

Divided Exhaust Period: Effects of Changing the Relation between Intake, Blow-Down and Scavenging Valve Area

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ABSTRACT

In a previous paper we showed the effects of applying the Divided Exhaust Period (DEP) concept on two heavy-duty diesel engines, with and without Exhaust Gas Recirculation (EGR). Main findings were improved fuel consumption due to increased pumping work, improved boost control and reduced residual gas content. However, some limitations to the concept were discovered. In the case of high rates of short route EGR, it was apparent that deducting the EGR flow from the turbine manifold impaired optimal valve timing strategies. Furthermore, for both of the studied engines it was clear that the size and ratio of blow-down to scavenging valve area is of paramount importance for engine fuel efficiency.

In this paper, the DEP concept has been studied together with a long route EGR system. As expected it gave more freedom to valve timing strategies when driving pressure for EGR is no longer controlled with the valve timing, as in the short route case. However, when evaluating different combinations of intake, blow-down and scavenging valve area, the optimal relation proves to be strongly dependent on the current EGR system and EGR rates. Hence, for different engine setups the trade-off between total intake and total exhaust area needs to be re-evaluated for optimal engine fuel efficiency. This paper also presents general trends in how different valve timing strategies and EGR rates affect both pumping work and boost pressure.

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INTRODUCTION

In our previous paper [1] the effects of applying the Divided Exhaust Period (DEP) concept on heavy-duty diesel engines were presented. The concept was studied on one engine model without Exhaust Gas Recirculation (EGR) and one with high rates of Short Route EGR (SR-EGR). Main findings in this paper were improved fuel consumption due to increased pumping work, improved boost control and reduced residual gas content. However, some limitations to the concept were discovered. In the case of high rates of SR-EGR, it was apparent that deducting the EGR flow from the turbine manifold impaired optimal valve timing strategies. When valve timing also regulated the EGR flow, they could not be set to only optimize fuel consumption. Furthermore, for both of the studied engines it was clear that the size and ratio of blow-down to scavenging valve area is of paramount importance for engine fuel efficiency. Based on the results from that study, this paper will investigate the DEP concept on a Long Route EGR (LR-EGR) engine. The reason for this is to assess if further efficiency gains can be made if the control of EGR flow is separated from the valve timing events. With a LR-EGR system the driving pressure for the

EGR flow is not controlled by valve timing as was the case with the SR-EGR system, hence the valve timing can be set for optimal efficiency instead. Furthermore, the effects of changing the relation and size between the intake, blow-down and scavenging valve area have been studied. Since it was clear that a small change in valve size gave large change to fuel efficiency it was of interest to investigate how different valve size setups affected the DEP concept. This paper will mainly deal with these two aspects.

Technical Concept

Introducing a turbocharger on an engine creates an exhaust back pressure for the piston to work against during the exhaust stroke. As a way to reduce this back pressure a second exhaust manifold is introduced, that leads the exhaust gases past the turbine. The standard two exhaust valves are each assigned to one of the two manifolds, as can be seen in [Figure 1](#). The valves and manifold connected to the turbine are denoted as the blow-down system, while the valves and manifold that are bypassing the turbine are denoted as the scavenging system. For the SR-EGR system the exhaust gas is fed from the high pressure pre-turbine side to the post-

compressor side. For the LR-EGR system the exhaust gas is fed from the low pressure post-turbine side to the pre-compressor side. The strategy of the DEP concept is to let the initial high energy blow-down pulse run the turbine, but lead the exhaust gases through the scavenging system during the rest of the exhaust stroke. Since the piston then can expel the exhaust gas out of the cylinder against atmospheric pressure instead of the turbine back pressure, an improvement of the pumping work is achieved. This in turn leads to a potential reduction in Break Specific Fuel Consumption (BSFC).

