

# 1-D Simulation Study of Divided Exhaust Period for a Highly Downsized Turbocharged SI Engine - Scavenge Valve Optimization

Bo Hu, Sam Akehurst, Chris Brace, and Colin Copeland  
University of Bath

James Turner  
Jaguar Land Rover

## ABSTRACT

Fuel efficiency and torque performance are two major challenges for highly downsized turbocharged engines. However, the inherent characteristics of the turbocharged SI engine such as negative PMEP, knock sensitivity and poor transient performance significantly limit its maximum potential. Conventional ways of improving the problems above normally concentrate solely on the engine side or turbocharger side leaving the exhaust manifold in between ignored. This paper investigates this neglected area by highlighting a novel means of gas exchange process.

Divided Exhaust Period (DEP) is an alternative way of accomplishing the gas exchange process in turbocharged engines. The DEP concept engine features two exhaust valves but with separated function. The blow-down valve acts like a traditional turbocharged exhaust valve to evacuate the first portion of the exhaust gas to the turbine. While the scavenge valve feeding the latter portion of the exhaust gas directly into the low resistant exhaust pipe behaves similarly to valves in a naturally aspirated engine. By combining the characteristics of both turbocharged and naturally aspirated engines, high backpressure between the turbine inlet and the exhaust port is maintained in the blowdown phase while significant reduction of the backpressure could be achieved in the latter displacement phase. This is directly beneficial for pumping work and residual gas scavenging. Combustion phasing & stability and turbocharger efficiency could also benefit from such concept.

This simulation study was carried out using a validated 1D model of a highly downsized SI engine. Two degrees of freedom including the lift and the duration of the scavenge valve were optimized to achieve minimum BSFC. The potential for higher attainable BMEP was also briefly investigated at low engine speed.

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## INTRODUCTION

A turbocharged SI engine has the ability to have higher thermal efficiency and less frictional loss and therefore to be more economical than a naturally aspirated counterpart delivering the same performance [1]. However, some negative effects by turbocharging including negative PMEP, knock sensitivity and poor transient performance are inevitably introduced. These problems significantly limit practical BSFC and BMEP performance [2]. If an engine has the ability to recover the high energy contained within the exhaust whilst also scavenging the low-energy mass flow as freely as in a naturally aspirated engine with a smaller turbocharger, then the advantage of the turbocharged engine could be retained while the negative effects could be offset.

The Divided Exhaust Period is such a gas exchange process. It utilizes two exhaust valves for different purposes. The blowdown valve feeds the first portion of the mass flow into the turbine to boost the engine. While the scavenge valve opens later to scavenge the remaining mass flow directly to the exhaust. By doing so, some of the waste energy from the exhaust is recovered through the turbocharger, while high backpressure is avoided when the scavenge valve opens. Figure 1 shows the schematic view of the exhaust system layout in DEP concept.

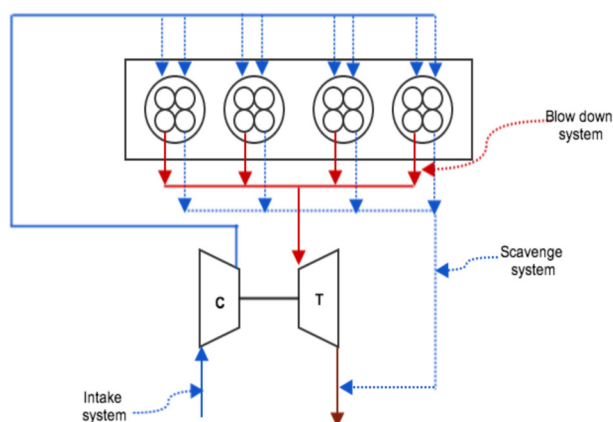


Figure 1. Schematic view of the exhaust system layout in DEP concept

Engines equipped with the DEP concept offer the potential to be more fuel-efficient for three reasons:

- Better gas exchange process (mainly for the exhaust process)
- Improved combustion phasing and stability
- Possible to modulate turbine or compressor to work in its higher efficient area

As the high backpressure between the turbine inlet and the exhaust port is isolated from the engine piston during the latter portion of the exhaust stroke, a decreased pumping loss could be attained.

