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Heavy Transport Diesel Engine Operational Energy Parameter Mathematical Modelling Research

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Abstract

Nowadays turbocharged diesel engines are prime movers of transport machines and are widely researched in order to optimise their performance. Significant percent of diesel engine's operation consists of transient operations. Transient operations, particularly acceleration, causes imbalance of fuel-air ratio, as a result of turbocharger lag in regard to fuelling. In this research two transient operations: acceleration and deceleration of CAT 3512B-HD engine are analysed. Results show a significant deviations during accelerations that causes 26% to 58% increase of specific fuel consumption during acceleration and no noticeable negative effects during deceleration.

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Keywords: diesel engine; transient operation; steady state operation; CAT3512B-HD; energy parameters.

1. Introduction

Nowadays turbocharged diesel engines are very popular in almost all transportation machines (road, rail sea transport). Reason for that is high efficiency as well as low air pollutant emissions (Rakopoulos, Giakoumis 2009). Multiple researchers analysed various aspects of diesel engine performance optimisations with regard to economic and ecological parameters. One particularly complex part of diesel engine research is transient operation. Transient (or unsteady – state) operation mode is characterised by the lack of balance between operations of multiple engine components that cause non optimal engine performance. Most well-known effect is the turbocharger lag when amount

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of air from the compressor is inconsistent with the amount of fuel portion in current operation mode (Rakopoulos, Giakoumis 2009). However although effects are known, optimisation of transient cycle is very complicated task since transient behaviour is difficult to predict and measure. An in-depth analysis of diesel engine transient operation was performed by the Tobias Nüescha (Nüescha et al. 2014). There an analysis of diesel – electric hybrid vehicle was performed with a goal to improve combustion chamber and turbocharger response during transient operations. Turbocharger improvement possibilities were also analysed by Niklas Winkler (Winkler 2008). However in literature it is much more common to find research of transient operation of light vehicle's (cars for example) engines. Where heavy duty marine, locomotive or other non-road machinery engines are analysed only in steady state operations (Bolla 2014; Katsanos et al. 2014; Benajes 2014). Although they are just as well exposed to transient operation scenarios and resulting loss of performance (Gudaitytė 2014a; Gudaitytė 2014b; Rapalis, Lebedeva 2014; Lebedeva et al. 2014).

In this research an analysis of different operational parameters is done to a heavy-duty non road diesel engine CAT3512B-HD. Research is based on real operation data that is registered by engine automatic control unit.

2. Diesel engine transient operation

According to literature there are two main transient event in diesel engine operation – increase in load and increase in engine speed (Rakopoulos, Giakoumis 2009). Each of these operation cause different instabilities:

- Load increase is described as a sudden increase of power consumer torque. This forces an engine speed drop which leads engine governors to increase the fuelling. However engine fails to supply enough air to the cylinder. As a result of that air/fuel ration may reach lower than stoichiometric values. (Rakopoulos, Giakoumis 2009).
- Speed increase – the increase of cyclic fuel portion by command (press of accelerator or controller handle). During such event the effects of turbocharger lag are considered less harmful since boost pressure builds up as a result of rapidly increased fuel portion (Rakopoulos, Giakoumis 2009).

In addition to mentioned transient operations a decrease in fueling or deceleration is also possible, however since the effects of deceleration are considered less noticeable there are usually little data on deceleration effects in common scientific literature.

3. Research subject

Research subject is a heavy-duty Caterpillar diesel engine CAT 3512 B-HD (Fig. 1). Engine specifications are given in the table 1. This type of engines are usually operating in wide variety of applications such as locomotives, marine and (both as prime movers as well as generators) and even in stationary operation modes (as prime or emergency diesel – generators) (CATERPILLAR 3512B locomotive engine specifications; Caterpillar company website; Avesco AG. CAT 3512BHD-1750; Caterpillar company website 2015 Caterpillar Marine 2015).



Fig. 1. CAT 3512B-HD turbocharged diesel engine (CATERPILLAR 3512B, 2000).

CAT 3512B-HD turbocharged diesel engine parameters are given in table 1.

Table 1. CAT 3512B-HD diesel engine main parameters (CATERPILLAR 3512B 2000).

