

Performance Sensitivity to Exhaust Valves and Turbine Parameters on a Turbocompound Engine with Divided Exhaust Period

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ABSTRACT

Turbocompound can utilize part of the exhaust energy on internal combustion engines; however, it increases exhaust back pressure, and pumping loss. To avoid such drawbacks, divided exhaust period (DEP) technology is combined with the turbocompound engine. In the DEP concept the exhaust flow is divided between two different exhaust manifolds, blowdown and scavenging, with different valve timings. This leads to lower exhaust back pressure and improves engine performance.

Combining turbocompound engine with DEP has been theoretically investigated previously and shown that this reduces the fuel consumption and there is a compromise between the turbine energy recovery and the pumping work in the engine optimization. However, the sensitivity of the engine performance has not been investigated for all relevant parameters. The main aim of this study is to analyze the sensitivity of this engine architecture in terms of break specific fuel consumption to different parameters concerning the gas exchange such as blowdown valve timing, scavenging valve timing, blowdown valve size, scavenging valve size, discharge coefficients of blowdown and scavenging ports, turbine efficiency, turbine size and power transmission efficiency. This study presents the sensitivity analysis of the turbocompound DEP engine to these parameters and defines a set of important parameters that should be examined in experimental studies.

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INTRODUCTION

According to the European Council for automotive R&D, one of the main priorities for research in the automotive sector is sustainable propulsion which aims to reduce the CO₂ emissions of internal combustion engines cost-effectively [1]. To reduce the fuel consumption, one of the main developments in both heavy-duty and light-duty engines is waste heat recovery [1]. This can be done by employing a power turbine in the exhaust line to convert exhaust gases heat to mechanical work. However, turbocompounding an engine create higher exhaust back pressure and pumping loss for the engine [2-3]. In addition to turbocompounding, DEP is another way to reduce fuel consumption that decreases mainly the pumping loss in engines [4, 5, 6, 7, 8, 9, 10].

Turbocompound engines have been widely investigated and it has been shown that they have fuel-saving potential in the range of 1-5% [2-3]. There have been a few investigations into the DEP engine that all studies are about turbocharged engines equipped with DEP [4, 5, 6, 7, 8, 9, 10]. Turbocharged DEP engines have limited fuel-saving potential.

A novel architecture of engine was introduced to enhance the fuel-saving potential of a turbocompound engine [11]. The gas exchange system was changed to DEP architecture and

combined with turbocompounding instead of turbocharging. It was concluded that the turbocompound DEP engine could improve BSFC from 0.5 to 3% in only low engine speeds while the cylinder head geometry, turbine efficiency and boost pressure of the original turbocharged engine were applied. The main limitation in this approach was the long duration of choked flow per cycle through the exhaust valves at high speeds [11].

DEP principally has two exhaust manifolds with separate valves, blowdown and scavenging, which have different timings. If we assume the exhaust stroke has two phases, the blowdown valve is open during first phase and the scavenging valve is open during the second phase with an overlap between blowdown and scavenging. Figure 1 shows that one port of each cylinder is connected to the blowdown manifold and the other port is connected to the scavenging manifold. The blowdown manifold feeds the turbine in the first phase of the exhaust stroke and the scavenging manifold bypasses the turbine during the second phase of the exhaust stroke. To be able to choose a proper swallowing capacity of the turbine, the turbocharger compressor is disconnected from the turbocharger turbine and they are mechanically connected to the engine crankshaft.

Figure 2 plots the conceptual lift curves and timings of the blowdown and scavenging exhaust valves with standard exhaust valve lift curve. As shown, the blowdown valve lift curve follows the original exhaust valve lift curve and it closes linearly depending on the blowdown duration. Therefore, the maximum peak lift can vary depending on the blowdown duration. The blowdown valve is assumed to be created by a lost motion system [6]. The scavenging lift curve always opens and closes linearly. According to the scavenging duration the maximum peak lift varies. Shorter blowdown duration leads to lower peak lift. However, the maximum allowable peak lifts of blowdown and scavenging valves are equal to the maximum peak lift of the original turbocharged engine. The scavenging valve is assumed to be created by a pneumatic fully variable valve train system [6] developed by Cargine Engineering.

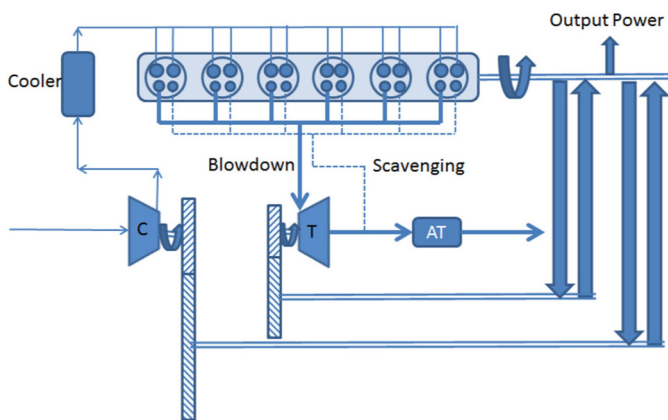


Figure 1. Single-stage turbocompound engine combined with DEP.

