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A Bayesian approach to the determination of ignition delay

Timothy Bodisco*, Samantha Low Choy, Richard J. Brown

2 George St, Science and Engineering Faculty, Queensland University of Technology, Brisbane 4000, Australia

HIGHLIGHTS

- Propose the use of Bayesian modelling for the determination of the start of combustion.
- Describe an appropriate statistical model for the determination of the start of combustion.
- Show how the statistical model is implemented.
- Use the model to investigate the inter-cycle variability of a common-rail multi-cylinder diesel engine.
- Confirm the importance of a modern technique that allows for inter-cycle variability studies of ignition delay.

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ABSTRACT

A novel in-cylinder pressure method for determining ignition delay has been proposed and demonstrated. This method proposes a new Bayesian statistical model to resolve the start of combustion, defined as being the point at which the band-pass in-cylinder pressure deviates from background noise and the combustion resonance begins. Further, it is demonstrated that this method is still accurate in situations where there is noise present. The start of combustion can be resolved for each cycle without the need for ad hoc methods such as cycle averaging. Therefore, this method allows for analysis of consecutive cycles and inter-cycle variability studies. Ignition delay obtained by this method and by the net rate of heat release has been shown to give good agreement. However, the use of combustion resonance to determine the start of combustion is preferable over the net rate of heat release method because it does not rely on knowledge of heat losses and will still function accurately in the presence of noise. Results for a six-cylinder turbo-charged common-rail diesel engine run with neat diesel fuel at full, three quarters and half load have been presented. Under these conditions the ignition delay was shown to increase as the load was decreased with a significant increase in ignition delay at half load, when compared with three quarter and full loads.

1. Introduction

Standard methods for determining the start of combustion have changed little in the last few decades. Most current studies [1–7] that examine the start of combustion, or ignition delay, use the net rate of heat release, with most citing the 1988 book *Internal Combustion Engine Fundamentals* written by John Heywood [8]. This method is commonly used because it is considered reliable and the net rate of heat release is simple to calculate. However, this paper will introduce the use of a statistical model in the Bayesian paradigm to accurately determine the start of combustion.

Calculation of the net rate of heat release comes from analysing the heat losses in an engine from a first law of thermodynamics perspective, in its most commonly used form [8]:

$$\frac{dQ_n}{dt} = \frac{\gamma}{\gamma-1} p \frac{dV}{dt} + \frac{1}{\gamma-1} V \frac{dp}{dt}, \tag{1}$$

where, dQ_n/dt is the net rate of heat release, γ is the ratio of specific heats, p is the in-cylinder pressure, V is the in-cylinder volume and t is time. More complicated versions of Equation (1) exist that take into account heat loss to the walls, effects of crevice regions and other possible sources for heat loss—which are mostly engine specific and not general. The start of combustion is defined as the point when the net rate of heat release begins increasing rapidly—some authors use the point that the net rate of heat release becomes positive [6].

* Corresponding author.
E-mail address: timothy.bodisco@qut.edu.au (T. Bodisco).

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From experimental in-cylinder pressure, another method for determining the start of combustion is from the rate of pressure rise [9]. This method locates the point at which the rate of pressure rise begins to increase rapidly, and can be done by analysing either the first or second derivative of the in-cylinder pressure signal. It has parallels with the net rate of heat release, which also requires the differentiation of the in-cylinder pressure data.

In a recent study by Rothamer and Murphy [10], six methods of determining the ignition delay were compared. The six methods used were:

1. location of 50% of pressure rise due to premixed burn combustion;
2. extrapoliation of the peak slope of pressure rise due to combustion to the zero crossing point;
3. location of the first peak of the second derivative of the pressure trace;
4. location of the first peak of the third derivative of the pressure trace;
5. location of 10% of the maximum heat release rate in the premixed burn; and,
6. a repeat of (5) using a low-pass (threshold 2000 Hz) filtered in-cylinder pressure trace.

Their study focused on jet fuels and diesel fuel in a heavy-duty direct-injection single-cylinder diesel and the data analysis was performed using 250 cycles of averaged data. A conclusion from their study found that the methods which required second or third derivatives were not optimal owing to the presence of noise and that the ignition delay determined by the heat release method using the low-pass filtered in-cylinder pressure signal gave a result 200–330 μs shorter than the other methods.