Parameter	Value
Model	CAT3512B-HD
Power, kW	1700
Speed, min^{-1}	1800
Cylinder number	12
Cylinder diameter, mm	170
Stroke, mm	215

CAT3512B-HD engine is equipped with ECU, that performs engine control ensuring optimal engine operation and in addition to that monitors and records engine energy parameters (CATERPILLAR 3512B 2000; Bosch 2005). Authors have developed methodology to use data from these indicators to perform steady-state and transient operation research (Rapalis, Lebedeva 2014). The mentioned methodology is used to obtain data for this analysis as well.

The research subject operates in the JSC “Lietuvos Geležinkeliai” locomotives that operate in the same railroad tracks day to day. As a result of that their operational cycle stays relatively the same and is determined by the weight of the train. Typical operational cycle is displayed in a figure 1. Engine data shown in figure 2 is recorded using engine control unit (ECU) recording system data. Data analysis method and acquisition technology is described in authors other publications (Lebedevas et al. 2015).

From figure 1 it is obvious that a significant amount of operational time is spent in transient operation modes. In fact up to 93% of total operational time. Operation in transient modes is less efficient because of previously described unbalanced air – fuel ratio. In order to reduce the negative effect of transient operation analysis of transient operation modes of cat 3512B-HD is done. In order to perform engine load variation analysis in $Pe = f(n)$ or $Pe = f(t)$ is no longer sufficient. There for an analysis based on two parameters have been chosen $X = f(n, t)$ (Fig. 3).

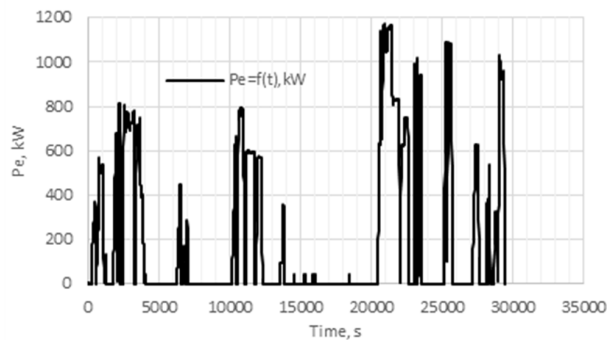


Fig. 2. Typical operational cycle of CAT3512B-HD turbocharged diesel engine.

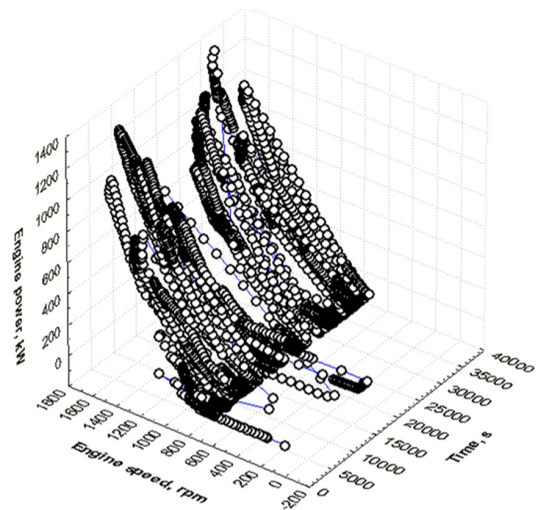


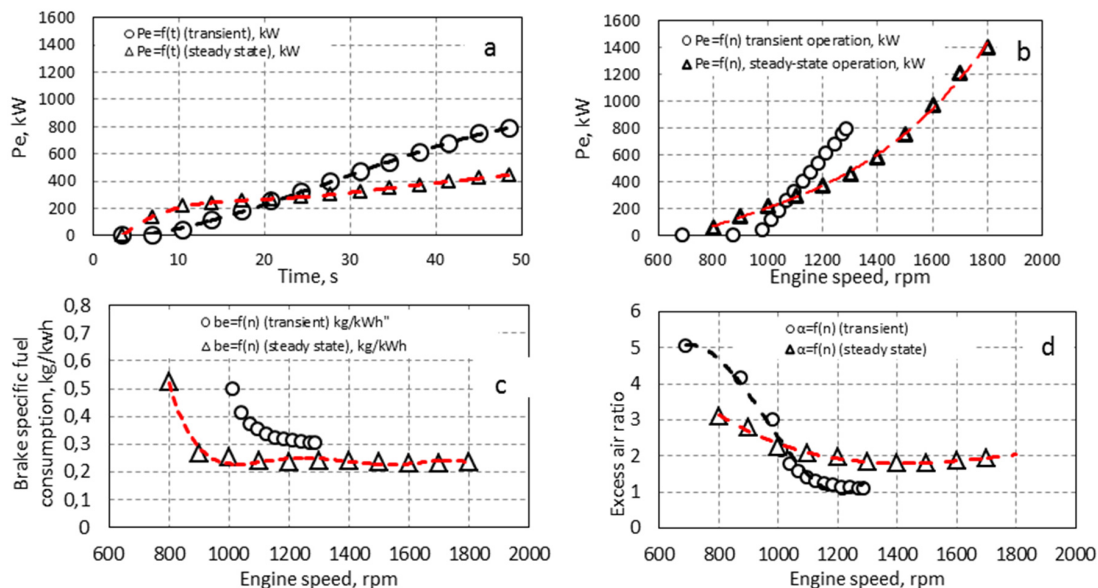
Fig. 3. Turbocharged diesel engine CAT3512B-HD typical operational cycle analysis by speed, power and time.

