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Fuel economy analysis of part-load variable camshaft timing strategies in two modern small-capacity spark ignition engines

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HIGHLIGHTS

- Valve timing strategies are explored at part-load in two small-capacity SI engines.
- Simplified graphical fuel-economy VCT strategies are provided for the two engines.
- Engine design specifics exert a profound influence upon optimal valve timing.
- The theoretical best strategy determines BSFC reduction above 8% for the PFI engine.
- Maximum BSFC reduction was about 5% for the more efficient GDI platform.

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ABSTRACT

Variable Camshaft Timing strategies have been investigated at part-load operating conditions in two 3-cylinder, 1.0-litre, Spark Ignition engines. The two small-size engines are different variants of the same 4-valve/cylinder, pent-roof design platform. The first engine is naturally aspirated, port fuel injection and features high nominal compression ratio of 12:1. The second one is the turbo-charged, direct injection version, featuring lower compression ratio of 10:1. The aim of the investigation has been to identify optimal camshaft timing strategies which maximise engine thermal efficiency through improvements in brake specific fuel consumption at fixed engine load.

The results of the investigation show that the two engines demonstrate consistent thermal efficiency response to valve timing changes in the low and mid part-load envelope, up to a load of 4 bar BMEP. At the lower engine loads investigated, reduced intake valve opening advance limits the hot burned gas internal recirculation, while increasingly retarded exhaust valve opening timing favours engine efficiency through greater effective expansion ratio. At mid load (4 bar BMEP), a degree of intake advance becomes beneficial, owing mostly to the associated intake de-throttling. In the upper part-load domain, for engine load of 5 bar BMEP and above, the differences between the two engines determine very different efficiency response to the valve timing setting. The lower compression ratio engine continues to benefit from advanced intake valve timing, with a moderate degree of exhaust timing retard, which minimises the exhaust blow-down losses. The higher compression ratio engine is knock-limited, forcing the valve timing strategy towards regions of lower intake advance and lower hot gas recirculation. The theoretical best valve timing strategy determined peak fuel economy improvements in excess of 8% for the port fuel injection engine; the peak improvement was 5% for the more efficient direct injection engine platform.

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1. Introduction

In 2011, the International Energy Agency, in conjunction with the Global Fuel Economy Initiative, published a report which addresses their long term goal as a 50% reduction in global average emissions by the year 2030 [1]. Policy changes, enhanced technologies, revised fuels and reduced vehicle and engine size are indicated as possible ways to improving vehicles fuel economy, which in turn reduces pollutant emissions. In the last three decades, advanced technologies such as direct injection, turbocharging and Variable Camshaft Timing (VCT), have contributed significantly to the evolution of engine design. Combinations of these technologies, along with engine down-sizing, have simulta-

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Nomenclature

ATDC	After Top Dead Centre
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Centre
CA	Crank Angle
COV	Coefficient Of Variability (of GMEP)
DI	Direct Injection
DI-VCT	Dual Independent Variable Camshaft Timing
DOHC	Double Over-Head Cam
E22	Gasoline-Ethanol Fuel Blend, 78/22 Volume Ratio
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valve Closing
EVO	Exhaust Valve Opening
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GMEP	Gross (Indicated) Mean Effective Pressure
I-EGR	Internal Exhaust Gas Recirculation
IMEP	Indicated Mean Effective Pressure
IT	Indicated Torque (Gross)
IVC	Intake Valve Closing
IVO	Intake Valve Opening
MAP	(Intake) Manifold Pressure
MBT	Maximum Brake Torque
MFB	Mass Fraction Burned
MFB50	Crank Angle Location of 50% Mass Fraction Burned
NEDC	New European Drive Cycle
PFI	Port Fuel Injection
PMEP	Pumping Mean Effective Pressure
RON	Research Octane Number
TDC	Top Dead Centre
VCT	Variable Camshaft Timing

neously delivered positive effects on fuel consumption and emissions [2,3], as well as on driving pleasure [4].

Today's engine technical developments are primarily focused on improved part-load driving performance and fuel consumption with stoichiometric operation [5,6]. One way of targeting these goals is through the implementation of VCT systems. The evaluation of the extent to which the VCT technology impacts on fuel savings, especially within the framework of current down-sized engines, is of paramount importance. This evaluation, which enables the relative importance of the VCT system to be assessed, is the primary objective of the present study.

