Simulation and Optimisation of a Variable Valvetrain System for a Compression Ignition Engine

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There are several potential benefits of applying Variable Valve Timing (VVT) to a diesel engine:

- Optimisation of charge motion to increase swirl
- Reduced pumping work by eliminating the need for a swirl flap
- Increased cycle efficiency from over-expanded cycle
- Reduced NO\textsubscript{x} emissions through reduced in-cylinder temperatures with an over-expanded cycle
- Increased low speed performance is also possible with increased valve overlap. However, this requires modification to the pistons and so was not considered for this work

GT-Power has been used to investigate the application of VVT using MAHLE CamInCam\textsuperscript{®} technology to independently vary the timing of the intake valves of a four valve passenger car diesel engine

The aim of this work was to improve part load fuel economy and emissions. Full load performance was checked to ensure the baseline peak power was maintained
CamInCam® consists of two main components, the concentric outer and inner shafts.

The variable lobes are attached to the inner shaft, the fixed lobes to the outer shaft. 60 crank degrees of phasing is available with the current design.

This can be used to enable VVT on a single cam engine or, as in this case, to alter the effective inlet duration by fixing one inlet cam and phasing the other.

Phasing the variable cam relative to the fixed cam gives a longer effective duration, allowing Late Inlet Valve Closing (LIVC).

A shorter cam duration gives Early Inlet Valve Closing (EIVC) with the cams in phase and CamInCam® can be used to increase the effective duration when the cams are phased.

For this application, the exhaust cam was left unchanged.
Description of the Baseline Model

- Baseline engine:
  - 2.0l common rail direct injection, with variable geometry turbine and exhaust gas recirculation
  - 4 valve head has separate swirl and flow intake ports and fully variable swirl flap to control the charge motion

- A GT-Power model of the baseline engine was built and correlated to a full load power curve and fourteen part load minimap points

- The engine was tested at MAHLE Stuttgart, with test data including high speed pressure transducer measurements of the intake, exhaust and EGR systems

- Port flow testing was performed by MAHLE Powertrain and turbocharger maps were provided by Bosch Mahle TurboSystems
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Diagram of the Baseline GT-Power model

- EGR Cooler
- Intake Ports and Swirl Valve
- EGR Valve
- Plenum
- Catalyst and exhaust system
- Intercooler
- Airbox and Compressor Inlet Duct
- Exhaust Manifold
- Turbocharger
The baseline engine has two intake valves, with 2 different intake port characteristics. Modelling these ports and valves using flow coefficients from a standard flow test would not distinguish between the two ports.

Because CamInCam® allows the cam timing of each inlet valve to be varied individually this method is not adequate.

The model was also required to investigate the effect of CamInCam® on charge motion which will vary with the offset in cam timing.

To achieve these aims, a matrix of port flow tests was developed to test every combination of valve lifts for the flow and swirl ports:

- 3D maps were generated for flow, swirl and tumble coefficients.
- The flow coefficient map is shown, right, with the locus of different degrees of cam phasing on the map.
Swirl and tumble coefficient maps were also measured and added into the model.

The swirl coefficient map (right) shows very strong asymmetry due to the different port characteristics.

Swirl and tumble coefficients were evaluated in the model using the EngCylFlow object. This calculates the in-cylinder swirl and tumble ratios at each timestep based on the massflow and data taken from the 3D maps.

Detailed cylinder geometry objects were not used, so the predicted swirl ratio will not be directly comparable with other predictions.

Target swirl ratios were determined by calculating the swirl ratio generated by the baseline engine with different positions of the swirlflap.
The 3D maps of flow, swirl and tumble coefficients were entered into GT-Power using the Lookup2D and XYZmap objects.

The valve lift is sampled at each timestep and the appropriate coefficients for these lift values looked up from the maps.

These values are entered back into the models using the flow area multiplier and swirl and tumble coefficient multipliers added to GT-Power for this work (from V7 build 4).
CamInCam® was investigated and optimised using Design of Experiments (DOE) techniques

DOE’s were set up using GT-Power’s DOE tool
- The plots shown in the following slides are full factorial 2 factor DOE’s of inlet valve opening point for the flow and swirl cams

The results were processed using GTPost, not the DOE postprocessor
- Only linear interpolation between points, no statistics on DOE fit
- More advanced fit not required due to large number of points

Runs were performed at peak power and a range of part load operating points

The swirl flap was set to be open for all points

The DOE’s were repeated with different cam durations, obtained by scaling the baseline profile