4. Research results

For the analysis steady state operation selection algorithm (Lebedevas et al. 2015; Rapalis, Lebedeva 2014) is used in reverse. So that transient operation modes are selected and extracted from the operation cycle. The transient operations consists mostly of acceleration and deceleration as a result of the fact that transient operations are caused by the increase and decrease of fuel portion to increase and decrease speed, rather than a sudden increase in load. Each operation was compared with engine parameters operating in steady-state mode, recorded during experimental measurements and real operation data. Analyzed data shows that individual deviations of engine parameters during transient operation reach significant values that can effect engine operation efficiency and reliability.

Acceleration. During acceleration (Fig. 4) the cyclic portion of fuel is progressively and quickly increased by the governor up to almost maximum fueling (Fig. 4f). The turbocharger cannot instantly match the quick increase in fueling, while cyclic fuel portion is below normal steady state operation values (up to 1000 rpm in Fig. 4f) the turbocharger is capable of ensuring sufficient amount of air, when engine accelerates above 1000 rpm (after 20th second, (figure 4a)) the fuel portion rises above steady state operation values, engine speed and boost pressure starts to lag behind fueling. Boost pressure reaches only about ~30% in comparison to normal operation (Fig. 4e) while fuel portion is close to maximum value at the same engine speed (Fig. 4f). At this point the excess air ratio (α) drops below normal operation (from 2.25 at 1000 to a 1.08 at 1400 rpm). The insufficient boost pressure as well as lag of engine speed increase have a drastic effect on fuel economy. The specific fuel consumption (be) is higher by 26% at 1288 rpm to 58% at 1040 rpm (Fig. 4c). In addition to impaired fuel economy, the lack of air in combustion process during transient operations is known to cause increased soot and smoke emissions (Rakopoulos, Giakoumis 2009).

Deceleration (reduction of cyclic fuel portion by the governor) is often considered less important in literature because it doesn't cause negative effect on the engine. During deceleration, the cyclic fuel portion in gradually decreased (Fig. 5f). During this process, in contrast to acceleration, the turbocharger lag causes higher than steady state charge air pressure values, ensuring sufficient excess air ratio values (Fig. 5e). As a result of that both the excess air ratio and the specific fuel consumption values are close to equal of steady state operation with effect only noticeable difference in low speed operation (near minimal engine speed) (Fig. 5 c–d).



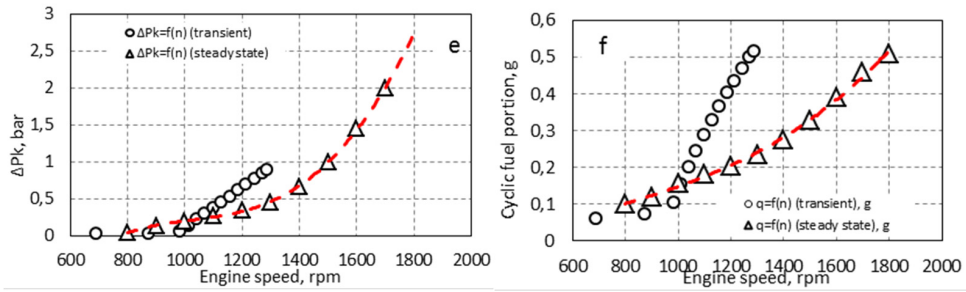


Fig. 4. CAT 3512B-HD engine acceleration analysis.

