

Turbocharger Dynamics Influence on Optimal Control of Diesel Engine Powered Systems

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ABSTRACT

The importance of including turbocharger dynamics in diesel engine models are studied, especially when optimization techniques are to be used to derive the optimal controls. This is done for two applications of diesel engines where in the first application, a diesel engine in wheel loader powertrain interacts with other subsystems to perform a loading operation and engine speed is dictated by the wheel speed, while in the second application, the engine operates in a diesel-electric powertrain as a separate system and the engine speed remains a free variable. In both applications, mean value engine models of different complexities are used while the rest of system components are modeled with the aim of control study. Optimal control problems are formulated, solved, and results are analyzed for various engine loading scenarios in the two applications with and without turbocharger dynamics. It is shown that depending on the engine loading transients, fuel consumption and operation time can widely vary when the turbocharger dynamics are considered in the diesel engine model. Including these, have minor effects on fuel consumption and operation time at minimum fuel operations of the first application ($\approx 0.1\%$) while the changes are considerable in the second application (up to 60%). In case of minimum time operations however, fuel consumption and operation time are highly affected in both applications implying that not considering turbocharger dynamics in the diesel engine models may lead to overestimation of the engine performance especially when the results are going to be used for control purposes.

CITATION: Nezhadali, V., Sivertsson, M., and Eriksson, L., "Turbocharger Dynamics Influence on Optimal Control of Diesel Engine Powered Systems," *SAE Int. J. Engines* 7(1):2014, doi:10.4271/2014-01-0290.

1. INTRODUCTION

Diesel engines are commonly used as the prime mover in vehicles, ranging from cars to heavy duty machinery. Productivity of engine operation can be determined by considering time and costs of performing operations where fuel consumption is a major issue. Optimal control of diesel engine operation is used to analyze time or fuel optimal engine operations. To this goal, diesel engines are modeled with different complexities where mean value engine modeling (MVEM) is a commonly used alternative [1]. Diesel engine operation is constrained by phenomena such as the lag due to turbocharger speed buildup or smoke generation caused by insufficient air pressure in the intake manifold [2]. Turbocharger dynamics can be described in the engine model by including additional states and control variables, however these dynamics are not always included in the models as the optimization becomes more computationally expensive or the dynamics may not be interesting as in [3].

In this paper, minimum time (min T) and minimum fuel (min m_f) transients of diesel engines with and without turbocharger dynamics are studied with the novelty being that corresponding

changes in the system dynamics, fuel consumption, and operation time are analyzed both qualitatively and quantitatively for two separate applications.

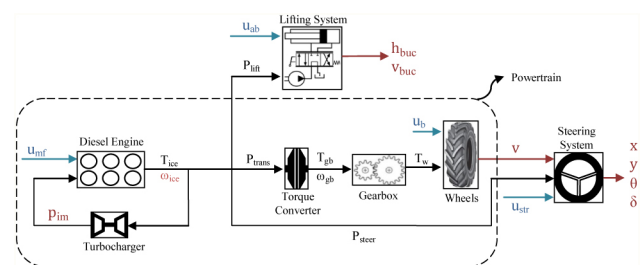


Figure 1. Application 1, structure of the WL model, components as well as the connection between them (system states in red, control inputs in blue and other parameters in black)

In the first application, the diesel engine is considered as a component in wheel loader (WL) powertrain. A frequent application of WLs is in short loading cycles which are highly transient cycles with several power consumers, i.e. vehicle traction, bucket lifting, and vehicle steering, that all have to be supplied by the diesel engine. During the WL operation engine speed is coupled to the wheel speed via transmission components and is thus affected by the vehicle maneuver.

between loading point and load receiver. These short loading cycles are normally repeated several times over a certain period, why reducing the fuel consumption and operational time of them is a major interest for the manufacturers as it will reduce the total cost of ownership. The structure of WL model of the first application is illustrated in [Figure 1](#).

In the second application, the diesel engine transients in a diesel-electric powertrain are studied. A nonlinear MVEM represents the diesel engine which is mechanically coupled to a generator (GENSET) providing the electricity for electric motors. Since there is only an electric link between the GENSET and electric load, the engine speed can be chosen freely which has the benefit that the engine operating point can remain independent of the load properties on the electric motors while the performance of the whole powertrain can be improved because of the electric machine torque characteristics. The structure of the diesel engine model in the diesel electric powertrain is illustrated in [Figure 2](#).

