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Spark ignition engine control strategies for minimising cold start fuel consumption under cumulative tailpipe emissions constraints

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ABSTRACT

This paper proposes a methodology for minimising the fuel consumption of a gasoline fuelled vehicle during cold starting. It first takes a validated dynamic model of an engine and its aftertreatment reported in a previous study (Andrianov, Brear, & Manzie, 2012) to identify optimised engine control strategies using iterative dynamic programming. This is demonstrated on a family of optimisation problems, in which fuel consumption is minimised subject to different tailpipe emissions constraints and exhaust system designs. Potential benefits of using multi-parameter optimisation, involving spark timing, air–fuel ratio and cam timing, are quantified. Single switching control policies are then proposed that perform close to the optimised strategies obtained from the dynamic programming but which require far less computational effort.

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1. Introduction

Road vehicles with internal combustion engines are a significant source of air pollution (Seinfeld, 2004). The pollutants found in the exhaust include carbon monoxide (CO), nitrogen oxides (NO and NO_2, also referred to as NO_X), unburned hydrocarbons (HC) and particulates. These substances present significant environmental and health risks, and are therefore regulated. To improve the air quality and account for the increasing number of road vehicles, the allowable emissions limits are continually tightened.

In most vehicles with gasoline fuelled engines, these emissions limits are achieved with the use of three-way catalysts in the exhaust system, designed to convert engine-out CO, NO_X and HC emissions to CO_2, H_2O and N_2. However, the chemical processes involved depend strongly on the catalyst temperature. Whilst the conversion efficiency of a hot catalyst can be high, a cool catalyst performs poorly. Consequently, cold start emissions play a critical role in meeting emissions standards.

Engine control is a cost effective approach to limit cold start emissions, whilst avoiding the need for additional or upgraded hardware. A common strategy is to retard the spark timing. This enables more heat to be rejected into the exhaust, which heats the catalyst more quickly. Another approach is to raise the engine's idle speed to produce an increased number of combustion events, and thus higher enthalpy input to the catalyst. Both of these approaches, however, result in increased fuel consumption. More generally, maximising vehicle fuel economy whilst meeting emissions standards is a key and ongoing problem faced by all car manufacturers.

Manufacturers have traditionally relied heavily on experimentation to identify engine control set-points during cold starting (the work of Dohner, 1978 is an early example). However, since every cold start test must be followed by a cooling period, these approaches are both time consuming and costly. To reduce both the amount and duration of the testing required, a variety of model-based methods have been proposed. Some of these do not directly consider tailpipe emissions (Benz, Hehn, Onder, & Guzzella, 2011; Keynejad & Manzie, 2011b; Sanketi, Zavala, & Hedrick, 2006; Shaw & Hedrick, 2003; Sun & Sivashankar, 1997), whilst other methodologies make use of black-box (e.g. Cohen, Randall, Tether, VanVoorhies, & Tennant, 1984) or phenomenological (e.g. Kang, Kolmanovsky, & Grizzle, 2001; Kolmanovsky, Siverguina, & Lygoe, 2002; Kum, Peng, & Bucknor, 2011) models. However, indirect consideration of tailpipe emissions in the optimisation can yield inaccurate or misleading results. Furthermore, use of black-box and phenomenological models can be impractical, as a significant amount of engine testing can be required for their calibration.

This paper takes a different approach. The minimisation of fuel consumption under cumulative tailpipe emissions constraints is viewed as a dynamic optimisation problem, involving a computationally practical and validated cold start model of a spark ignition engine, an exhaust system and a three-way catalyst (Andrianov et al., 2012). In contrast to other numerical optimisation approaches, which use black-box or phenomenological models of similar functionality (e.g. Bérard, Cotta, Stokes, Thring, & Wheals,

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Nomenclature

Variables

e_X	normalised emissions (mol X/kg fuel)
$\dot{m}_{cyl}$	exhaust mass flow rate (kg/s)
$\dot{m}_{fuel}$	fuel mass flow rate (kg/s)
$\dot{m}_{X,out}$	mass flow rate of tailpipe emissions X (kg/s)
N	engine speed (rad/s)
n_{cat}	number of nodes in the catalyst model
p	pressure (Pa)
T	temperature (K)
t_f	final time constant (s)
t_{sw}	switching time (s)
$\mathbf{u}$	integrated model input vector
$\mathbf{u}_c$	engine control vector
$\mathbf{x}$	integrated model state vector
$\mathbf{z}$	integrated model algebraic vector
α	throttle angle (deg)
λ	normalised air–fuel ratio
τ_{brake}	brake engine torque (N m)
θ	spark timing (CAD BTDC)
θ_{adv}	spark advance from MBT spark timing (CAD)
ϑ_{exh}	exhaust valve closing angle (CAD)
ϑ_{int}	intake valve closing angle (CAD)
ϑ_{ovlp}	valve overlap (CAD)