Combustion phasing and stability could also benefit from DEP concept. By bypassing the turbine during the latter exhaust stroke, positive pressure across the intake and the exhaust system may be achieved, leading to improved scavenging and thus a lower residual gas fraction (RGF). Combined with reduced boost pressure, combustion phasing would be advanced. In addition, engine stability, knock resistance and volumetric efficiency could also benefit from such concept as back flow is largely limited [3].

Lastly, the DEP concept engine only utilizes the first high-pressure exhaust mass flow leaving the later low-pressure mass flow bypassing the turbine. This in turn could result in higher average turbine efficiency as the optimization procedure could be conducted on more stable operating points [4]. However, this benefit will depend heavily on the engine's specification with more benefit for 6 or 8 cylinder engines than for conventional 4 cylinder downsized engines. Meanwhile, by modulating the turbine inlet pressure and mass flow, it is also possible to shift the compressor operating point and therefore improving low-speed performance.

## METHODOLOGY AND CONTROL STRATEGY

For the simulation work presented in this paper a validated 1D model of a highly downsized SI engine detailed in [table 1](#) was used as a starting point. The engine had a BMEP designed to facilitate a 60% downsizing ratio when compared with an equivalent NA engine [5]. Noted here that the supercharger was deactivated to only investigate the benefits DEP concept brings to the turbocharger system. In order to implement the DEP functionality the two exhaust valves were re-routed as shown in [figure 1](#). The blow-down and scavenge valves were actuated by two unique cam profiles. The wastegate function of the conventional fixed geometry turbocharger was replaced by adjusting the timing of the scavenge valve to maintain or exceed the target BMEP.

Table 1. Technical data of the downsized SI engine

|                     |            |                                                                          |
|---------------------|------------|--------------------------------------------------------------------------|
| Engine Type         | -          | Inline-4-cylinder                                                        |
| Capacity            | cc         | 1991                                                                     |
| Bore                | mm         | 83                                                                       |
| Stroke              | mm         | 92                                                                       |
| Compression ratio   | -          | 9.0:1                                                                    |
| Firing Order        | -          | 1-3-4-2                                                                  |
| Combustion System   | -          | Gasoline GDI                                                             |
| Valvetrain          | -          | DOHC, Cam Phasers and Cam Profile Switch on Intake and Exhaust Camshafts |
| Spec. Power         | kW/l @ min | 142 @ 6500                                                               |
| Spec. Torque        | Nm/l @ min | 255 @ 3500                                                               |
| max. BMEP           | bar @ min  | 35 @ 3500 and 25 @ 1000 & 6500                                           |
| Air Charging System | -          | HP: Eaton R410, LP: Honeywell GT30                                       |

The DEP scavenge system can be considered as a more efficient wastegate for the following three reasons:

- Mitigate the engine backpressure since pre-turbine pressure is controlled separately
- Improve boost control through precise control of valve events

Firstly, high backpressure is produced partly due to the use of the wastegate as when the boost pressure is larger than desired, the wastegate is more prone to choke thus resulting in unexpected backpressure. While instead of evacuating the whole mass flow into the turbine, the exhaust valve timing

mechanism scavenges some mass flow directly into the less resistant exhaust when the choking is not produced which helps result in a decrease of the average engine backpressure.

From figure 2, it can be seen the relationship between the timing of the scavenge valve and the BMEP performance indicating the ability to modulate engine boost via the scavenge-camshaft phasing with a non-wastegated turbocharger.

