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Optimal control for integrated emission management in diesel engines ☆

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ABSTRACT

Integrated Emission Management (IEM) is a supervisory control strategy that minimises operational costs (consisting of fuel and AdBlue) for diesel engines with an aftertreatment system, while satisfying emission constraints imposed by legislation. In most work on IEM, a suboptimal heuristic real-time implementable solution is used, which is based on Pontryagin's Minimum Principle (PMP). In this paper, we compute the optimal solution using both PMP and Dynamic Programming (DP). As the emission legislation imposes a terminal state constraint, standard DP algorithms are sensitive to numerical errors that appear close to the boundary of the feasible sets. Therefore, we propose two extensions to existing DP methods, which use an approximation of the forward reachable sets to reduce the grid size over time and an approximation of the backward reachable sets to avoid the aforementioned numerical errors. Using a simulation study of a cold-start World Harmonised Transient Cycle for a Euro-VI engine, we show that the novel extension to the DP algorithm yields the best approximation of the optimal cost, when compared to existing DP methods. Furthermore, we show that PMP yields almost the same results as DP, and that the real-time implementable solution only deviates approximately 0.08–0.16% from the optimal solution.

1. Introduction

Modern emission legislation forces tailpipe emissions of nitrogen oxides (NO_x) and particulate matter (PM) of heavy-duty trucks towards near-zero impact levels. Moreover, the current challenge set by the European Commission is to achieve a 20% fuel consumption reduction in heavy-duty trucks by 2020. To meet these requirements, several new technologies have been, and will continue to be, introduced in heavy-duty trucks. This leads to an increased complexity of the truck's engine and aftertreatment system and to an increased complexity of the supervisory control system that is used to exploit the synergy between the engine and aftertreatment system. Traditional supervisory control strategies are often based on heuristic rules, which do not lead to optimal solutions. It is believed that an increased fuel efficiency can be realised by designing an improved supervisory control strategy that uses ideas from optimal control theory. Such a strategy is sometimes referred to as Integrated Emission Management (IEM).

Some results on emission management can be found in the literature (Ao, Qiang, Zhong, Mao, & Yang, 2008; Serrao et al., 2013). In IEM, as proposed in Cloudt and Willems (2011) and experimentally demonstrated in Willems, Mentink, Kupper, and Van Den Eijnden (2013), the objective is to minimise operational costs, while satisfying emission legislation constraints. This is achieved by a delicate combination of doing Exhaust Gas Recirculation (EGR) in the engine, to reduce engine-out NO_x at the cost of higher fuel consumption, and converting NO_x in the engine's aftertreatment system, which leads to a higher AdBlue consumption. The IEM strategy of Cloudt and Willems (2011) and Willems et al. (2013) uses ideas from Energy Management Systems (EMS) for hybrid electric vehicles, which are extensively discussed in, e.g., Onori and Serrao (2011),Pisu and Rizzoni (2007), Sciarretta and Guzzella (2007), Salmasi (2007), Koot et al. (2005), and the book de Jager, van Keulen, and Kessels (2013). In the work on EMS, Dynamic Programming (DP) is often used to find the optimal solution. As this optimal solution is inherently noncausal and requires the drive cycle to be known a priori, suboptimal real-time implementable solutions have been proposed in the form of an Equivalent Cost Minimisation Strategy (ECMS). ECMS is based on

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Pontryagin's Minimum Principle (PMP) and aims at approximating the optimal solution. Although the real-time implementable solution to the IEM problem of Cloudt and Willems (2011) is based on PMP and has a resemblance to ECMS, a comparison of this real-time solution with the optimal solution obtained through DP has only been made in a preliminary version of this paper (Van Schijndel, Donkers, Willems, & Heemels, 2014). Still, Van Schijndel et al. (2014) consider a simplified dynamic model, and only use DP without making a comparison with the optimal solution obtained through the application of PMP. Comparing the optimal solution with the real-time implementable solution is relevant, as the experimental results of IEM presented in Willems et al. (2013) show a 2.1% fuel consumption reduction and a 1.5% total operational cost reduction with respect to a Euro-VI production type powertrain, which raises the question how much further the IEM results of Willems et al. (2013) can be improved.

This paper presents the optimal solution to the IEM problem for the diesel engine of a Euro VI heavy-duty truck completing a cold-start World Harmonised Transient Cycle (WHTC). A cold start is considered, since this cycle is more challenging from a thermal management and emissions point of view. The main contribution of this paper is a comparison of the real-time implementable strategy with the exact optimal solutions obtained through both DP and the application of PMP. The comparison between DP and PMP is relevant, as DP suffers from the ‘curse of dimensionality’, while PMP does not. However, PMP only provides a necessary condition for optimality, while DP is guaranteed to provide the global optimal solution.