Subscripts

cp	connecting pipe
cyl	exhaust port gas conditions
em	exhaust manifold
eng	lumped engine conditions
g	gaseous phase
idp	result of iterative dynamic programming
im	intake manifold
in	gas conditions at the inlet
max	maximum value
MBT	maximum brake torque
min	minimum value
out	gas conditions at the outlet

Superscripts

ref	reference
$\star$	optimal, optimised

2000; Cohen et al., 1984; Fiengo, Glielmo, Santini, & Serra, 2002; Fussey, Goodfellow, Oversby, Porter, & Wheals, 2001; Sanketi et al., 2006), this work takes advantage of physics-based modelling to significantly reduce the amount of engine testing required. In the following sections the methodology for obtaining optimised engine control strategies is demonstrated on several examples, where spark timing, air–fuel ratio and cam timing are subject to optimisation. The control policies found are then compared and validated experimentally when possible.

2. Problem formulation

To enable the dynamic optimisation, a computationally practical model capable of simulating fuel consumption and legislated tailpipe emissions as a function of the engine control setpoints is required. Throughout this work it is assumed that perfect setpoint controllers are in place to deliver the developed trajectories. The validated model of Andrianov et al. (2012) includes the appropriate control setpoint to fuel consumption and tailpipe emissions functionality. The accuracy in simulating cumulative fuel consumption and tailpipe emissions under transient driving conditions is of order 2% and 10% respectively with respect to experimental results. In this section this model is first briefly described, and then the optimal engine control problem is formulated.

2.1. The integrated model (Andrianov et al., 2012)

The structure of the model used is shown in Fig. 1. The engine is represented by a second order mean value model similar to that of Keynejad and Manzie (2011a) and considers fluid, thermal and mechanical domains. It calculates the intake manifold pressure p_{im}, exhaust port gas temperature T_{cyl} and fuel mass flow rate $\dot{m}_{fuel}$ as a function of throttle angle α, engine speed N, normalised

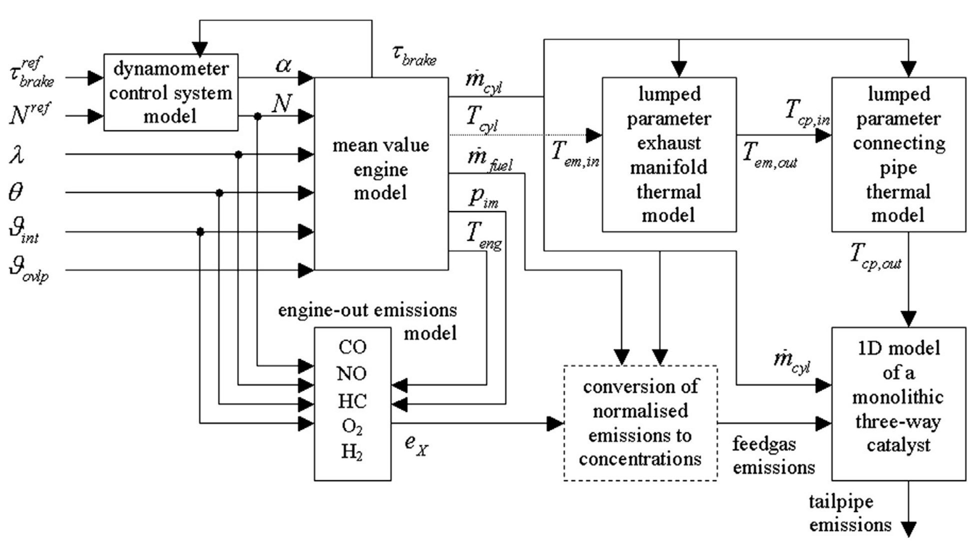

Fig. 1. Structure of the combined engine, emissions, exhaust and aftertreatment system model.

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