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Reducing auxiliary energy consumption of heavy trucks by onboard prediction and real-time optimization

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HIGHLIGHTS

- Development of an MPC controller for an electrified engine-cooling system.
- Formulation of the optimal-control problem as a quadratic program.
- Comparison of the MPC controller to dynamic programming and a base-line controller.
- The MPC controller reduces fuel consumption by 0.36–0.69%.
- The MPC controller is implemented and successfully tested on a real truck.

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ABSTRACT

The electric engine cooling system, where the coolant pump and the radiator fan are driven by electric motors, admits advanced control methods to decrease auxiliary energy consumption. Recent publications show the fuel saving potential of optimal control strategies for the electric cooling system through offline simulations. These strategies often assume full knowledge of the drive cycle and compute the optimal control sequence by expensive global optimization methods. In reality, the full drive cycle is unknown during driving and global optimization not directly applicable on resource-constrained truck electronic control units. This paper reports state-of-the-art engineering achievements of exploiting vehicular onboard prediction for a limited time horizon and minimizing the auxiliary energy consumption of the electric cooling system through real-time optimization. The prediction and optimization are integrated into a model predictive controller (MPC), which is implemented on a dSPACE MicroAutoBox and tested on a truck on a public road. Systematic simulations show that the new method reduces fuel consumption of a 40-tonne truck by 0.36% and a 60-tonne truck by 0.69% in a real drive cycle compared to a base-line controller. The reductions on auxiliary fuel consumption for the 40-tonne and 60-tonne trucks are about 26% and 38%, respectively. Truck experiments validate the consistency between simulations and experiments and confirm the real-time feasibility of the MPC controller.

1. Introduction

The engine cooling system regulates the temperature of the internal combustion engine and is vital for engine performance, fuel economy, emission characteristics, maintenance, and life [1]. It is also a major source of parasitic energy loss in heavy trucks. Around 2–4% of a heavy truck's fuel consumption is incurred by the cooling system and other auxiliary loads. Substantial improvement in the energy efficiency of the cooling system results in non-trivial fuel reduction [2–4]. Even though the percentage number on fuel reduction may appear small, the improvement is still beneficial for truck owners and the environment, because an average heavy truck consumes a large amount of diesel per year.[1]

A conventional cooling system contains a coolant pump and a radiator fan that are both mechanically coupled to the engine crankshaft through simple transmission mechanisms with a limited number of transmission ratios. The transmission mechanism often relies on friction force and hence has low energy efficiency.

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[1] US Department of Energy, Average Annual Fuel Use of Major Vehicle Categories, Last update June 2015, http://www.afdc.energy.gov/data/.

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Nomenclature

$\Delta \dot{m}_f$	additional fuel rate
$\dot{m}_f$	fuel rate
$\dot{m}_r$	air mass flow rate through the radiator
η_c	coulombic efficiency of the battery
λ_0, λ_1	model parameters for the coolant flow rate through the pump
ω_f	fan speed
ω_p	pump speed
ω_e	engine speed
$\omega_{f,max}$	maximal fan speed
$\omega_{p,lb}$	lower bound for pump speed
$\omega_{p,max}$	maximal pump speed
$\omega_{p,min}$	minimal pump speed
τ_a	alternator torque
τ_d	driveline torque
τ_e	engine torque
$\tau_{a,lb}$	lower bound for alternator torque
$\tau_{a,max}$	maximal alternator torque
$\tau_{a,min}$	minimal alternator torque
$\tau_{a,ub}$	upper bound for alternator torque
$\tau_{d,max}$	maximal driveline torque
$\tau_{d,min}$	minimal driveline torque
$\tau_{e,max}$	maximal engine torque
$\tau_{e,min}$	minimal engine torque
$\mathbf{u}$	control vector
$\mathbf{w}$	disturbance vector
$\mathbf{x}$	state vector
θ_m	thermostat opening ratio
$\tilde{\tau}_d$	expected driveline torque
ξ	punishment factor for battery SOC
c_1, c_2, c_3	model parameters for the dynamics of coolant temperature
f_0, f_1, f_2	model parameters for fan power
h_0, h_1	model parameters for engine heat
$I_{alt,max}$	maximal alternator current
I_{alt}	alternator current
$I_{b,max}$	maximal battery current
$I_{b,min}$	minimal battery current
l	parameter to determine the lower bound of the coolant flow rate
M_{alt}	mechanical power loss in the alternator
p_0, p_1, p_2	model parameters for pump power
P_{alt}	alternator's output power
P_{bat}	battery power
P_{fan}	electrical power consumption of the fans
P_{oth}	power consumption of other electrical loads
P_{pump}	electrical power consumption of the pump
Q_{in}	heat power transmitted from the engine to the coolant
r_0, r_1, r_2	model parameters for engine fuel rate
SOC_{max}	maximal battery state of charge
SOC_{min}	minimal battery state of charge
t	time
T_e	coolant temperature
T_a	ambient temperature
$T_{e,high}$	coolant temperature to fully open the thermostat
$T_{e,low}$	coolant temperature to fully close the thermostat
$T_{e,max}$	maximal coolant temperature
$T_{e,min}$	minimal coolant temperature
u_p	coolant volumetric flow rate through the pump
U_b	battery voltage
$u_{p,min}$	minimal coolant flow rate through the pump
v	vehicle speed