1.1. Variable camshaft timing

In engines with fixed camshaft timing, the exhaust valve is normally closed 15–30 Crank Angle (CA) degrees After Top Dead Centre (ATDC), whereas the intake valve is opened 10–20 CA degrees Before Top Dead Centre (BTDC). These timings represent a compromise between several functions, intended to provide sufficient valve overlap duration for good cylinder scavenging, but avoiding at the same time excessive backflow from the exhaust port. By contrast, the flexibility associated to the VCT technology has the potential to improve fuel economy, performance, as well as emission levels of gasoline engines over wide ranges of running conditions [7]. The advantage of wide valve overlap occurs especially at higher engine load and increasing engine speed, owing to improved volumetric efficiency. At low engine speed, wide overlaps are generally detrimental, yielding higher residual gas fraction [8] which may significantly degrade the combustion stability. Improvements in Brake Specific Fuel Consumption (BSFC) of up to 10%, as a result of early Intake Valve Opening (IVO) strategies, have been reported in recent studies [9,10]; these explain the observed changes referring to the displacement of fresh mixture with residuals during valve overlap, ultimately reducing the *need for throttling* [6]. If the intake cam profile is fixed, the effects of IVO are inevitably linked to those of Intake Valve Closing (IVC) timing. Because of fresh mixture backflow at low engine speed, and inertia of the incoming gas flow at higher speed [11], the IVC timing shows significant effects on cylinder trapped mass, and hence on the resulting pumping (intake throttling) losses. Sizeable improvements in thermal efficiency have been observed with early IVC strategies, owing to greater effective compression ratio [12,13].

In traditional, fixed camshaft timing engines, the exhaust valve timing setting is a compromise between improved exhaust blowdown (achieved with early Exhaust Valve Opening, EVO) and greater work per cycle, associated to greater effective expansion ratio (late EVO). The influence of exhaust VCT on Internal Exhaust Gas Recirculation (I-EGR) is another very relevant factor. At part-load, the beneficial influence of late Exhaust Valve Closing (EVC) on cylinder scavenging, normally seen at high engine speed, tends to reduce; as speed and load are reduced, retarded EVC enables increasingly larger backflow from the exhaust to the intake system, which increases the fresh charge burned fraction. A similar though generally smaller effect is associated to early EVC taking place Before Top Dead Centre (TDC), due to trapping large amounts of burned gases within the cylinder at the end of the exhaust stroke.

As of today, the exhaust-only and intake-only variable camshaft timing schedules remain the most practical and cost-effective in use. Typically, at part-load running conditions, intake-only strategies entail significantly advanced intake valve timing and asymmetric valve overlaps extended well into the exhaust stroke. In terms of benefits on fuel consumption, Leone et al. [14] found that due to increased charge dilution, a higher intake manifold pressure is required to maintain a given load, which in turn reduces the pumping work. Similar reasoning, along with increased expansion work, justifies the use of retarded exhaust valve timing at part-load, in the case of exhaust-only strategies. The Dual or Twin Independent VCT systems, where the two camshafts can be phased continuously and independently of one another, would synthesize the benefits of both exhaust and intake-only schedules; however, DI–VCT mechanisms are bulkier, more expensive and more complicated to operate. Kramer and Philips [15] found that, using a DI–VCT strategy, the fuel economy was improved due to the following three, concurrent phenomena: de-throttling due to late IVC (backflow of mixture into the intake manifold); de-throttling due to late EVC (internal Exhaust Gas Recirculation); increased effective expansion ratio due to late EVO (more work extracted in each engine cycle).

1.2. Engine down-sizing

Internal combustion engine down-sizing is becoming increasingly common because of the inherent advantages of high specific power and torque, lower fuel consumption and emissions, as well as improved driveability [4,16]. Due to lower displacement volume, the down-sized engine tends to work at higher load with reduced throttling/pumping losses [17]. The potential reduction in engine fuel consumption, averaged upon the New European Drive Cycle (NEDC), has been shown to increase exponentially with the factor of down-sizing [18]. High specific outputs are often

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