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Combustion Phasing Controllability with Dual Fuel Injection Timings

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Introduction
Reactivity Controlled Compression Ignition through in-cylinder blending of gasoline and diesel to a desired reactivity has previously been shown to give low emission levels, combined with an efficiency advantage. To determine the possible viability of the concept for on-road application, a determination of the control space of injection parameters with respect to combustion phasing is presented.

The experiments have been performed on a heavy duty test engine, equipped with an intake port fuel injection (PFI) system for gasoline and a common-rail direct injection (DI) system for diesel.

Measurement matrix and procedure
For all measurements the following conditions are kept constant:
- 1200 rpm (σ=0.44 rpm),
- Fuel flow of 1.23 g/s (σ=0.022 g/s),
- 2 bar absolute intake pressure (σ<0.005 bar),
- 1.13 bar abs. exhaust pressure (σ=0.014 bar),
- 62wt% heavily cooled EGR (σ=0.9wt%),
- 306 K intake temperature (σ=2.4 K),
- Port injected gasoline of 80% of injected mass.

For these constant load, speed and ambient conditions, which result in a lambda value of 1.60 (σ=0.03), four diesel injection strategies are investigated:

First, 20 wt% of injected mass is injected in a single diesel injection. For injecting such small amounts, a diesel injection of 1000 bar is used. This is the minimal pressure to have stable operation of the injector, using a 500 microsecond (=3.6CAD) actuation duration. The start of injector actuation (SOA) is swept from -40 to -90 degrees aTDC, with 10 degree increments.

In the second and third strategies the 20 wt% diesel is equally divided over two injections. To enable stable operation of the injector, the injection pressure has to be lowered to 500 bar, to obtain a sufficiently long actuation duration. In the second strategy the late injection is fixed at -10 degrees aTDC, with an early injection variation from -40 to -90, with 10 degree increments. In the third strategy the early injection is fixed at -70 degrees aTDC, with a late injection variation from -25 to -5, with 5 degree increments.

The fourth strategy is derived from the third one, with the early injection fixed at -70 degrees aTDC, with a late injection variation from -25 to -5, with 5 degree decrements and the early-late mass balance is shifted to 70:30.

Results: Combustion phasing control
The combustion phasing response of all four injection strategies is combined in Figure 1. As discussed above, the single and early injections have an inverse effect on combustion phasing. A first order fit of the measured points gives a quantification of this negative slope, defined as

\[ s_{ID} = \frac{\partial CA50}{\partial SOA} . \]

Furthermore the linear association of the response is not very strong and in a double injection strategy, the response of CA50 on a variation of the first injection is (very) weak.

![Image](image.png)

**Figure 1 – Timing of CA50, for injection timing variations in 4 different injection strategies. Marker and vertical errors depict the mean and standard deviation, respectively, of 50 measured cycles per operating point. The given slope and coefficient of determination \(R^2\) are based on a linear regression fit.**

The response to a variation in the late injection has a positive \(s_{ID}\), which is nearly exactly linear and has a larger value compared to the early injection variation strategies. Furthermore, above it was shown that the more fuel is admitted in the second injection, the larger \(|s_{ID}|\) is. Therefore the third strategy was found to be most favorable with respect to combustion phasing response.

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Results: Efficiency

For the double injections, the injection pressure had to be lowered to 500 bar, and together with the very short injections, this appears to be dramatic for the completeness of combustion (combustion efficiency). As can be expected, this has a significant effect on the gross indicated fuel efficiency.

All double injection strategies have an indicated efficiency of about 10 percent lower than the single injection strategy. Other tests have shown that the dual-fuel concept, even with double injections, is possible of producing very high efficiencies, and thus low fuel consumption. However, because of the low completeness of combustion, this is not achieved in the present investigation.

Results: NO\textsubscript{x} and smoke emissions

It is general practice to plot smoke emissions versus nitrogen oxides emissions to see how different strategies behave with respect to the common NO\textsubscript{x}-soot trade-off. From Figure 2 it can be seen that the present injection strategies largely escape from this trade-off, with both smoke and NO\textsubscript{x} emissions being near zero.

Therefore, the chosen injection strategy does not have a big impact. For smoke, also the combustion phasing has a minor effect, whereas for nitrogen oxides the emission levels increase with advancing combustion, but remain reasonably low.

Results: Maximum pressure rise rate

Largely premixed combustion can lead to unacceptably high pressure rise rates. From Figure 3, it shows that the maximum pressure rise rate is largely independent from the chosen injection strategy, but mainly depends on the resulting combustion phasing.

For all strategies the pressure rise rates are efficiently suppressed by the high dilution rates used. Therefore, it is desired to have an injection strategy that offers a wide range of control. With such an injection strategy, combustion phasing can be shifted such that the maximum pressure rise rate always stays below acceptable levels.

![Figure 3 – Maximum pressure rise rate vs. CA50 for injection timing variations in 4 different injection strategies.](image)

Conclusions

- A variation in the timing of the first or single diesel injection has an opposite effect on combustion phasing. The response is reasonably linear, but the sensitivity of the first injection is weak.
- The sensitivity of the late injections is positive and larger in absolute value compared to the early injections variation strategy. Furthermore, the sensitivity correlates with the amount injected in the second injection. As such the third strategy is most favorable.
- All three double injection strategies give very poor combustion efficiency. For these double injections, injection pressure had to be lowered to 500 bar, and together with the very short injection this results in a low combustion efficiency.
- Because of the high dilution level and largely premixed mixture, all present injection strategies break with the common soot-NO\textsubscript{x} trade-off, with both smoke and NO\textsubscript{x} emissions being near or below upcoming legislated levels.
- For all strategies, the pressure rise rates are efficiently suppressed by the high dilution rates used, and mainly depends on combustion phasing. Therefore it is desired to have an injection strategy that offers a wide range of control.

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Reference