Experimental Investigation on Intake Air Temperature and Air-Fuel Ratio Dependence of Random and Deterministic Cyclic Variability in a Homogeneous Charge Compression Ignition Engin...

Article *in* SAE Technical Papers · April 2011

DOI: 10.4271/2011-01-1183

1 author:

Avinash Kumar Agarwal
Indian Institute of Technology Kanpur

SAE International™

Experimental Investigation on Intake Air Temperature and Air-Fuel Ratio Dependence of Random and Deterministic Cyclic Variability in a Homogeneous Charge Compression Ignition Engine

2011-01-1183
Published
04/12/2011

Avinash Kumar Agarwal
Indian Institute of Technology Kanpur

doi:10.4271/2011-01-1183

ABSTRACT

Due to the increasingly stricter emission legislations and growing demand for lower fuel consumption, there have been significant efforts to improve combustion efficiency, while satisfying the emission requirements. Homogenous Charge Compression Ignition (HCCI) combustion offers significant efficiency improvements compared to conventional gasoline engines. However, due to the nature of HCCI, fully homogeneous charge HCCI combustion can be realized only in a limited operating range. Control of HCCI engines to obtain the desirable operation requires understanding of how different charge variables influence the cyclic variations in HCCI combustion. Under certain operating conditions, HCCI engines exhibit large cyclic variations in ignition timing. Cyclic variability ranging from stochastic to deterministic patterns can be observed. One important design goal for engine development is to minimize cyclic variability. A small amount of cyclic variability can produce undesirable engine vibrations. At the same time, larger cyclic variability leads to increased hydrocarbon emissions. To control HCCI ignition timing, it is often necessary to know the characteristics of HCCI cyclic variations.

This study investigated the cyclic variations in HCCI combustion ignition timing using a range of experimental data with varying intake air temperature and air-fuel ratio at different engine speeds. Temporal dynamics of cyclic variations in HCCI combustion is analyzed using statistical and chaotic theory methods. The analysis of cyclic variation of combustion phasing for a gasoline fuelled HCCI combustion engine is performed. A symbol-sequence statistics method is used to find the occurrence of possible probabilities of the data points under the same operating conditions. The results show that as fuel air mixture becomes richer, the determinism in the ignition timing increases. The quantile return map of the cycle based time series of ignition timing values also confirm that deterministic portion of dynamics occurring in a HCCI engine increases as charge becomes richer or the intake air temperature increases.

INTRODUCTION

Emission legislations for automotive vehicles are being made more and more stringent by agencies like Environmental Protection Agency and EU. The primary challenge for the automotive industry is to meet the regulations related to nitric oxides and soot emissions. To meet these challenges, new combustion concepts are being developed by researchers in this area. Homogeneous charge compression ignition (HCCI) in internal combustion engines is of considerable interest to the automotive community because of its vast potential in reducing nitric oxides (NO_x) and particulate matter (PM) emissions simultaneously [1-2]. HCCI combustion concept has an advantage of high fuel flexibility and can be utilized in any size of transportation engine, ranging from a small motorcycle engine to a large ship engine [3]. The fundamental idea of HCCI combustion is using a very lean homogeneously premixed fuel/ air mixture in order to achieve low emissions of nitric oxides and high efficiency combustion. HCCI combustion engine operation can be described as a combination of a conventional spark ignition (SI) engine and direct injection compression ignition (DICI) engine. A homogeneous charge is prepared in the inlet manifold, where fuel and air are mixed to form a homogeneous mixture before the intake stroke of the engine, just like in a SI engine. After the intake stroke, valves are closed and the onset of combustion is governed by a compression of the pre-mixed homogenous charge, similar to a conventional DICI engines. The combustion happens because of auto-ignition of this mixture. Fast heat release with reduced heat transfer losses combined with the complete elimination of throttling losses and use of high compression ratios (similar to diesel engines) leads to a significantly higher thermal efficiency, which improves the fuel economy in a HCCI engine. HCCI engines have an advantage in terms of higher fuel economy compared to conventional diesel engines [4]. However, HCCI combustion engines generate higher amount of unburned hydrocarbons (HC) and carbon monoxide (CO) compared to conventional engines and have poor cold starting capability. Other than these factors, two major challenges, namely limited operating range and difficulty in controlling combustion timing, restricts the commercial exploitation of the HCCI combustion concept [5,6,7]. These two factors are directly influenced by cyclic variations. The main problem with the HCCI is that the ignition is completely controlled by chemical kinetics, and is directly affected by the fuel composition, equivalence ratio, and thermodynamic state of the fuel-air mixture [8-9]. There is no external control of initiation of combustion such as the fuel injection or spark timing that are used in traditional CI or SI engines. Achieving the required level of control during transient engine operation is even more challenging since charge temperature has to be correctly matched to the operating condition during rapid transients with a high repeatability, when the engine speed and loads are changing [10]. Developing new methods to control ignition timing properly for wide operating ranges and combustion-mode switching requires an improved understanding of HCCI cyclic variations. The in-cylinder process of HCCI cyclic variations needs to be studied in order to understand how to control these properties and make HCCI combustion more stable and free from cyclic variations.