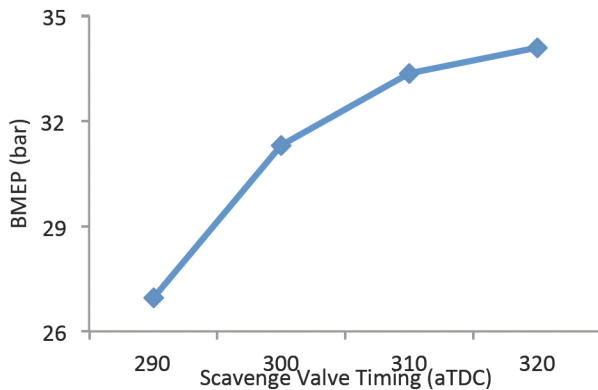


Figure 2. The relationship between the scavenge valve timing and BMEP at 4500RPM

This paper only investigated the timing of the scavenge valve to be the control parameter. But it is also conceivable that variable blow-down valve is a reasonable solution for PFI engines where larger scavenging is significantly undesirable.

By varying the timing of the scavenge valve, the overlap between the blow-down and the scavenge valve changes, which has a strong influence on the mass flow into the turbine and also the mass flow bypassing straight to the exhaust system. Meanwhile, the overlap between the scavenge valve and the intake valve influences the flow characteristics across the engine from the intake to the exhaust system [6][7].

The exact timing of the scavenge valve required to maintain or exceed the target BMEP depends on the profile of the blowdown and scavenge valves. The aim of this paper therefore is to optimize the profile of the scavenge valve to achieve minimum BSFC. The potential of a DEP scheme to produce higher BMEP at low engine speed is also briefly investigated.

The calibration of the original model was retained except for the size of the turbocharger. The turbine was scaled to be 80% of the original size due to the fact that less mass flow was evacuated from the turbine path. The size of the turbocharger was not fully optimized. While this is an interesting topic in its own right, it is deemed that for different sizes of turbochargers, the procedure for optimizing the lift and the duration of the scavenge valve should be similar.

It was decided to sweep the design parameter one by one in GT-Power (1-D simulation software as can be referred in [8]) to investigate the effect of each variable on the gas exchange process, combustion phasing & stability and turbocharger performance. In this paper, only full load operating points were presented. In order to fully understand the underlying gas exchange process, both high speed and low speed simulation were conducted.

## RESULTS

The results are presented in two sections, discussing first the high-speed behavior of the system and then the low-speed operating region.

### High Speed Simulation (4500RPM)

#### Sweep of Scavenge Valve Lift

For this simulation, the multiplier of the scavenge valve lift was varied from 0.6 to 1 while maintaining BMEP performance. The corresponding timing of the scavenge valve is shown in figure 3.

First it can be seen that all of the optimized scavenge valve events were somewhat retarded from the blow-down event. This is as would be expected from the intended operation of the system. Secondly, it can be seen that as the scavenge valve lift increased it became progressively further retarded relative to the blow-down valve in order to achieve the required BMEP. This is due to the fact that when the scavenge valve lift was increased, the corresponding mass flow into the turbine would be decreased for the same valve timing. In order to provide the same BMEP performance, the scavenge valve needed to be retarded to promote sufficient mass flow into the turbine side instead of running into the exhaust freely.

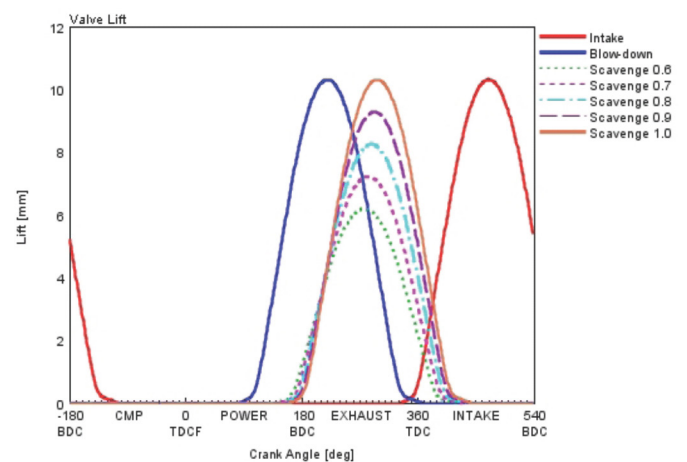


Figure 3. The profile of the intake, blow-down and the scavenge valve