The limited number of transmission ratios hinders the precise speed control on the pump and fan. Moreover, the full capacity of the conventional cooling system is usually designed for the engine's peak load at hot ambient temperature, which rarely occurs [5]. Consequently the actuators often operate with more power than the cooling system requires [6] thus incurring unnecessary energy loss.

1.1. Benefits of the electric cooling system

Replacing the mechanically driven pump and fan with electrical ones is an effective way to reduce parasitic energy loss from the cooling system [7–11]. The benefits of using the electric engine cooling system are reducing frictional losses, achieving thermally optimized engines, increasing lubricant oil life, decreasing engine emissions, increasing engine life and system flexibility [12]. This paper focuses on the reduction of fuel consumption, which consequently results in CO_2 emission reduction. Reduction of 2.8–5% in fuel consumption is achieved in [5,13,14] by using the electric coolant pump and valve. This reduction is not only due to the reduced energy consumption of the auxiliaries but also to the improved engine efficiency thanks to its higher temperature. The energy consumption of the pump alone is decreased by 16% in [15] and 87% in [16]. Electrification of both the pump and the fan results in 3% reduction in fuel consumption [17]. Choukroun and Chanfreau [18] improve fuel economy by 2–3% using controllable electric pump, fan and valve. All these studies indicate around 2% fuel reduction of the electric cooling system compared to the conventional one.

The above saving of the electric cooling system results from simple control methods without optimization, e.g., PI [18], PID [8,13–15,19], and rule-based control [17]. Khaled et al. [3,4] propose feedback control methods to dynamically adjust the geometric positions of the heat exchangers for enhancing cooling efficiency. The methods are applicable to both electric and mechanical cooling systems. The precise controllability of the electric pump and radiator fan enables the application of advanced control methods. In [7,20] a Lyapunov-based nonlinear control algorithm is proposed for thermal management. Salah et al. [21] develop a nonlinear back stepping robust controller to regulate the engine coolant temperature. Al Tamimi and Salah [22] apply a neural network-based optimal control strategy to regulate engine temperature with the electric cooling system. Zhou et al. [23] reduce energy consumption of the electric thermal management system by 57% compared to the conventional one by a combination of feedforward and feedback controllers. The feedforward controller minimizes the instant power consumption of the coolant pump, the oil pump, and the fan while keeping the coolant temperature constant.

These methods effectively regulate coolant temperature at the desired level and reject disturbances, but do not focus on reducing the overall energy consumption of the cooling system for a complete drive cycle. Furthermore, they do not utilize prediction of the future driving conditions.

1.2. Optimal control of the electric cooling system

Optimal control methods have also been applied to minimize the fuel consumption of the electric cooling system and other elec-