Transportation Research Part C 92 (2018) 486–503

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

A multi-layer control hierarchy for heavy duty vehicles with off-line dual stage dynamic programming optimization

Fabrizio Donatantonio*, Antonio D'Amato, Ivan Arsie, Cesare Pianese

Energy and Propulsion Laboratory – Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano (SA), Italy

ARTICLE INFO

Keywords:
Eco-Driving
Look-ahead control
Velocity reference optimization
Gear shifting optimization
Heavy duty truck fuel economy
Multi-layer control
Fuel-optimal control
Dynamic programming
Optimal control
Constrained operation
Off-line optimization
Heavy-duty diesel
Energy minimization
Energy optimization
Energy management

ABSTRACT

In this paper, a multi-level, comprehensive control technique for a heavy duty vehicle, capable of reducing fuel consumption while complying with engine constraints on both operating conditions and smoke emissions has been developed. The higher control layer, using road data, engine and vehicle parameters, computes the optimal speed and gear shifting profiles through an off-line, dual step dynamic programming algorithm. Since fuel consumption alone could be potentially decreased by driving at lower speeds and thus increasing travel time, this last aspect is also taken into account in the presented algorithm. The lower control layer, operating in real time, computes suitable powertrain control signals assuring the tracking of both reference speed and gear trajectories, while respecting the constraints imposed on engine operation. After the general description of the optimal control problem aimed at minimizing fuel consumption, an approach for its solution, implemented in the higher control layer, is presented. Afterwards, the lower control layer is described. In conclusion, the effectiveness of the developed control structure and the achievable improvement in terms of fuel consumption in comparison with a traditional fixed-point cruise controller are assessed through simulations in different driving scenarios.

1. Introduction

The stiffening of regulations on the production of both harmful and greenhouse gases of road vehicles, along with the oscillations in fuel prices, have brought both industry and research communities to focus on solutions aimed at the reduction of environmental impact and fuel consumption. These arguments are of great concern for heavy-duty road vehicles, featuring an average mileage of 150,000 km per year and a fuel consumption in the order of 30–40 l/100 km. Therefore, a significant share of their life cycle cost is represented by the cost of fuel, thus, even a reduction of a small percentage of fuel consumption can make consistent savings in economical terms.

Advances in heavy-duty Diesel engine control have played a key role in the pursuit of the reduction of both fuel consumption and emissions. Despite the noticeable achievements of the last decade, further fuel economy improvements may face the trade-off between engine efficiency and cleaner exhaust gases due to stricter constraints imposed on the exhaust emissions of NO_x and soot. Indeed, some technologies such as EGR and aftertreatment systems (e.g. lean NOx traps, particulate filters) can reduce the potential benefits achievable with those solutions that may guarantee higher efficiency engine operation. More recently, alternative powertrain architectures such as hybrid and full electric technologies have further stretched the horizons of powertrain industry. In perspective, other technologies may improve the current fuel consumption standards by recovering heat from the exhaust gases. In this area turbocompound solutions have been already tested and implemented (Algrain, 2005; Arsie et al., 2015), whereas thermoelectric generators

* Corresponding author.
E-mail addresses: fadonatantonio@unisa.it (F. Donatantonio), adamato@unisa.it (A. D'Amato), iarsie@unisa.it (I. Arsie), pianese@unisa.it (C. Pianese).

https://doi.org/10.1016/j.trc.2018.05.006
Received 21 July 2017; Received in revised form 26 December 2017; Accepted 7 May 2018
0968-090X/