A second contribution is an investigation, a comparison and the proposition of two novel extensions to existing DP algorithms. Namely, as emission legislation poses a constraint on the terminal state, the standard DP algorithm is sensitive to numerical errors (Sundström, Ambühl, & Guzzella, 2010). These numerical errors are caused by interpolating between grid points in general, and between finite and infinite costs in particular, where the latter are induced by the terminal state constraint. We will first review a baseline DP algorithm and the algorithm proposed by Elbert, Ebbesen, and Guzella (2013). Subsequently, we will extend this latter algorithm by adding a fast overapproximation of the so-called forward reachable sets. Namely, by approximating the forward reachable sets, the grid size over time can be reduced, which yields smaller numerical errors due to better interpolation. To reduce the numerical errors due to interpolation between finite and infinite cost, we approximate the backward reachable sets in the DP algorithm. This can be done using an approach based on an extension of Sundström et al. (2010). In particular, as the work of Sundström et al. (2010) can only be applied to scalar-state systems, we extend the aforecited work towards the particular higher-order system of IEM. The potential of the methods will be demonstrated by a simulation study of a cold-start WHTC. This provides insight into how the real-time implementable solution and optimal solutions to the IEM problem cope with the drive cycle and shows that the novel extension to the DP algorithm outperforms the existing DP algorithms.

The outline of this paper is as follows. First, a problem description is given in Section 2, including the objectives of this paper, the model of the engine plus aftertreatment system and the formulation of IEM as an optimal control problem. In Section 3, we show four different DP approaches and explain their advantages and disadvantages. This includes our novel extensions to existing DP algorithms. In Section 4, the optimal solution using PMP is discussed and the real-time implementable solution that which is based on PMP is discussed. The discussed DP and PMP methods are applied to the IEM problem and the optimal costs are compared in Section 5 and, finally, conclusions are drawn in Section 6.

2. Problem description

The objective of this paper is to find the optimal solution to the Integrated Emission Management (IEM) problem, which corresponds, loosely speaking, to *minimising engine operational costs* over a drive cycle while *satisfying emission constraints* imposed by legislation. Before being able to formalise the IEM problem, which we will do at the end of this section, we will first discuss the controller structure and present the necessary models.

2.1. System description and control structure

In this paper, we consider a state-of-the-art Euro VI heavy-duty powertrain, consisting of a 6 cylinder, 12.9 l, 375 kW engine and an Engine Aftertreatment System (EAS), see Fig. 1. The engine is equipped with a cooled high-pressure Exhaust Gas Recirculation (EGR) system and a Variable Turbine Geometry (VTG) with charge-air cooler. The EAS consists of a Diesel Oxidation Catalyst (DOC), a Diesel Particulate Filter (DPF), a 32.6 l Cu-Zeolite Selective Catalytic Reduction catalyst (SCR) and an Ammonia Oxidation catalyst (AMOX).

A block diagram of the control structure can be found in Fig. 2. The amount of fuel fed to the engine is taken so that the requested power is delivered. The AdBlue dosing strategy, which controls the SCR, aims at achieving maximal NO_x conversion. It is calibrated for a certain amount of NH_3-slip and is assumed to work autonomously. The air management controls the position of the EGR valve and the change of geometry of the VTG. The supervisory control strategy determines the desired EGR and VTG mass flows, which result in a tradeoff between emissions and fuel economy. As a first step towards the optimisation of the operational costs, we focus on NO_x emissions, because present Euro VI technology is capable of reducing other emissions such that they comply with the Euro VI legislation. DPF regeneration is outside the scope of this paper.

2.2. Engine and aftertreatment models

The EAS is described by a dynamic model, whereas the engine is described by a static (stationary) model. This is because the physical phenomena occurring in the EAS are relatively slow compared to the ones occurring in the engine. Both models have been parameterised and experimentally validated in Willems et al. (2013). We first discuss the static model of the engine, and subsequently the dynamic model of the EAS.

The engine model used in this paper is static (stationary) and is based on Wahlström and Eriksson (2011). In fact, it can be derived from Wahlström and Eriksson (2011) by assuming that all dynamics are in steady state. The inputs and outputs of the engine model are shown in Fig. 3. The model predicts the fuel mass flow $\dot{m}_f$ (kg s^{-1}), the total exhaust gas mass flow $\dot{m}_{\text{exh}}$ (kg s^{-1}), the engine-out NO_x mass flow $\dot{m}_{NO_x,\text{eo}}$ (kg s^{-1}) and the exhaust gas temperature T_{exh} (K) as a function of desired torque τ (N m) for a specific desired rotation speed ω (rad s^{-1}), and as a function of the mass flow through the EGR and VTG, denoted by u_1 (kg s^{-1}) and

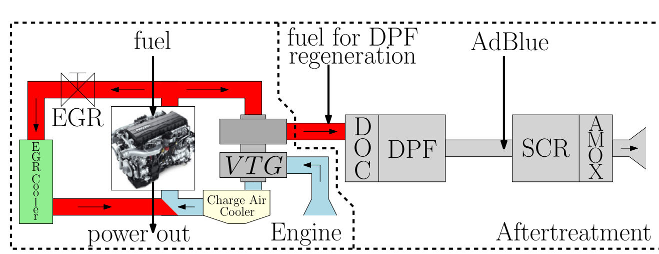

Fig. 1. Schematic overview of the powertrain.

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