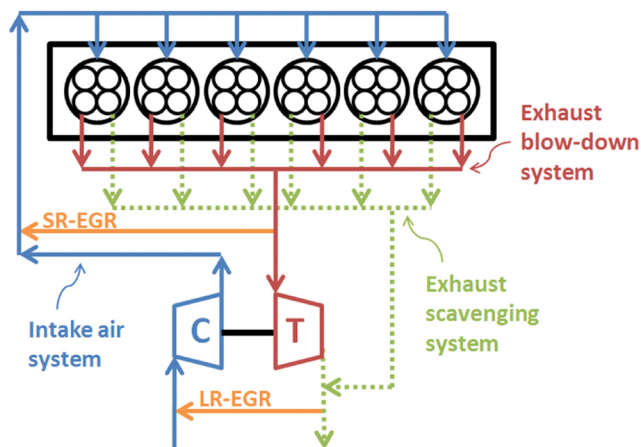


Figure 1. Manifold layout for the DEP concept

To be able to control the quantity of the exhaust flow distribution (which depends on the current load point) to the different manifolds, the DEP concept requires a variable valve train system for the exhaust side, see Figure 2. Since the blow-down valve only needs a variable closure time but requires stability because it opens at high cylinder pressure, a lost-motion valve system similar to the UniAir system [2] may be considered. The scavenging valve on the other hand requires more degrees of freedom in terms of opening- and closure time, but it opens at low pressure. Therefore a Fully Variable Valve Train (FVVT) system such as Cargine [3] or FEV [4] may be considered. It should be noted that no study has been made as to which valve system is best suited, but these systems have been acting as templates for a possible real implementation.

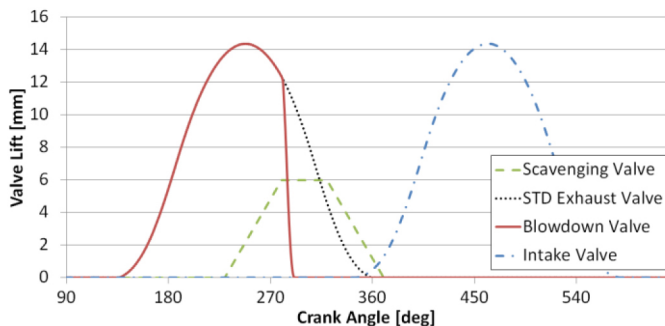


Figure 2. Conceptual valve lift curves for the DEP concept

As can be seen in Figure 2, the strategy is to let the blow-down valve follow the lift profile of the original cam lobe until the blow-down phase is over, at which point it will be closed. The scavenging valve will then open to reduce the cylinder pressure to atmospheric level. This allows easier expulsion of the exhaust gases during the last phase of the exhaust stroke. A certain overlap between the blow-down and the scavenging valve is necessary to avoid choked flow. The closure time of the scavenging valve can be adjusted accordingly depending on what is being optimized, fuel consumption or residual gas content. The term *early scavenging* will be used to refer to early closure of the blow-down valve and early opening of the scavenging valve. The term *late scavenging* will be used to refer to late closure of the blow-down valve and late opening of the scavenging valve.

Related Work

The base of this concept was first mentioned in a British patent from 1924 [5] and was investigated further in a more recent study [6] where additional patent claims [7] were made. The investigation was carried out on a passenger car spark-ignited engine which aimed at increasing full load torque, improving pumping work, reducing residual gas content (to increase cylinder filling and knock resistance) and reducing catalyst light-off time with higher exhaust gas temperature. The investigation showed improvements in all these areas but some negative aspects such as high turbine inlet temperature, choking of valves and the need for a Variable Valve Timing (VVT) system were pointed out.

Another numerical study of this concept was performed with the help of a VVT system [8]. The difference in this study is that the two exhaust manifolds are both connected to one turbocharger each to offer the possibility of sequential or two-stage turbo charging. This setup allows the two turbines to be adapted for the different characteristics of the mass flow in the beginning and the end of the exhaust stroke. The conclusion from this study was improvement in the scavenging behavior, reduction of fuel consumption and improved torque build up. This has been patented for SI engines in a German patent [9]. It should be pointed out that this concept does not improve pumping work in the same manner as explained previously since a turbine, that creates backpressure, is used for both manifolds.

In recent papers [10, 11] the DEP concept has been explored further with both simulations and engine tests for a turbocharged SI engine with different EGR systems. Their concept, called Valve-Event Modulated Boost (VEMB) System, showed improvements in both boost control and boost levels. Furthermore, improved fuel efficiency due to improved pumping work and reduced residual gas fraction was proved. The reduced residuals make it possible to move spark timing towards maximum brake torque timing and increase the compression ratio without risk of knock.

Furthermore, DEP has been studied in a Turbo-Discharging concept [12], where the turbine on the blow-

down manifold is used to drive a compressor that depressurizes the scavenging manifold. This concept can be used for both naturally aspirated as well as turbocharged engines and shows potential of improved pumping work and increased engine efficiency.