Mechanism and control of cycle-to-cycle variation in SI engines are systematically investigated for decades [11-12], but only few researchers carried out experimental work [13,14,15,16,17,18,19,20,21] to investigate the cyclic variations in HCCI combustion engines. Xingcai *et al.* investigated the combustion stabilities and cycle-to-cycle variations of HCCI combustion using n-heptane, PRF20 (Primary reference fuels 20), PRF40, PRF50 and PRF60 [13]. Kalghatgi *et al.* investigated limits of HCCI combustion on a single-cylinder engine for 19 different gasoline-like fuels with octane numbers higher than 60 [14]. An octane index is developed to characterize high HCCI cyclic variation limits and a knock limit is defined. They have also observed that acceptable HCCI cyclic variations occur only within a narrow range of ignition timing around top dead center (TDC). Koopmans *et al.* investigated the cycle-to-cycle variations in a camless gasoline fuelled compression ignition engine [15]. Shahbakhti *et al.* performed investigations of cyclic variation of ignition timing using primary reference fuels [16]. Maurya *et al.* investigated the cycle-to-cycle variations of HCCI combustion in a gasoline and methanol fuelled engine [19-20]. Stability of late-cycle auto ignition is studied for a single cylinder diesel engine run in the HCCI mode [17] and it was observed that variations of indicated mean effective pressure (IMEP) increases rapidly after a certain combustion phasing or late limit. Persson *et al.* performed preliminary studies on cylinder-to-cylinder and cycle-to-cycle variations of a controlled auto ignition (CAI) combustion with trapped residual gas [18]. These cyclic variations and combustion instabilities lead to necessity of closed loop control for combustion phasing. Understanding cyclic variations of ignition timing and performance parameters is an essential step to be able to implement future effective combustion phasing control algorithms. This motivates the researchers to investigate the cycle-to-cycle variations in HCCI combustion engines.

Conventional methods for investigation of cycle-to-cycle variations employ the assumption that cyclic variations are stochastic in nature [22]. It means that each cycle is an independent and random event hence there is no relationship between successive cycles. Studies related to SI engine combustion indicate that cycle-to-cycle variations are both deterministic and stochastic in nature [23,24,25,26,27]. The observed combustion patterns are attributed to the combined effect of stochastic parametric variations and global nonlinear dynamics arising from the effects of residual gases from previous cycles. This combination of processes results in dynamic behavior typically associated with deterministic chaos [24-25]. The observation of determinism in cycle-to-cycle variations may have important diagnostic implications since cyclic variations in engines is not a purely random process. The presence of dynamical structure in combustion parameters makes it possible to use new data analysis tools from non-linear dynamics and chaos theory to reveal more information about engine behavior than what was previously possible with conventional statistical techniques [25]. Specifically, more important conclusions can be derived about the effect of various engine parameters on cycle-to-cycle variations due to the presence of deterministic behavior. The presence of determinism implies that intelligent control of the system could be a potential approach to extend the limits of engine operation significantly. If a controller can take advantage of the deterministic nature of the variations and the non-linearity of the system, small changes to control inputs such as fuel or intake air temperature can push the system back to stable operating point [27]. The non-linearity of the combustion system and lack of a precise compact model that satisfactorily describes the dynamic behavior makes neural-network based controllers a promising approach. These nonconventional methods are not used much in the analysis of cyclic variation of HCCI combustion and have the potential to deliver better understanding of HCCI combustion dynamics. These factors motivate the authors to investigate the effect of various engine operating conditions on random and deterministic cyclic variability in HCCI combustion engines.