and organic Rankine cycles (Arsie et al., 2016; Amicabile et al., 2015) are not yet available on production trucks. These solutions entail the use of an electric storage and share the goal of augmenting the flexibility of on-board energy management, by increasing the number of decision variables. This allows a better optimization of the operating conditions thanks to the decoupling of the different processes occurring on-board (from driver demand to fuel conversion and energy storage). On the other hand a major drawback is the increased complexity of both system and controller. In the last decade, the interest towards both scheduling of driver actions and optimization of on-board energy management over either known or predictable horizon for fuel consumption minimization has received great attention, mainly for hybrid vehicles. The development and capillary diffusion of GPS systems and the integration of elevation data in its maps have opened the opportunity to optimize the velocity profile to be followed during a given driving mission. Previous works have demonstrated the potential benefit of look-ahead control with known route for heavy-duty vehicles (Hellstrom et al., 2006, 2009, 2010) and passenger cars (Ozatay et al., 2014a). These works solve an optimal control problem through the dynamic programming (DP) method, optimizing the gear shifting policy as well. The same approach has also been used in the case of electric hybrid vehicles (Ye, 2003; Rousseau et al., 2007; Hsieh et al., 2014; Yuan et al., 2013; Arsie et al., 2005). The main drawback of dynamic programming is the high computation time and high memory utilization, both increasing exponentially with the number of control and state variables and number of space steps. Other works reformulate the optimal control problem in order to use the direct shooting method (DSM) like (Saerens et al., 2013). Other analytic approaches are based on Pontryagin's minimum principle (Ozatay et al., 2014b). This classes of methods show low calculation times and memory usage in comparison of DP (Saerens et al., 2013; Yuan et al., 2013; Xu et al., 2017; Ozatay et al., 2017), but require heavy simplifications in the problem and in the model in order to be used. In this paper, a multi-layer control structure for a heavy-duty vehicle is presented. The higher control layer is dedicated to the off-line computation of fuel-optimal velocity and gear shifting profiles through a dual-stage dynamic programming using realistic engine maps and vehicle data along with road slope information. For this purpose, the problem has been split in two distinct optimal control problems solved sequentially. Constraints on engine operation and driving mission such as speed limits and maximum travel time have been taken into account and handled in both the off-line optimization phase and the designed on-line engine control. The technique hereby described has shown to allow an acceptable computational time while preserving the goodness of the obtained solution.

In Section 2 the problem and the solution approach are envisioned, in part 3, the higher control layer is described and its operation analyzed along with the dual stage dynamic programming technique. In part 4, the lower control layer hereby developed is presented. In the last part, a thorough set of simulation results is presented for a test track and a real stretch of road data, then a comparison is made between the developed method and a traditional, fixed point cruise controller.

2. Problem description

An effective way of pursuing a reduction of fuel consumption and polluting emission consists in leveraging the sequence of uphill and downhill sections to reduce the amount of energy spent. The main idea is to take advantage of the knowledge of the elevation profile of the road ahead to compute the sequence of control commands minimizing fuel consumption while accounting for constraints on both mission (i.e. speed limits, desirable travel time) and engine operation. Theoretically, the optimal control problem of minimizing the fuel consumption of a vehicle on a given road could be formulated and the optimal trajectory for powertrain actuators calculated. Nevertheless, it is straightforward that computational time and required hardware would nullify the feasability of this approach. The objective of this paper is to propose an off-line algorithm able to optimize the vehicle velocity profile as well as the gear shifting schedule for the entire vehicle mission. The algorithm hereby presented, requiring a feasible calculation time, comparable with a truck warm up time or GPS cold start, could be executed in cloud computing before beginning the driving mission as proposed by Ozatay et al. (2014a) and Ozatay et al. (2014b). The presented technique, exploits actual engine steady state maps to model maximum torque curve and fuel consumption maps, whose influence on the goodness of the solution is analysed in Ivarsson et al. (2009) with respect to a simple parabolic model. The engine constraints that have been considered include maximum and minimum engine speed, minimum A/F ratio (in order to limit soot formation) and maximum turbocharger speed (for durability reasons). These last constraints could not be handled in the off-line optimization phase and are considered as exogenous; their fulfilment is assured by the lower control layer operating on-line, directly on the powertrain and presented in Section 4. The overall control structure with the modules and the two control levels (off-line and on-line) is schematically reported in Fig. 1.

3. Cloud-based velocity and shifting profile optimization

This section deals with the description of the higher layer of the control structure, reported in Fig. 1, whose objective is to supply to the lower control layer both speed and gear shifting reference profiles. The former and the latter are then used to compute powertrain actuators' signals.

3.1. Problem formulation

The problem of minimizing the fuel consumed by a vehicle of mass m, to travel along an assigned path of length S with given slope profile $\alpha(s)$, can be written as the following optimal control problem (1) formulated in the space s domain:

$$\underset{\dot{m}_f,\gamma}{\operatorname{argmin}}\, M_f(\dot{m}_f,\gamma,v) = \int_0^T \dot{m}_f\, dt = \int_0^S \frac{\dot{m}_f(s)}{v(s)}\, ds \tag{1a}$$