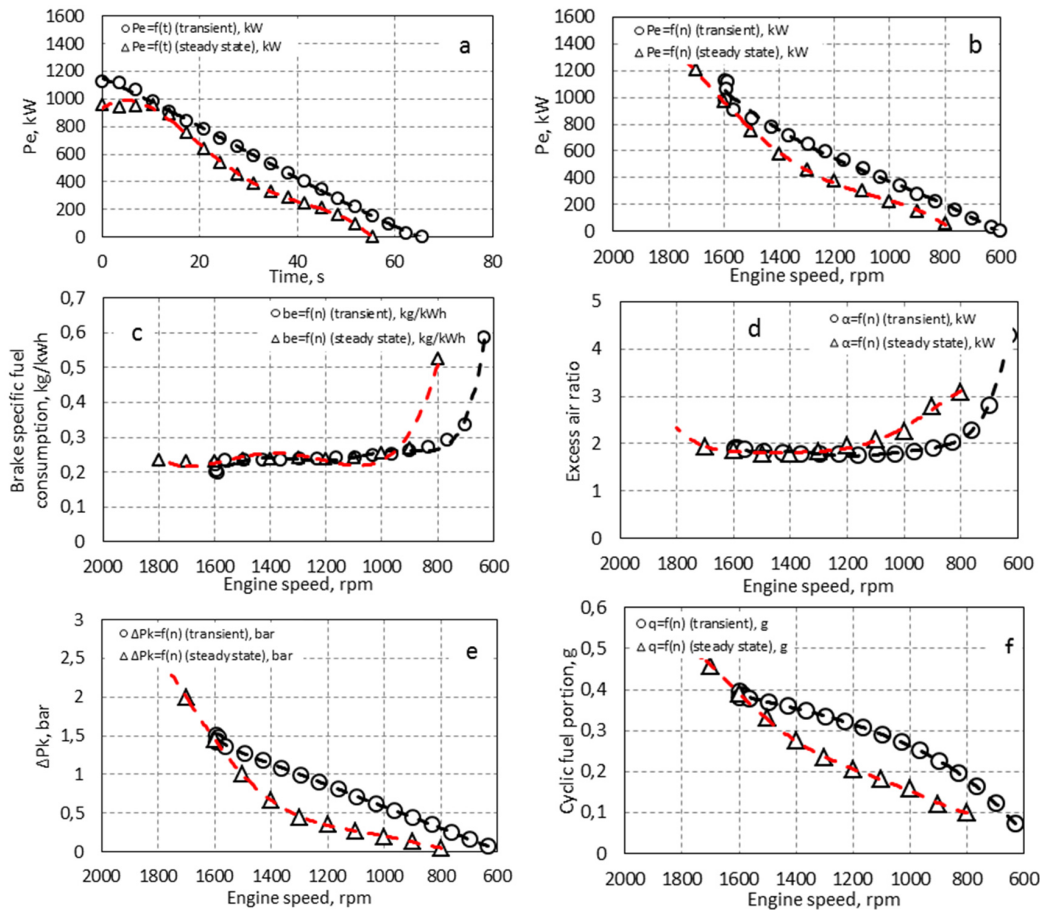


Fig. 5. CAT 3512B-HD engine acceleration analysis.

5. Transient operation effects

The operational cycle of CAT 3512B-HD diesel engine consists mostly of transient operations that causes significant effects on fuel economy and potentially greater emissions of pollutants. It is there for logical to seek for ways of evaluating and controlling the effects of transient operations (especially this is true to acceleration). To achieve this goal a need to quantify the effects of transient operations and find factors that determine the level of instability

during transient modes, For that research is being done by the authors to determine parameter fluctuation in comparison to steady state operation during the acceleration and deceleration in various speed and amplitude.

6. Conclusions

1. Research subject CAT3512B-HD diesel engine operates almost constantly in transient operations that consists of acceleration where fueling is increased by the governor to increase engine speed and power and deceleration where fuel portion is gradually decreased and engine power and speed decreases.
2. The transient operation analysis is performed for acceleration and deceleration operations. Acceleration showed a significant turbocharger lag, since the exhaust gas parameters can't instantly match increase in fueling and insufficient energy is supplied to turbocharger, and a possible decrease of excess air ratio up to stoichiometric values. As a result of that efficiency of the operation impaired and significant increases of soot emissions and NOx are possible.

Deceleration showed no turbocharger lag and as a result of that – effect on engine operation efficiency.

3. In order to solve the acceleration problem, it is necessary to continue research and analyze speed and amplitude of transient operations in order to determine parameters that would allow to make transient operation to be performed as similarly as steady state operations as possible.

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