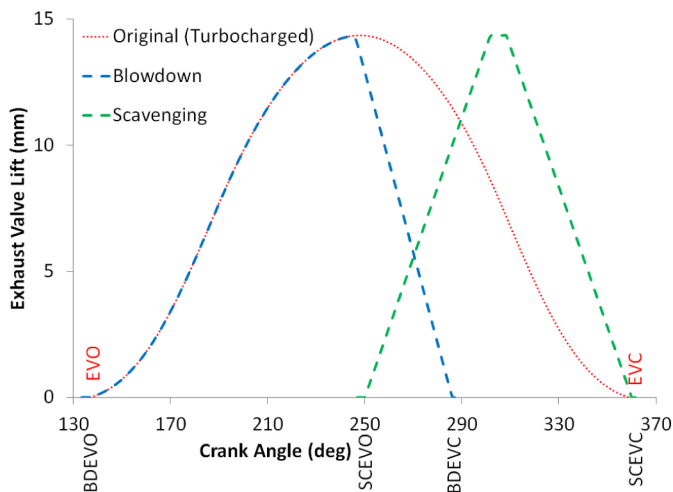


Figure 2. Exhaust valve lift curves of blowdown, scavenging and original turbocharged engine.

A turbocompound DEP engine is more fuel efficient because of the reduced pumping loss. However, the turbine energy recovery is lower due to the reduced amount of exhaust flow into the turbine [11]. Furthermore, the importance of the effective flow areas of the blowdown and scavenging exhaust valves in a turbocompound DEP engine has been investigated by increasing the size of the exhaust valves and modifying the lift curves of the blowdown and scavenging exhaust valves at

low engine speed [12]. The result showed that increasing the size of the exhaust valves could improve the BSFC in the order of 0.5% at low engine speed [12].

Obviously, there are several parameters that can be considered in development of a turbocompound DEP engine and it is not easy to make conclusion from different publications how significant different parameters are influencing BSFC of the engine. Therefore, it was decided to perform a sensitivity analysis of a turbocompound DEP engine to several parameters concerning the exhaust valves and the turbine, simultaneously. Our primary objective in this paper was to provide a set of important parameters and their effects in the turbocompound DEP engine, rather than the overall optimization of the engine. This study has been performed at a low engine speed with 100% load and a medium speed with 65% load.

SIMULATION

The simulations have been performed in GT-Power [13] on an 11.7 liter, in-line six cylinder heavy-duty turbocharged Diesel engine with no EGR, which was chosen to keep the complexity of the initial study at a minimum. Kruiswyk [3] has concluded that removal of EGR on a turbocompound engine improves the BSFC benefit by 1-1.5% at high loads. The original engine specifications are provided in Table 1. GT-Power is a 1D fluid dynamic tool with engine flow models. It uses maps, lookup tables and empirical models for some components such as valves, turbochargers and cylinders. The baseline model for this engine was calibrated in a previous work [6] and it was used as the base for the simulations. To model the combustion under different engine speeds and torques, heat release rates based on measured cylinder pressures were used.

Table 1. Engine specifications.

Engine label	SCANIA DC1201
Emission class	Euro 3
Max. Power [hp]	380
Max. Torque [Nm]	1900
Displacement [dm ³]	11.7
Bore [mm]	127
Stroke [mm]	154
Conn. rod length [mm]	255
Compression Ratio	18
IVO [°ATDC]	346
IVC [°ATDC]	-142
EVO [°ATDC]	136
EVC [°ATDC]	359
Turbocharger	Twin-entry
EGR System	No

The turbocharged engine model was then modified and equipped with a compound turbine, variable valve timing (VVA) and exhaust manifolds for DEP. Firstly, the turbocharger

turbine and compressor were disconnected from each other. The turbine shaft was connected directly to the engine crankshaft by a continuously variable transmission (CVT). This was done for the compressor shaft, as well. The boost pressure was kept constant for a studied load point while the turbine swallowing capacity was changed. This is a single-stage turbocompound engine that has been simulated previously with electric generator and motor instead of mechanical transmissions [2]. Secondly; the turbocompound engine was equipped with a VVA for each exhaust valve and two separate exhaust manifolds, as illustrated previously in Figure 2. The size of the exhaust manifolds and their properties have been extracted from the previous study [6].

