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Optimal control of a fuel-fired auxiliary heater for an improved passenger vehicle warm-up

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ABSTRACT

In order to mitigate the comfort problems during a vehicle warm-up, the vehicles propelled by high-efficiency engines are increasingly equipped with auxiliary heaters. Although the usage of an auxiliary heater improves engine efficiency during warm-up, a higher total fuel consumption results in general. In this paper, an optimal, model-based feedback control law for the optimal operation of a fuel-fired heater with respect to passenger comfort and fuel economy is derived. To this end, a control-oriented mathematical model of the system is established, calibrated, and validated. Based on this model, an optimal control problem is formulated and solved. In simulation studies, the functionality of the resulting optimal controller is demonstrated, and its superiority to the state-of-the-art control laws is assessed.

1. Introduction

Statistical studies on the use of passenger cars revealed that the warm-up phases represent a significant part of the total vehicle operation time, as the number of cold-starts is high and the mean length of travels is short. In the work of Kyriakis and André (1998), for example, it is reported that about one-third of all trips taken are traveled in thermal transient operation.[1] In order to counter the comfort and safety problems during the warm-up, the vehicles propelled by high-efficiency engines are increasingly equipped with auxiliary heating systems. Different types of auxiliary heating systems exist. A very common type of heater is the fuel-fired heater. It burns fuel directly and is characterized by a high thermal output power. The emitted heat is usually supplied to the engine coolant, upstream of the compartment heat exchanger. Besides accelerating the engine warm-up and improving the heating of the passenger compartment due to higher coolant temperatures, the auxiliary heating also mitigates other performance issues concomitant with the vehicle warm-up. Specifically, the efficiency of the engine rises with higher engine working temperatures, which leads to a lower fuel consumption of the engine. Further, as a consequence of an improved combustion process and reduced friction losses, lower emissions are produced and the engine lifetime is extended. However, additional fuel consumption may result from the fuel requirements of the heater.

The effect of the usage of fuel-fired auxiliary heaters on the warm-up process of a passenger vehicle has been reported in various publications. In the study of Lindl (2002), for example, the impact of the operation of a fuel-fired coolant heater on the emissions, the fuel consumption, and the cabin temperature is described. The effect on the cabin temperature and the design and application of such a heating system are reported by Renner (2002). Simulation studies for different auxiliary heater concepts were presented by Haubner and Koch (2002), by Hager, Stroh, and Damböck (2004), and by Yoldjou, Tuschinski, and Deußen (2002).

In several publications, the contradiction of passenger comfort demands and fuel economy was noticed, and a sophisticated management of the auxiliary heaters was identified as an appropriate measure to handle this trade-off (e.g., Eilemann & Kampf, 2001; Haubner & Koch, 2002). However, only scant attention has been given to the control of the auxiliary heaters so far. Thus, the objective of this research project was to derive feedback control laws for the optimal operation of auxiliary heaters with respect to passenger comfort and fuel economy.

The methodology applied in this paper is based on the theory of optimal control. In order to formulate and solve an optimal control problem, the dynamic behavior of the system under consideration has to be quantified first. Therefore, a control-oriented, mathematical model of the system is developed, parametrized and validated. Then, the formulation of the optimal

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[1] The study referenced is based on real-world data of vehicle operation in Europe. Similar studies exist for the US and Canada.

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control problem is addressed and an optimal feedback controller is derived. In the subsequent section of the paper, the functionality and the performance of the optimal controller are analyzed and discussed. Finally, the paper is summarized, and the conclusions are drawn.

2. Model of the vehicle system

The scope of the model is the prediction of the main temperature dynamics and of the fuel consumption characteristics during the vehicle warm-up. A causality diagram of the model with its components is shown in Fig. 1. The model consists of the vehicle dynamics subsystem, the auxiliary heater subsystem, the engine subsystem, and the passenger compartment subsystem. The controllable inputs are the control signal of the auxiliary heater, u_{FH}, the air mass flow through the compartment heat exchanger and entering the passenger compartment, $\dot{m}_{Air}^{CHx}$, and the coolant volume flow passing through the compartment heat exchanger, $\dot{V}_{Ct}^{CHx}$. The vehicle speed, v_{Veh}, the transmission ratio of the gearbox, z_{GB}, the additional external mechanical and electrical loads, θ_{Aux}^{Misc} and P_{El}^{Misc}, the ambient temperature, T_{Amb}, and an external heat flow to the passenger compartment, $\dot{Q}_{2Comp}^{Misc}$, are uncontrollable input signals. The output signals of the system are the rotational speed of the engine, ω_{Eng}, the engine torque, θ_{Eng}, the total fuel mass flow rate, $\dot{m}_{Fuel}$, the lumped engine temperature, T_{Eng}, the mean passenger compartment air temperature, T_{CAir}, the temperature of the cabin interior material, T_{Int}, and the heat flow rate transferred from the coolant in the compartment heat exchanger to the passenger compartment, $\dot{Q}_{CHx}^{Ct2Comp}$. Note that, for the sake of brevity, the explicit statement of the time dependency of the signals is omitted in the first part of this paper (up to Section 3.4).

