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Supervisory control of a heavy-duty diesel engine with an electrified waste heat recovery system

Emanuel Feru [a,b,*], Nikolce Murgovski [c], Bram de Jager [b], Frank Willems [a,b]

[a] Powertrains, TNO Automotive, Automotive Campus 30, 5708 JZ Helmond, The Netherlands
[b] Department of Mechanical Engineering, Eindhoven University of Technology, De Rondom 70, 5612 AP Eindhoven, The Netherlands
[c] Department of Signals and Systems, Chalmers University of Technology, Hörsalsvägen 11, Göteborg, Sweden

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ABSTRACT

This paper presents an integrated energy and emission management strategy, called Integrated Powertrain Control (IPC), for an Euro-VI diesel engine with an electrified waste heat recovery system. This strategy optimizes the CO_2-NO_x trade-off by minimizing the operational costs associated with fuel consumption, AdBlue dosage, and active particulate filter regeneration, while satisfying the tailpipe emission constraints. For comparison purposes, the proposed control strategy is applied to different powertrain configurations: with and without waste heat recovery (WHR) system and a WHR system equipped with a battery for energy storage. The potential of each studied configuration is evaluated over the World Harmonized Transient Cycle for cold-start and hot-start conditions. In comparison to the existing Euro VI engine without WHR system, it is shown in simulations that the optimal IPC strategy with an electrified WHR system and battery provides an additional 3.5% CO_2 emission reduction and 19% particulate matter reduction, while satisfying the NO_x emission constraint.

1. Introduction

With the introduction of the new emission standards in Europe, USA, and Asia, the tailpipe pollutant emissions (CO, HC, NO_x, PM) of current heavy-duty diesel engines are forced towards near zero impact level. To achieve this goal, several measures have been taken, such as augmenting conventional engines with common rail fuel injection equipment, advanced turbocharging, exhaust gas recirculation and aftertreatment systems. In addition, the automotive industry is focusing on improving the fuel economy and, as a result, also reducing CO_2 emissions. However, the fuel economy of trucks remained nearly unchanged during the last two decades (ACEA, 2011). A promising way for improving fuel economy can be obtained by vehicle hybridization (Kessels, Willems, Schoot, & van den Bosch, 2010; Lyshevski, 2000; Nüesch et al., 2014). Using this approach, the pollutants need to be analyzed carefully, since a diesel hybrid electric vehicle can improve the fuel economy, but in the same time can emit more pollutants than a conventional vehicle (Filipi et al., 2006). A way to cope with pollutant constraints is by synthesizing an integrated energy and emission management strategy (Chen & Wang, 2014; Cloudt & Willems, 2011; Grahn, Johansson, & McKelvey, 2014).

Apart from vehicle hybridization, another promising solution to further reduce fuel consumption and to meet future CO_2 emission legislation is to use a Waste Heat Recovery (WHR) system (Peralez et al., 2013; Will, 2012; Xie & Yang, 2013; Yang et al., 2014). This system converts the engine exhaust gas thermal energy into mechanical energy useful for propulsion or for electrical power generation (Ziviani, Beyene, & Venturini, 2014). The WHR system is based on the Organic Rankine Cycle (ORC). The ORC uses an organic fluid instead of water better adapted to low-temperature heat sources.

Most of the studies on engines with WHR system focus on low-level WHR systems' control (Luong & Tsao, 2014; Peralez et al., 2013; Quoilin et al., 2011). Only a few studies deal with overall powertrain system performance with WHR systems (Horst, Tegethoff, Eilts, & Koehler, 2014; Willems, Kupper, Rascanu, & Feru, 2014). In Horst et al. (2014), the fuel saving potential for a passenger vehicle with WHR system based on RC is presented. The study shows the restrictions on WHR system power output due to the vehicle integration, the on-board electric system architecture, package considerations, increased weight, cooling demand, and exhaust gas backpressure. All these aspects can lead to a reduction of the fuel saving potential that can be achieved using a WHR system.

Optimizing the overall engine-aftertreatment-WHR system performance is a challenging task. This is due to interaction between the subsystems, highly dynamic nature of the driving cycle,

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* Corresponding author at: Powertrains, TNO Automotive, Automotive Campus 30, 5708 JZ Helmond, The Netherlands.
E-mail addresses: Emanuel.Feru@tno.nl (E. Feru), Nikolce.Murgovski@chalmers.se (N. Murgovski), A.G.de.Jager@tue.nl (B. de Jager), F.P.T.Willems@tue.nl (F. Willems).