Since the current study aims at studying the fuel consumption sensitivity of the turbocompound DEP engine to some parameters and comparing with the original turbocharged engine model, any discrepancy from measurements is assumed to equally affect the models. Therefore, all parameters are kept unchanged and constant in the turbocompound DEP engine model based on the original turbocharged engine such as:

- Total system output power = 193.7 kW (100% load)
- BMEP = 19.9 bar
- Engine speed = 1000 rpm
- Turbine efficiency = 64%
- Compressor efficiency = 70%
- Turbine speed = Compressor speed = 66000 rpm
- Intake valve timings
- Mechanical efficiencies of gear transmissions = 100%
- Discharge coefficients of the exhaust ports

Since the turbine efficiency is constant for the studied load point, dissimilar pulsating flows will not disturb the results. Different exhaust back pressures will make altered turbine power and pumping work. In the simulation of the turbocompound DEP engine, the exhaust back-pressure was varied by scaling the swallowing capacity of the turbine. This can be done by varying turbine mass multiplier in GT-Power.

To study the sensitivity of the engine to each parameter, all possible combinations of nine parameters concerning the exhaust valves and the turbine are considered in a full factorial design of experiment (DOE), summarized in Table 2. It has been tried to minimize the number of trials in the realistic range of each parameter by decreasing the levels of the parameters. However, to find the best fit for non-linear responses, it is necessary to consider at least three levels. For the studied load point, 5184 cases were considered; however, not all the combinations could be converged or provide the requested output power, for example, the cases that had no overlap between blowdown and scavenging or very short blowdown duration or very late SEVO. Therefore, the unfulfilled cases were excluded and this led to a partial factorial design of experiment with 3212 cases.

Table 2. Studied variables in the design of experiment.

Variables	Range	Levels
BDEVO (CAD)	120 – 180	3
BDEVC (CAD)	240 – 320	3
SCEVO (CAD)	180 – 320	4
SCEVC (CAD)	360 – 370	2
Discharge coefficients of the exhaust ports	0.37 – 0.57	3
BD port diameter (mm)	38 – 40	2
SC port diameter (mm)	38 – 40	2
Turbine mass multiplier	0.25 – 0.45	3
Turbine efficiency	0.64 – 0.74	2

BSFC is the main studied response, although some other parameters are studied to explain the effects on BSFC. The other studied responses are engine indicated power, engine attachment power, IMEP (720), Gross IMEP and PMEP. The relations between these parameters are according to equations (1), (2), (3):

$$\begin{aligned} \text{Total system power} &= \text{brake power} = \\ &= \text{engine attachment power} + \text{engine indicated power} + \text{engine friction power} \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Engine attachment power} &= \text{surplus turbine power} = \\ &= \text{turbine power} - \text{compressor power} \end{aligned} \quad (2)$$

$$\text{IMEP (720)} = \text{Gross IMEP} + \text{PMEP} \quad (3)$$

Then, fitting models have been made for the responses using GT-POWER. The goodness of the fits has been checked for all responses by calculating the coefficient of determination (R squared). They were all very close to 1.

MAIN EFFECTS ON BSFC

To study the main effect of each studied parameter on BSFC of the turbocompound DEP engine in the studied load point, the modeled response of BSFC will be presented when all parameters are kept constant and just one of the parameters is swept. Table 3 provides the set of parameters in this study. These parameters are chosen equal to the corresponding parameters in the original turbocharged engine, for instance BDEVO is equal to the original exhaust valve opening in the base turbocharged engine. This is the case for SCEVC, discharge coefficients of exhaust ports, blowdown port diameter, scavenging port diameter, turbine mass multiplier and turbine efficiency.

Figures 3 (a), 3 (b), 3 (c), 3 (d), 3 (e), 3 (f), 3 (g), 3 (h), 3 (i) show the main effects of the parameters on the BSFC of the turbocompound DEP engine. Vertical axes are all BSFC in g/kWh and have the same scale. The horizontal axes of the figures are the studied parameters. The figures are shown in

order of importance. Apparently, the effects of SCEVO, BDEVC and BDEVO on the BSFC are greatly significant. The effects of discharge coefficients, turbine efficiency and turbine mass multiplier are significant; however, they are not as great as the first mentioned parameters. The effects of the 2 mm changes in the diameters of the blowdown and scavenging ports are insignificant in this engine speed. Moreover, SCEVC has completely insignificant effect on BSFC of the turbocompound DEP engine.

According to Figure 3 (a), (b), (c) and (f), SCEVO, BDEVC, BDEVO and turbine mass multiplier should be optimized to make the minimum BSFC. However, according to figures 3 (d), (e), (g) and (h), as much as we increase the discharge coefficient of the exhaust ports, the turbine efficiency, blowdown port diameter and scavenging port diameter, the turbocompound DEP engine consumes less fuel. It has to be mentioned that it is important to watch out the range of studied parameters in comparing them with each other, for example the

turbine mass multiplier is swept between 0.25 and 0.45. One can imagine that if the turbine mass multiplier is increased until 1, the BSFC will increase on the polynomial curve and the order of significance in Figure 3 would change.