In this paper, engine data is collected at different engine operating conditions and analyzed to determine dynamics of HCCI combustion parameters. The cyclic variations of combustion phasing are investigated to determine their behavior for stochastic and deterministic ranges. The stochastic and deterministic components of the cyclic variability are determined using a method called symbol sequence statistics method, which is explained in later sections of the paper.

EXPERIMENTAL SETUP

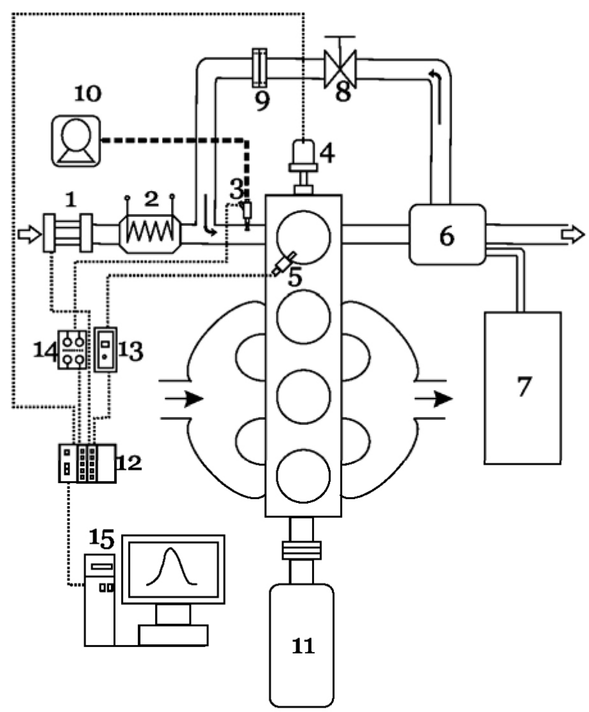
A four cylinder, four-stroke, water-cooled, naturally aspirated, direct injection diesel engine (Make: Mahindra and Mahindra Ltd., India; Model: Loadking NEF 3200 TCI) was modified for the present experiments. The specifications of the unmodified test engine are given in table 1. The engine is coupled with an eddy current dynamometer. One of the four cylinders of the engine is modified to operate in HCCI mode, while the other cylinder operate like an ordinary diesel engine at zero load, thus motoring the first cylinder for achieving and starting the HCCI combustion. The intake and exhaust manifold of HCCI combustion mode cylinder in separated from the other three CI mode cylinders. A detailed schematic diagram of the experimental setup is shown in Figure 1. Test fuel used for the present investigations is gasoline. The specifications of gasoline used for present investigation are provided in table 2. The fuel is premixed with air through gasoline port injector installed in the intake manifold of the HCCI cylinder. Electronic fuel injector having 4 holes injects the fuel in engine manifold at 3 bars fuel injection pressure developed by fuel pump installed in the gasoline tank. The quantity of fuel and injection timing is controlled through Compact-RIO through a custom made driver circuit. Compact-RIO (Reconfigurable Input-Output) combines an embedded real-time processor, a high-performance field-programmable gate array (FPGA), and hot-swappable input/ output (I/O) modules. Each I/O module is connected directly to the FPGA, providing low-level customization of timing and I/O signal processing. The FPGA is connected to the embedded real-time processor via a high-speed PCI bus. Compact-RIO is programmed by LabVIEW FPGA and LabVIEW Real-Time module softwares. LabVIEW contains built-in data transfer mechanisms to pass data from the FPGA to the embedded Real time processor for real-time data analysis, data logging, or communication to a networked host computer. The Compact-RIO takes signal from a high rotary shaft encoder, Air mass meter, and an in-cylinder piezo-electric pressure sensor. Compact RIO generates the output pulse to operate the fuel injector based on the analysis of acquired signals and engine operating conditions. Based on the output pulse generated by Compact RIO, fuel injector injects the required amount of fuel in the intake manifold.

Table 1. Test engine specification.