Objectives

Based on the previous results in [1], this paper will focus on the numerical simulation of the DEP concept on a heavy-duty diesel engine with a SR-EGR and LR-EGR system, with emphasis on the LR-EGR case. The aim of this paper is to investigate if efficiency improvements are made with DEP by:

- Using standard exhaust valve area
- Increasing exhaust valve area, by decreasing intake area and thereby maintaining total valve area
- Increasing total exhaust valve area
- Decreasing EGR-rate, hence reducing boost levels while maintaining the same air excess factor (λ)

METHOD

This section describes the engine for which the simulations have been carried out and the implementation of the DEP concept on the engine models. Furthermore, the selection of operating conditions chosen for the simulations is motivated.

Studied Cases

The DEP concept has been studied through simulations with GT-Power [13] on a heavy-duty diesel engine with two different EGR configurations, long route and short route. The baseline engine for which these studies have been made is a 12.7 liter, six cylinder, in-line, heavy-duty diesel engine, see Table 1. This engine has a Variable Geometry Turbine (VGT) and a SR-EGR system leading the EGR flow from the pre-turbine side to post-compressor/intercooler side, via a two-stage EGR cooling system. The VGT is used to regulate the backpressure to drive the EGR flow to the intake side, via an EGR-valve. The GT-Power model for this engine was then modified to incorporate a LR-EGR system, leading EGR flow from post-turbine side to pre-compressor side. An EGR throttle on the exhaust pipe is used to drive the correct EGR flow to the intake side. Here the VGT was replaced by a twin-entry turbine. The EGR rates are the same as in the SR-EGR engine and λ was kept identical as far as the fix geometry turbine allowed. From now on these two configurations will be referred to as the baseline SR-EGR and baseline LR-EGR case.

The baseline GT-Power model for the SR-EGR engine was calibrated and provided by the engine manufacturer and was verified to measurements performed on the engine at the KTH engine test facility. The verification was performed based on measurements for the European Stationary Cycle (ESC) points. Key parameters were measured, such as:

- Cylinder pressure
- Intake pressure
- Exhaust backpressure
- Turbocharger speed
- Air and fuel mass flow
- Temperature before and after turbine
- Temperature before and after compressor

Measured pressures, mass flows and turbocharger speed deviated less than ± 5 % of simulation results, and temperatures less than ± 15 °C on intake side and ± 60 °C on exhaust side. The larger temperature discrepancies may be due to a modified intercooler and engine cooling system of the KTH engine test facility. Since the current study aims at comparing a baseline model to a modified version of the model, any discrepancy from measurements is assumed to equally affect both models. Therefore, no further calibration of the provided model was performed for the purpose of this study.

Table 1. Engine specifications for the baseline engine

Engine label	Scania DC1306
Emission class	Euro 5
Max. power [hp]	360
Max. torque [Nm]	1900
Displacement [dm ³]	12.7
Bore [mm]	130
Stroke [mm]	160
Conn. rod length [mm]	255
Compression ratio	17.3
IVO [°ATDC]	344
IVC [°ATDC]	-136
EVO [°ATDC]	118
EVC [°ATDC]	378
Intake dia. [mm]	44
Exhaust dia. [mm]	41
Turbocharger	VGT
EGR System	Short route

DEP Model Implementation

The baseline engine was then modified to incorporate the DEP concept. A second manifold connected to one valve per cylinder was introduced that leads the exhaust gas to the post-turbine side according to Figure 1. A single-entry, fixed geometry, turbine was used with the DEP concept for both engine configurations. Since only the scavenging valve is open at the end of the exhaust stroke, there will be no expected blow-down pulse interference between the cylinders which is usually the case in an in-line six cylinder engine. Note that the baseline LR-EGR engine uses a twin-entry turbine due to this pulse interference. In the SR-EGR case the VGT turbine can be omitted since it is possible to change the

exhaust valve timing instead to control the backpressure. The backpressure is then adjusted with proper valve timing strategies to get the necessary pressure difference to drive the EGR flow to the intake side.

The valve lift profiles for the scavenging valves were based on an idealization of the valve dynamics of the Cargine valve and data for opening/closure velocity were used accordingly [14, 15]. The blow-down valve lift profile was modeled with a lost motion system in mind and valve closure velocity was set close to the original valve system closing velocity.

