of the CAC and radiator airflows create some controls challenges. Note that the airflows through the CAC and radiator cannot be controlled independently. Furthermore, since the intake air and engine metal temperatures are known to be affected by these flows, controlling each of these temperatures independently can be difficult. Therefore, the controller was designed to regulate the intake air temperature within a range and to control the engine metal temperature to a setpoint. The three-way valve also provided an additional degree of freedom to allow for setpoint tracking.

GRILL SHUTTER AND RADIATOR FAN INTERACTIONS

Since the grill shutters and fan can both interact to control airflow, coordination needs to take place to ensure that there are not counteracting actions, causing inefficiencies. For example, if the grill shutters were completely closed, the fan should not be commanded to full speed. By comparing the vehicle drag benefit of closing the grill shutters to the electrical power consumption of the fan, the optimal split of grill shutter angle and fan power at a given vehicle speed can be determined in order to achieve the desired airflow. In this work, we assumed that the fan energy cost was relatively high compared to the grill shutter drag benefit. This means that the fan would only be used after the grill shutter airflow was maximized. Minimizing the fan usage may also be beneficial from an NVH perspective.

Considering the grill shutters and fan to be separated actuators, one can envision a threshold where the grill shutters are not restricting airflow and the fan is not yet used to further increase airflow. This threshold will be referred to as the base airflow and it is shown below in [figure 3](#). It allows for the grill shutters to be thought of as an airflow decreasing actuator, while the fan would be an airflow increasing actuator. The challenge is that the unrestricted (base) airflow actually comes at different grill shutter positions for the CAC and radiator (as shown in [Figure 2](#)). This conflict adds to the challenges discussed in the next section.

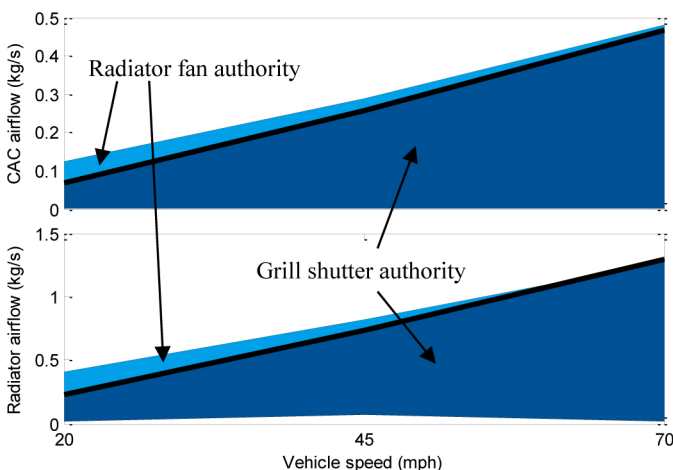


Figure 3. Radiator fan and grill shutter authority over CAC and radiator airflow as a function of vehicle speed. Radiator fan authority is shown in light blue and grill shutter authority is shown in dark blue.

Airflow Control

As alluded to in the previous section, careful attention must be given to the interactions of the control inputs, particularly the ones related to the airflows in the system. Not only does the interaction of the grill shutters and fan need to be managed, but also, the ability of these actuators to affect the airflow (control gain) changes greatly as a function of vehicle speed. For scheduled linear MPC, these nonlinearities can affect the amount of scheduled operating points and affect the controller footprint, as discussed later in the *Controller Formulation* and *Controller Footprint* sections.

Three different methods for controlling the CAC and radiator airflows were considered. The background and merits of each approach are discussed below, with the third method being the chosen solution used to generate the results found later in the paper.

1. **Radiator airflow control** – Create a virtual airflow actuator where the controller commands the radiator airflow only and it is then mapped to the respective grill shutter and fan positions by inverting the radiator airflow data.

Pros: This method avoids the nonlinearities in the actuator gains, possibly allowing for a reduction in the number of linearization points necessary in the MPC controller. It also allows for the control designer to manipulate the grill shutter and fan input conversion tables in order to achieve the desired level of interaction or separation.

Cons: Creating a virtual actuator to handle nonlinearities can cause new challenges. In this case, the actuator range becomes dynamic (maximum airflow is a function of vehicle speed) and must be computed and provided to the controller. Also, the controller is now controlling only a single airflow, which we have chosen to define as the radiator airflow. This would introduce nonlinearity into the CAC heat rejection behavior since there is not a fixed relationship between the CAC and radiator airflows. Furthermore, from [Figure 2](#) it can be seen that when the grill shutters are at higher opening percentages, and opening further to increase the radiator airflow, the CAC airflow is actually decreasing. This neglected gain sign change may be tolerable since the gain of the grill shutters is very small at high openings (can be thought of as un-modeled deadband), but it is still undesirable. Remember that the CAC intake air outlet temperature is only controlled within a range, rather than to a setpoint, providing more allowance for error.

2. **Delta radiator airflow control** – Create a virtual airflow actuator where the controller commands only the delta radiator airflow above or below the base radiator airflow.

Pros: This approach builds on the first method, where the actuator nonlinearities are improved, but it also allows for vehicle speed to be used as a disturbance variable in the controller. Therefore, if the controller is made aware of a future change in vehicle speed, potentially available via a preview, it could account for the change in airflow as a function of vehicle speed, which could potentially improve the control performance. This method also allows for easy separation of the actuators