Make	M&M Ltd., India
Model	Load King NEF 3200 TCI
Displaced volume	2609 cc
Stroke/ Bore	94 mm/ 94 mm
Connecting Rod Length	158 mm
Max Engine Output	53.5 kw (72.7 HP) @ 3200 rpm
Max Torque	195 Nm @ 1900 – 2000
Number of Valves/ Cylinder	2

Table 2. Gasoline specification [28]

Characteristics	Values
Density @15^{0}C kg/m^3	730
Research Octane Number	91
Benzene content, percent by volume, max	1
Olefin content, percent by volume, max	21
Aromatic content, percent by volume, max	42
Minimum Oxidation Stability, min	360



1. Hot-film Air Mass Meter 2. Air Heater 3. Fuel Injector 4. Rotary Shaft Encoder 5. Pressure Transducer 6. Exhaust Plenum 7. Emission Analyzer 8. EGR Valve 9. Orifice 10. Fuel Tank with Pump 11. Dynamometer 12. Compact RIO 13. Charge Amplifier 14. Driver Circuit 15. Computer

Figure 1. Schematic diagram of experimental setup.

Air delivered to HCCI combustion cylinder is measured through hot-film air mass meter, which precisely registers the actual air-mass. To achieve HCCI combustion with proper phasing, the air-fuel mixture must be preheated to a high temperature prior to entering the cylinder. Fresh air entering the engine is heated by an air pre-heater positioned upstream of the intake manifold. The intake air heater is operated by a closed loop controller, which maintains constant intake air temperature as set by user by feedback control. The heater controller takes feedback from a thermocouple installed in the intake manifold just upstream of fuel injector. A thermocouple in conjunction with a digital temperature indicator was used in measuring the intake and exhaust gas temperature. Provision for exhaust gas recirculation (EGR) is made for the HCCI combustion cylinder so that some of the exhaust gas can also be circulated in intake manifold through EGR valve for controlling the combustion timing. The in-cylinder pressure was measured using a piezo-electric pressure transducer mounted flush with the cylinder head. To measure the crank angle position, a high precision optical shaft encoder is coupled with the crankshaft using a helical coupling. The cylinder pressure history data acquisition and combustion analysis is done using a LabVIEW based program, which is developed at the Engine Research Laboratory, IIT Kanpur. In-cylinder pressure of the HCCI cylinder was recorded for 3000 consecutive engine cycles for each engine operating conditions with $1/6^{th}$ CAD resolutions and analyzed to calculate the detailed combustion phasing parameters.

Rate of heat release (ROHR): ROHR is calculated from the acquired pressure history data using the zero dimensional heat release model [29]. Consequently, the main combustion parameters were extracted from the heat release and in-cylinder pressure curves. ROHR was calculated as

$$\frac{\partial Q}{\partial \theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{\partial P}{\partial \theta} + \frac{\partial Q_{HT}}{\partial \theta}$$

The following assumptions were made in this calculation:

- Cylinder charge was considered to behave as an ideal gas.
- Distributions of thermodynamic properties inside the combustion chamber were considered to be uniform.
- Dissociation of combustion products was neglected.
- No variation of cylinder mass due to blow-by was considered.

Relative air fuel ratio (λ) is the ratio of the actual air/ fuel ratio to the stoichiometric air/ fuel ratio. The results in this investigation are presented with respect to different relative air/ fuel ratios (λ), which are in the HCCI combustion region. Experiments were conducted on the modified engine at different engine speeds with varying intake air temperatures.

DATA ANALYSIS TECHNIQUES

Non-linear dynamics and chaos theory have been used to develop several mathematical analysis techniques for deriving important inferences from time-series data. A very useful method for time series data analysis is known as 'symbol sequence statistics method'. This method gives important insight into the behavior observed for different combustion parameters in an engine operation. Finney *et al.* [29] documented this technique for SI engine combustion in detail and a brief description is also provided in this paper.

SYMBOLIZATION AND SYMBOL SEQUENCE HISTOGRAM

Symbolization of engine combustion measurements provides simple and effective method to minimize the effect of dynamic noise and measurement errors so that deterministic effects of previous cycle or inherent structure in data points can be detected accurately for appropriately chosen partition size, as dynamic noise appears if number of partitions is higher. If this technique is applied at the time of data acquisition, symbolization also becomes a means of data compression and can greatly speed up data processing. These characteristics make data symbolization a useful tool for onboard engine diagnostics and real time control [30]. Data symbolization involves the conversion of time series data of many possible values into a symbol series of only a few distinct values. This method distribute the values of time series data into few partitions and each partition assigned a particular symbolic value (e.g. 0 or 1 for n_{part}= 2). Here n_{part} is the number of partitions made in data series. In symbol sequence statistics method, partition is done in such a way that each partition is equi-probable so that there is equal number of data points in each partition. The simplest example of partition of cycle based time series data in engine combustion measurement is binary partitions, where experimental data values above median value are represented by 1 and values below the median are represented by 0. Figure 2 illustrates a sequence of 1000 data points for CA_{50} values showing binary partitions. It is also possible to use more than two partitions, which would result a different number system (e.g. 0, 1, 2, 3, 4, 5, 6 and 7 for n_{part}= 8). In this study, binary and octal partitions are used for the analysis of combustion timing dynamics, these partitions are chosen based on the partitions used in the published engine combustion related literature [27, 30-31]. Relative frequency of all possible symbol sequences number in the CA_{50} data is calculated from the symbol sequence vector of cycle length 'L'. The sequence of sysmbols reveal some important information about the experimental measurement dynamics [32]. The total possible number of sequences 'N' is a combination of number of partition and symbol sequence length 'L' and related by equation $N = (n_{part})^L$ [32]. Figure 3 illustrates the fequency varition with different sequence number using sequence length of six. Total possible sequence number using binary partition for sequence length six is 2^6 or 64.