Table 3. Set values of the studied parameters for studying the main effect of each parameter on BSFC.

Variables	Value
BDEVO (CAD)	136
BDEVC (CAD)	283
SCEVO (CAD)	263
SCEVC (CAD)	360
Discharge coefficients of the exhaust ports	0.47
BD port diameter (mm)	38
SC port diameter (mm)	38
Turbine mass multiplier	0.3
Turbine efficiency	0.64

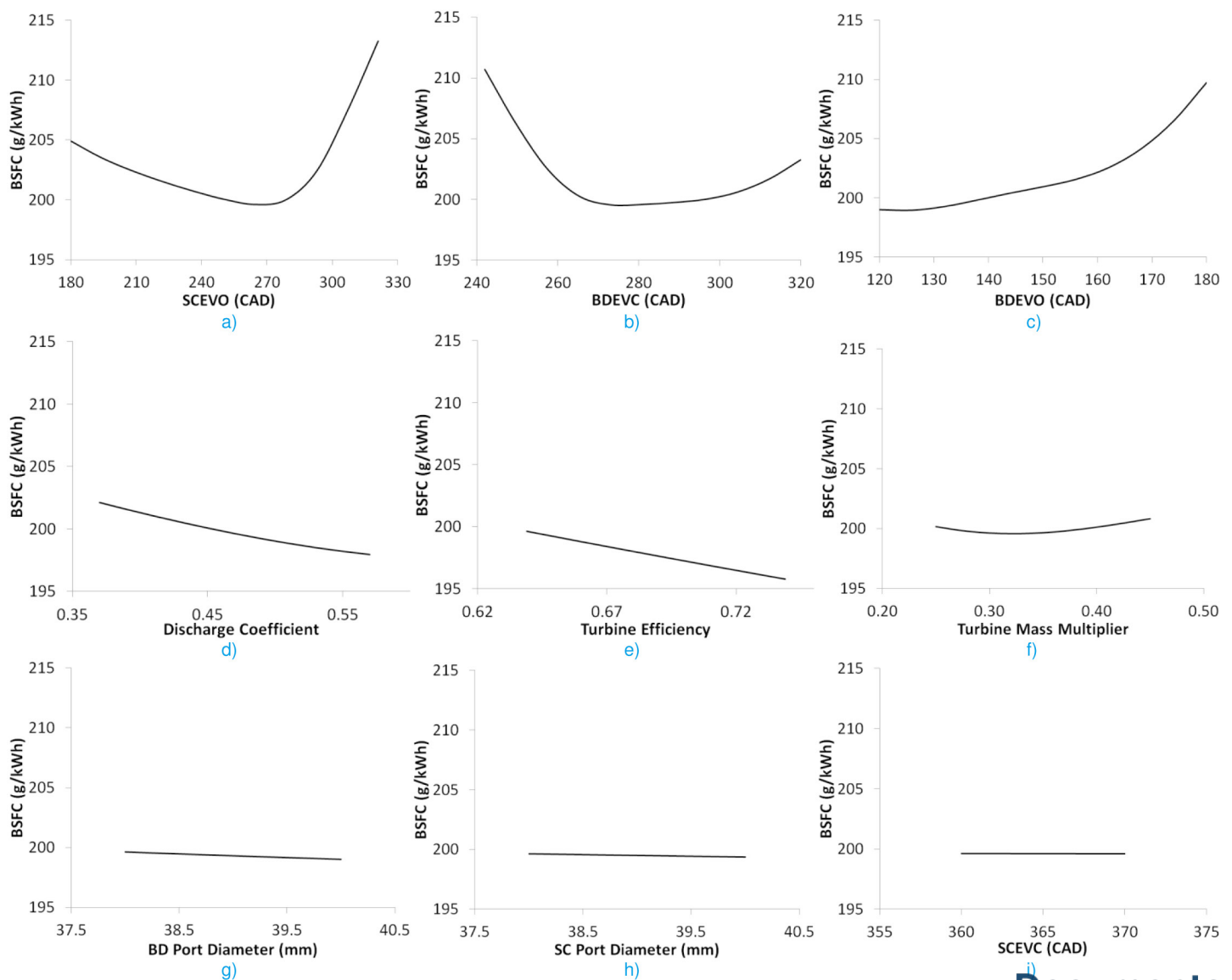


Figure 3. Main effect of each variable on BSFC at 1000 rpm and 100% load; the scales of vertical axes in all figures are the same.