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Nomenclature

A	cross-sectional area, m^2
E	energy, J
H	Hamiltonian, –
S	surface area, m^2
c_p	specific heat capacity, J/(kg K)
I	current, A
L	length, m
P	power, W
S	surface area, m^2
T	temperature, K
V	volume, m^3
$\dot{Q}$	heat flow rate, W
$\dot{m}$	mass flow rate, kg/s
SOE	state of energy, –
c_p	specific heat capacity, J/(kg K)
h	specific enthalpy, J/kg
n	number of cells, –
p	pressure, Pa
v	space velocity, 1/s
z	space coordinate, m

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
β	battery quadratic losses, 1/W
χ	vapor quality, –
δ	thickness, m
η	efficiency, –
γ	auxiliary variable, –
κ	thermal conductivity, W/(m K)
λ	Lagrange multiplier, –
ω	speed, rpm
π	price, €/g
ρ	density, kg/m^3
τ	torque, N m
ζ	time constant, s

Subscripts, superscripts and abbreviations

a	AdBlue
amb	ambient
AMOX	Ammonia Oxidation catalyst
B	battery
CAC	Charge Air Cooling
d	delivered
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
E	engine
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
exh	exhaust gas downstream aftertreatment
exp	expander
f	working fluid
fl	fuel
G	generator
g	exhaust gas
i	index
in	inlet
l	liquid
loss	losses
M	motor
max	maximum
min	minimum
MPC	Model Predictive Control
oc	open circuit
ORC	Organic Rankine Cycle
out	outlet
p	pump
PM	Particulate Matter
req	request
S	internal
SCR	Selective Catalytic Reduction
tp	tailpipe
v	vapor
VTG	Variable Turbine Geometry
w	wall
WHR	Waste Heat Recovery

different time constants of subsystems, nonlinearities, and constraints. In Willems et al. (2014), a cost-based optimization strategy is presented. This strategy integrates energy and emission management, the so-called Integrated Powertrain Control (IPC), by minimizing the total operational cost, while explicitly taking into account the tailpipe emission constraints set by legislation. The operational costs to be optimized consist of the costs for fuel, AdBlue dosage, and the fuel costs associated with active Diesel Particulate Filter regeneration.

In this paper, the integrated energy and emission management from Willems et al. (2014) is extended to a heavy-duty diesel engine with an electrified WHR system. For comparison purposes, the proposed control strategy is applied to different powertrain configurations to show the impact on operational costs. Moreover, it is investigated which configuration is most suitable for urban, rural and highway driving conditions in terms of the powertrain performance and complexity.

This paper is organized as follows. In Section 2, the studied powertrain configurations are described. Sections 3 and 4 present the high-fidelity simulation model and the control model, respectively. In Section 5, the control problem is formulated and the proposed IPC strategy is presented. The simulation results are shown in Section 6. Finally, conclusions are drawn in Section 7.

2. System description

In Fig. 1, a schematic representation of the studied system is illustrated. It is based on a state-of-the-art 12.9 l, 6 cylinder, 375 kW Euro-VI diesel engine. This engine is equipped with a common rail injection system, a turbocharger with Variable Turbine Geometry (VTG), Charge Air Cooling (CAC) and Exhaust Gas Recirculation (EGR) system. Within the EGR system, an EGR evaporator replaces the conventional EGR cooler. To meet Euro-VI emission legislation, an exhaust gas aftertreatment system is installed. This aftertreatment system includes a Diesel Oxidation Catalyst (DOC), a Diesel Particulate Filter (DPF) and an urea-based Selective Catalytic Reduction (SCR) system with an Ammonia Oxidation catalyst (AMOX) (Cloudt, Saenen, Eijnden, & Rojer, 2010). The DPF is used to filter out particulates from the exhaust flow. Periodically, the trapped particulates are oxidized by injecting fuel upstream of the DOC. This is the so-called *DPF regeneration process*. Downstream of the DPF system, the NO$_x$ component is converted into harmless products over the Cu–Zeolite SCR catalyst. This catalytic process requires ammonia (NH$_3$). The ammonia is formed by decomposing the injected urea solution (AdBlue) in the hot exhaust gases, upstream of the SCR. To avoid unacceptable ammonia slip, an AMOX catalyst is used.