Note CamInCam® only allows operation on a single line either across or up the DOE, depending on which cam is phased (see over the page)
- DOE used as a useful way of showing trends
- Also allows the effect of dual VVT CamInCam® or variation of fixed cam operating point to be shown
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Cam Optimisation – Explanation of DOE Plot

Locus of Operation of CamInCam on Swirl Port

Standard Valve Timing

Data Points

Locus of Operation of CamInCam on Flow Port
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DOE Results – Part Load, Cam Duration 80% of Baseline
Variation of Massflow through Flow and Swirl Ports

- Retarding the timing of either cam reduces the massflow through that port
  - Retarding the flow cam increases massflow through the swirl port and vice versa
- A large variation possible: Minimum – maximum flow varies by a factor of 3
- Total massflow is relatively constant, with a variation of 10% over the map range
Increasing massflow through the swirl port increases charge motion – both swirl and tumble

The swirl ratio with flow cam phased by 60° is similar to the swirl ratio achieved with the standard cams and the swirl flap 80% closed
The previous plots can be explained by looking at the massflow through the valves.

Retarding either cam causes a large increase in massflow through the fixed cam earlier in the cycle.

The massflow through the port with the retarded cam is greatly reduced.

At maximum phase angle, backflow does occur through the retarded cam but, due to the reduced duration, the massflow involved is relatively small.

Longer cam durations give increasing levels of backflow when phased.
The variation in swirl ratio, as predicted by the EngCylFlow object, is shown here for 3 different cases:

- Cams in phase
- 30º retard of flow cam
- 60º retard of flow cam

It can be seen how phasing the cam affects the predicted in-cylinder swirl ratio. Early in the induction stroke, very high swirl ratios are created with high massflow through the swirl port. This is ‘diluted’ by later flow through the flow port.

The predicted swirl for the baseline model with swirlflap fully closed and 80% closed is also shown.
The aim of this work was to match the full load performance of the baseline engine with a valve lift profile that gave a benefit at the part load operating points.

Due to limitations of the compressor match and fuelling, this required the full load volumetric efficiency with CamInCam® to be similar to that of the baseline engine.

Reducing the cam duration does give reduced volumetric efficiency, but it can be increased with shorter durations by phasing CamInCam®. The 80% profile with 40° phasing gives a reduction in volumetric efficiency of just 3% from the baseline, which was considered acceptable.

The optimum cam timing moves closer to zero phasing with cams closer to the standard duration.
Early or late inlet valve closing affects in-cylinder temperature, potentially giving a reduction in peak in-cylinder temperatures and NO$_x$.

A predictive emissions models was not used for this work so in-cylinder temperature is used as an indication to estimate the effect on NO$_x$ instead.

The plot shows the variation in in-cylinder temperature at start of injection:
- 2 cam profiles; standard and 80% duration
- Swirl cam fixed, flow cam timing swept
- Fuelling is set for constant torque, boost pressure set to give constant massflow

It can be seen that both EIVC (short cam without phasing) and LIVC (standard cam phased) reduce charge temperatures – and so NO$_x$ - compared to the baseline engine.
The pumping work for a sweep of flow cam timing with standard and 80% duration cams is shown here. Again, EIVC is achieved with a reduced duration and no phasing, LIVC by standard duration with phasing.

The turbo match has been adjusted to compensate for the change in volumetric efficiency with different valve timings and this affects the pumping work. It can be seen how pumping losses are reduced, and even turned into positive work, with both EIVC and LIVC.

As with the in-cylinder temperature prediction, the optimum configuration varies with different speed and load points. At some EIVC gives the best results, at some LIVC, and no benefit was seen at others.
Summary and Conclusions

- GT-Power has been used to investigate the application of CamInCam® to a passenger car diesel engine
  - The model was correlated to full load and part load test data
  - Swirl and tumble numbers have been calculated from flow bench tests and added in to the model as 3D maps to enable prediction of the effect of cam in cam on charge motion
- DOE’s were performed for variations of cam phasing and for different cam durations at full load and part load points
- CamInCam® is able to alter the proportion of massflow through the two inlet valves
  - This allows the swirl and tumble characteristics to be altered
  - Retarding the flow cam increases the flow through the swirl port. A 60º phase shift gives an in-cylinder swirl ratio greater than the standard cam with swirl flap 80% closed
- Variable cam duration allows the use of early or late inlet valve closing with the potential for reductions in both pumping work and NOₓ
- If CamInCam® is used with reduced duration cams, at full load the cams can be phased to minimise any reduction in airflow, allowing the cam profile to be optimised for part load