Turbocharger matching was performed by scaling the mass flow axis (using mass multiplier in GT-Power) of the standard engines turbocharger maps. In the previous study, when a good match was achieved for the selected valve timings, new performance maps were implemented. These new maps correspond to the scaled maps, but represent a turbocharger in production. In this way a large number of turbochargers could be tested without handling a large number of different performance maps. For this study both the baseline and DEP engine use the same performance maps (except for the VGT turbine), and only mass multiplier has been used to differentiate the size of the turbocharger. This was done for a more fair comparison, so that any difference between baseline and DEP models is due to the concept itself and not to specific turbocharger maps. For both the SR-EGR and LR-EGR case, the DEP models were run with the same EGR rates as baseline and λ could vary within $\pm 4\%$. By keeping identical EGR rates and λ , the same combustion model could be used and emission formation was assumed to be identical to baseline.

Operating Conditions

The strategy for the simulations was to optimize the engine with the DEP concept for one load point considered important from a fuel economy perspective. This means that the hardware like exhaust valve size, exhaust manifold geometry, turbocharger etc. was chosen based on optimization around this one load point. The optimization for the rest of the engine operating map was then based solely on valve timing strategies of the two exhaust valves.

Parallel to this study a thesis [16] was performed investigating engine operating time statistics. The aim of the thesis was to investigate at which torque and speed a truck engine operates most of its run time in the vehicle. Depending on vehicle load and type of road (highway, city, hillside) the trends on which load point had most operating hours differed. A trend that can be seen though is that the automatic gearbox controls the engine speed to stay within a quite narrow range around 1400 RPM for most cases. For engine torque it is harder to find a single point that is more prominent than others. For city and hillside driving operating hours are more spread out in terms of torque, but always close to 1400 RPM. For highway driving the most prominent operating point lays around 100 kW and 1400 RPM. Since the comparison between the standard and the DEP engine is

carried out on the ESC cycle points, it was decided to optimize the hardware for an ESC load point close to this condition. The chosen load point is denoted A9 in Figure 3. Aside from the 12 ESC cycle points (idle is omitted) four 100 kW points were added to the study to represent highway driving at different gears.

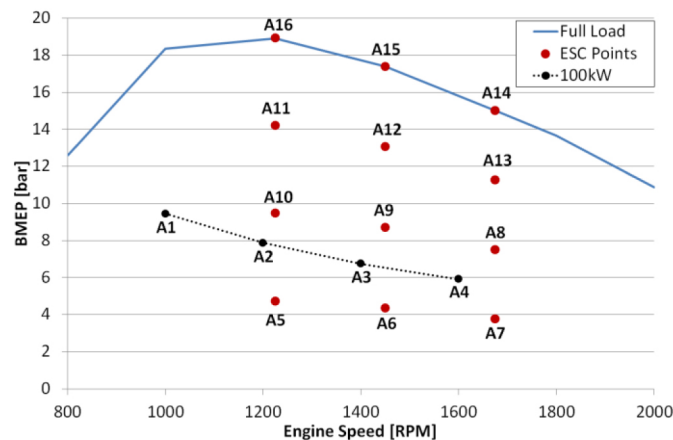


Figure 3. Map of load points for which the simulations are carried out

Pumping Work

To clarify, this section will briefly define what is being referred to when discussing pumping work. Throughout the thesis the pumping mean effective pressure (PMEP) will be used as defined by Equation 1.

$$PMEP = \int_{180}^{540} \frac{pdV}{V_d} \quad (1)$$

Where p is cylinder pressure, V is cylinder volume and V_d is the displacement volume. PMEP is then calculated as an average of all cylinders. *Pumping work* is proportional to PMEP but with a different unit. PMEP multiplied by V_d gives pumping work in joules per cycle. In short, PMEP is the work added to the crankshaft during the exhaust and intake stroke and is linked to the work it takes to the exchange exhaust gas with the fresh charge. This means that with positive PMEP, work is added to the crankshaft during the gas exchange phase. With negative PMEP, work is subtracted. Consequently, a higher positive PMEP is better for engine efficiency than a negative PMEP.

RESULTS & DISCUSSION

The previous paper [1] showed that increased exhaust valve area was more beneficial to the DEP concept than the baseline engine, so the traditional trade-off between intake and exhaust area needs to be re-evaluated. Therefore it is of interest to investigate if using a smaller intake area, thus allowing a larger exhaust area, would lead to a net gain in PMEP. This section shows results of how fuel consumption is