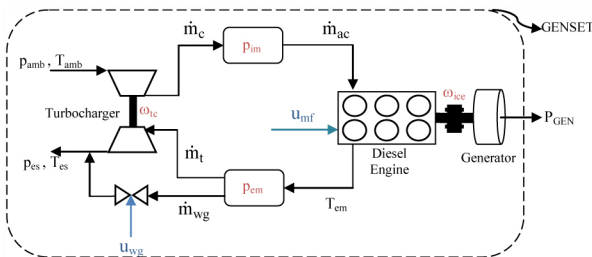


Figure 2. Application 2, structure of the MVEM in a GENSET, components as well as the connection between them (system states in red, control inputs in blue and other parameters in black).

1.1. Paper Outline

In the first part of the paper, the modeling of the diesel engine and WL powertrain is described with and without turbocharger dynamics. Formulating and solving optimal control problems, $\min T$ and $\min m_f$ transients of the WL during the short loading cycle are calculated and the differences in engine operation are analyzed.

In the second part of the paper a model of a diesel-electric powertrain is described. This model is then simplified, removing the turbocharger dynamics. The optimal controls for steps in power and energy are then found for both models, both for $\min T$ and $\min m_f$ and the differences are analyzed.

2. MODEL

2.1. Application 1, Wheel Loader

The WL model consists of three main subsystems namely powertrain, lifting and steering where a 6-cylinder 12.7-liter diesel engine produces the power required in other subsystems. The detailed version of the WL model as a

nonlinear system with nine states and four control inputs is available in [4]. The states in the system, as seen in [Figure 1](#), are engine speed ω_{ice} , intake manifold pressure p_{im} , vehicle speed v , bucket lifting speed v_{buc} , bucket height h_{buc} , vehicle positions in xy plane, vehicle heading angle θ and steering angle δ . The four control inputs are fuel injection per combustion cycle of engine u_{mf} , bucket acceleration u_{ab} , braking torque signal u_b and derivative of steering angle u_{str} . The engine model is presented once as a full model (FM_{WL}) including the turbocharger dynamics and then with no turbocharger dynamics called reduced model (RM_{WL}). [Figure 3](#) shows a WL and its trajectory while operating in the short loading cycle.

Full Model, Wheel Loader

The FM_{WL} diesel engine is represented by a simplified version of the MVEM in [1] where engine speed, ω_{ice} , and intake manifold pressure, p_{im} , are states and injected fuel mass, u_{mf} is the control input. The turbocharger dynamics are represented by a first order system with a time constant that describes the intake manifold pressure. Engine power is consumed in order to lift the loaded bucket and perform steering, P_{lift} and P_{str} respectively, while consuming power for vehicle transportation P_{trans} . Dynamics of engine speed are then calculated by Newton's second law as:

$$\frac{d\omega_{ice}}{dt} = \frac{1}{J_{ice}} \left(T_{ice} - \frac{P_{lift} + P_{str} + P_{trans}}{\omega_{ice}} \right) \quad (1)$$

where J_{ice} is engine inertia and T_{ice} the engine torque. Intake manifold pressure is related to a static pressure model, p_{model} , by a first order system according to:

$$\frac{dp_{im}}{dt} = \frac{1}{\tau}(p_{model} - p_{im}), \quad \tau = c_{\tau 1} \omega_{ice}^{c_{\tau 2}} \quad (2)$$

where τ is the time constant in the intake manifold pressure buildup due to turbocharger dynamics, and the static pressure map is calculated as follows

$$p_{model} = c_{p,1} T_{ice} + c_{p,2} \omega_{ice}^2 + c_{p,3} (T_{ice} \omega_{ice})^2 + c_{p,4} \quad (3)$$

with $c_{p1,2,3,4}$ and $c_{r1,2}$ tuned to correspond to the stationary intake manifold pressure values at different engine loads and speeds, and the response time during intake manifold pressure transients at different engine speeds respectively. The net engine torque T_{ice} is modeled as the subtraction of the friction torque T_{fric} from the gross indicated torque T_{io} according to:

$$T_{ice} = T_{ig}(u_{mf}) - T_{fric}(\omega_{ice}) \quad (4)$$

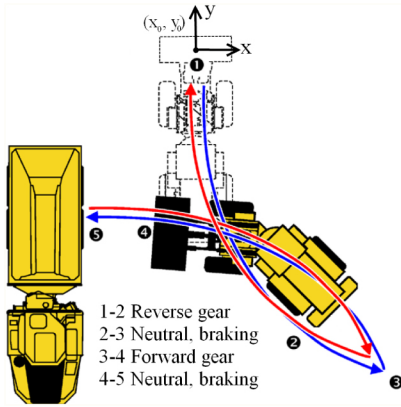


Figure 3. WL trajectory and the numbered sequence of actions in the short loading cycle, picture from [7]