An early method for estimating ignition delay was proposed by Hardenberg and Hase [11]. They developed an empirical relationship between the parameters which they determined had the most impact on ignition delay: mean piston speed (m/s), M_{PS}; in-cylinder temperature at the time of injection (K), T; the compression ratio, r_c; the polytropic index of compression, n; the cetane number, CN; and, the absolute charge-air pressure at the time of injection (bar), P. In crank-angle degrees the empirical relationship as determined by Hardenberg and Hase is:

$$ID = (0.36 + 0.22M_{\mathrm{PS}})e^{\frac{618840}{CN+25}\left(\frac{1}{RT}-\frac{1}{17190}\right)+\left(\frac{21.2}{P-12.4}\right)^{0.063}}, \quad (2)$$

where, R is the universal gas constant (8.31434 J/mole). The polytropic index of compression, n, and the compression ratio, r_c, impact on the temperature and pressure of the charge-air. Estimates of T and P can be obtained from the inlet manifold conditions [8,11].

$$T = T_i r_c^{n-1}$$

$$P = P_i r_c^{n}$$

Later work done by Prakash et al. [12] extended this model to incorporate dual-fuel operation of diesel engines.

Since the work done by Hardenberg and Hase, other estimators of ignition delay based on engine parameters have been developed. Assanis et al. [13] have extensively reviewed these and proposed their own method for estimating ignition delay. However, for experimentally validating their ignition delay estimator, Assanis et al. compared their estimator to measured values by taking the peak of the second derivative to be the start of combustion.

Flame luminosity is another method used by researchers for determining the start of combustion. Heywood [8] argues that the use of flame luminosity detectors as a means to determine the start of combustion increases the potential for error. This is because the first appearance of the flame occurs after the increase in pressure. However, a recent study has argued that the first appearance of the flame coincides well with results from analysing the net rate of heat release [14]. Perhaps, with improving technology this method is becoming more reliable. Flame luminosity sensors are, however, prohibitively expensive for widespread practical use.

All of these approaches have practical difficulties or offer little, or no, information regarding cycle-by-cycle changes and hence do not allow for inter-cycle variability studies. In this paper a methodology for determining the start of combustion is proposed that requires no knowledge of difficult to estimate parameters such as heat loss to the walls and is still accurate with noisy data. Using only the in-cylinder pressure signal a statistical modelling approach is used to determine the start of combustion. A Bayesian approach to statistical modelling is used because it estimates the plausible range of parameter values (which includes the start of combustion), given the data observed [15]. In contrast a classical statistical analysis would provide the logical reverse: being estimates of the plausibility of the data, under specific (null or alternative) hypothesis of the parameter values. The latter would be better suited to confirmatory analyses where experimentalists wished to confirm whether parameter values took on specific values in a new situation. In this paper a new Bayesian modelling framework which provides posterior estimates of the start of combustion is given and is implemented across 4000 consecutive cycles at various engine loads to demonstrate its utility.

2. Experimental configuration

Experiments were conducted at the QUT Biofuel Engine Research Facility (BERF) in June 2011. Table 1 contains the technical specifications of the engine and data acquisition equipment. The engine was run at 2000 rpm on neat automotive diesel at full load (760 Nm) and at three quarters (570 Nm) and half (380 Nm) of full load.

Table 1
Engine and data acquisition specifications.

Engine Specifications	
Make	Cummins ISBe220 31
Capacity	5.9 l
Maximum power	162 kW at 2000 rpm
Maximum torque	820 Nm at 1500 rpm
Number of cylinders	6
Number of valves per cylinder	4
Compression ratio	17.3:1
Bore	102 mm
Stroke length	120 mm
Dynamometer	Electronically controlled water brake dynamometer
Injection system	Common-rail
Data acquisition	
Pressure transducer	Kistler piezoelectric transducer (6053CC60)
Analogue-to-digital converter	Data Translation (DT9832)
Software	National Instruments LabView
Sample rate	200 kHz
Sample time	4 min
Data collected	In-cylinder pressure Band-pass filtered in-cylinder pressure (allowing 4–20 kHz) Diesel injection timing Crank-angle rotation information