For the parametrization and the validation of the model, experimental data was provided by Robert Bosch GmbH. The measurements were performed on an experimental vehicle of the type Mercedes-Benz E220 CDI (1999), a medium-size vehicle with a turbocharged 4-cylinder common-rail direct injection diesel engine. Table 1 lists a few technical specifications (manufacturer's data) of the vehicle. The experimental vehicle is equipped with a fuel-fired coolant heater. Some technical specifications of the fuel-fired coolant heater, as given by the manufacturer, are shown in Table 2. The coolant heater is of the type Webasto Thermo Top Z/C-D.

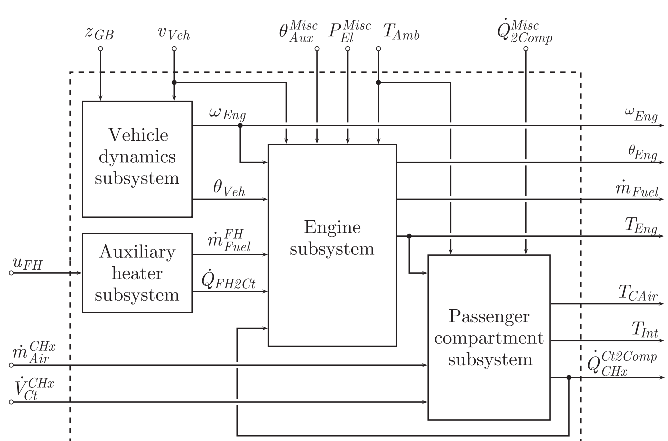

Fig. 1. Signal flow chart of the system model with vehicle dynamics subsystem, auxiliary heater subsystem, engine subsystem, and passenger compartment subsystem.

Table 1
Technical specifications of the experimental vehicle (Mercedes-Benz E220 CDI (1999)).

Characteristic	Value
Engine type/no. of cylinders	Inline/4
Engine displacement (cm^3)	2149
Power output (kW at rpm)	105 at 4200
Maximum torque (Nm at rpm)	315 at 1800
Fuel consumption[a] (L/100 km)	8.5/4.8/6.2
Vehicle weight empty (kg)	1610

[a] Urban/extra-urban/combined.

Table 2
Technical specifications of the fuel-fired coolant heater (Webasto Thermo Top Z/C-D).

Characteristic	Value
Nominal thermal output power (kW)	5.0
Nominal fuel consumption (kg/h)	0.50
Weight (kg)	2.9

2.1. Model equations

A mean value approach, mainly based on first principles, was applied to derive the mathematical model equations. In order to be able to use test cycles or driving patterns recorded on real vehicles as inputs to the system, the fuel path was modeled backward. Hence, the causality is inverted and the fuel mass flow rate follows from the speed trajectory that the vehicle is required to follow. All the system parameters are assumed to be constant unless otherwise stated.

2.1.1. Vehicle dynamics subsystem

The vehicle dynamics subsystem captures the dynamics of the longitudinal motion of the vehicle for horizontal road conditions. According to the inverse causality approach, the torque θ_{Veh} that has to be provided by the engine to drive the vehicle at a given speed, v_{Veh}, with a requested acceleration, $a_{Veh} = (\mathrm{d}/\mathrm{d}t)v_{Veh}$, is calculated from the vehicle parameters and the gear ratio, z_{GB}, as

$$\theta_{Veh} = \frac{r_W}{z_{GB} z_{Diff} \eta_{PT}} \cdot \left[\frac{1}{2} c_D A_{Veh} \rho_{Air} v_{Veh}^2 + m_{Veh} g c_R + \left(m_{Veh} + \frac{\Theta_{Tot}}{r_W^2} \right) \frac{\mathrm{d}v_{Veh}}{\mathrm{d}t} \right], \quad (1)$$

where the total inertia follows from the inertias of the wheels, the power train, and the engine, as

$$\Theta_{Tot} = 4\Theta_W + \Theta_{PT} + (z_{GB} z_{Diff})^2 \Theta_{Eng}. \quad (2)$$

The rotational speed of the engine, ω_{Eng}, is a linear function of the vehicle speed,

$$\omega_{Eng} = \frac{z_{GB} z_{Diff}}{r_W} v_{Veh}. \quad (3)$$

When the clutch is disengaged, the vehicle propulsion torque is set to zero and the rotational speed of the engine is set to idle speed.

2.1.2. Auxiliary heater subsystem

The fuel-fired coolant heater is characterized by the amount of heat supplied to the coolant, which is modeled to be proportional