The air mass flow to the engine, $\dot{m}_a$ calculated using a constant volumetric efficiency, η_{vol} and mass of injected fuel, $\dot{m}_f$ are calculated as follows:

$$\dot{m}_a = \frac{\eta_{vol} V_D \omega_{ice} p_{im}}{4 \pi R_a T_{amb}}, \quad \dot{m}_f = \frac{10^{-6}}{4 \pi} u_{mf} \omega_{ice} n_{cyl} \quad (5)$$

where V_D , R_a , T_{amb} and n_{cyl} are respectively engine displacement volume, gas constant, ambient temperature and number of engine cylinders.

The minimum relative air to fuel ratio according to the environmental limits on smoke generation is denoted by λ_{min} , and a parameter $\phi\lambda$ representing the smoke generation during the engine operation is defined as:

$$\phi\lambda = \dot{m}_a - \dot{m}_f (A/F)_s \lambda_{min} \quad (6)$$

where $(A/F)_s$ is the stoichiometric air to fuel ratio of the fuel.

Reduced Model, Wheel Loader

The RM_{WL} for the diesel engine does not include the intake manifold pressure dynamics in (2) and has only the engine speed as state determined by (1) while the only control input to the diesel engine as in the FM_{WL} is injected fuel mass u_{mf} . All other system states and control inputs mentioned in section 2.1 are left without any change and the net engine torque is calculated by (4) similar to the FM_{WL} case.

2.2. Application 2, Diesel-Electric

The modeled powertrain consists of a 6-cylinder 12.7-liter SCANIA diesel engine with a fixed-geometry turbine and a wastegate for boost control, equipped with a generator. To study the effects and importance of including a turbocharger model in the optimization, two different models are used where the full and reduced models are denoted by FM_{DE} and RM_{DE} respectively. The first model, FM_{DE} , models the physics of the

powertrain, incorporating the nonlinear nature and turbocharger dynamics. In the second model, RM_{DE} , only the stationary efficiency map of the engine is modeled, neglecting turbocharger dynamics.

Full Model, Diesel-Electric

The model is a nonlinear, four state, three input MVEM, used together with models for the generator losses. The diesel engine model is the same as the one used in [8], augmented with a model for the generator losses as in [9].

The states of the MVEM are engine speed, ω_{ice} , inlet manifold pressure, p_{im} , exhaust manifold pressure, p_{em} and turbocharger speed, ω_{tc} . The controls are injected fuel mass, u_{mf} , wastegate position, u_{wg} , and generator power, P_{gen} . The engine model consists of two control volumes, intake and exhaust manifold, and four restrictions, compressor, engine, turbine, and wastegate. The control volumes are modeled with the standard isothermal model, using the ideal gas law and mass conservation. The engine and turbocharger speeds are modeled using Newton's second law. The governing differential equations of the MVEM are:

$$\frac{d\omega_{ice}}{dt} = \frac{1}{J_{genset}} (T_{ice} - \frac{P_{mech}}{\omega_{ice}}) \quad (7)$$

$$\frac{dp_{im}}{dt} = \frac{R_a T_{im}}{V_{im}} (\dot{m}_c - \dot{m}_{ac}) \quad (8)$$

$$\frac{dp_{em}}{dt} = \frac{R_e T_{em}}{V_{em}} (\dot{m}_{ac} + \dot{m}_f - \dot{m}_t - \dot{m}_{wg}) \quad (9)$$

$$\frac{d\omega_{tc}}{dt} = \frac{P_t - P_c}{\omega_{tc} J_{tc}} - w_{fric} \omega_{tc}^2 \quad (10)$$

where $\dot{m}$ denotes massflows, $T_{im/em}$ manifold temperatures, $J_{genset/tc}$ inertias, $V_{im/em}$ manifold volumes, R_e gas constant, P_{tc} turbine/compressor powers, T_{ice} engine torque, and P_{mech} mechanical generator power, with connections between the components as in Figure 2. There is also a summation state, to keep track of the produced energy:

$$\frac{dE_{gen}}{dt} = P_{gen} \quad (11)$$

The model consists of eight submodels, connected as seen in Figure 2. The submodels are models for compressor massflow and power, intake manifold pressure, engine torque and exhaust temperature, exhaust manifold pressure, wastegate massflow, turbine massflow and power, and generator losses. The diesel engine smoke generation is represented by $\phi\lambda$ parameter similar to (6).



Documents

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