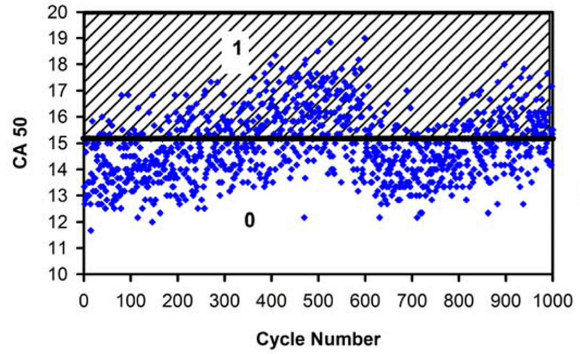


Figure 2. CA_{50} Sequence for λ=2.5, Ti = 120°C at 1800 rpm, illustrating two symbolic partitions.

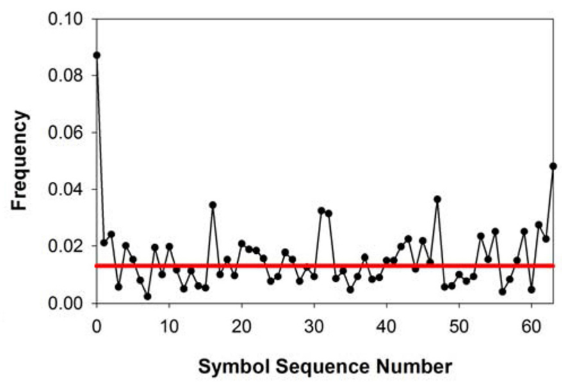


Figure 3. Symbol sequence histogram for two partition with sequence length of six for CA_{50} at λ=2.5, Ti = 120°C.

In symbol sequence statistics method, due to equi-probable partitioning rule the relative frequencies for truly random data sequences will be equal and all histogram bins will be equally probable within the uncertainty due to a finite data set. Thus any significant deviation from equi-probability is indicative of time correlation and deterministic structure in the experimental data series [30]. On a histogram plot of data, those sequences that appear as peaks rising above the background 'noise' level would correspond to repeating deterministic events. The frequency F_b, that would be observed for all sequences for purely random data is the probability given by $F_b = (1/n_{part})^L$ [27]. This baseline frequency is shown by the thick line in figure 3. In this particular case, several peaks rise above this baseline, but some are noteworthy. This analysis method is explained in more detail as a general approach for analysis of noisy deterministic data [33-34]. In this method, choosing the optimum sequence length is important to find significant determinism in the experimental data. To find the optimum sequence length, modified Shannon entropy is used which is explained in next section.

OPTIMIZATION OF SYMBOLIZATION PARAMETERS

A modified form of Shannon entropy can be used to quantify the deviation of symbol sequences from randomness [27, 30]. The modified Shannon entropy H_s is defined by

$$H_s = \frac{1}{log\ n_{seq}} \sum_k p_k \log p_k$$

where p_k is the probability with which sequence 'k' occurs and n_{seq} is total number of sequence with non-zero probability.

Shannon entropy of one indicates random data, while values less than one indicate correlation between sequential data points. The Shannon entropy can be used to determine the optimal sequence length to be considered in a symbol sequence histogram, since the sequence length giving the lowest Shannon entropy indicates the greatest presence of determinism in the data. Figure 4 shows the variation in Shannon entropy with sequence length for engine running at 1800 rpm and 120°C intake air temperature, using binary and octal partitions.

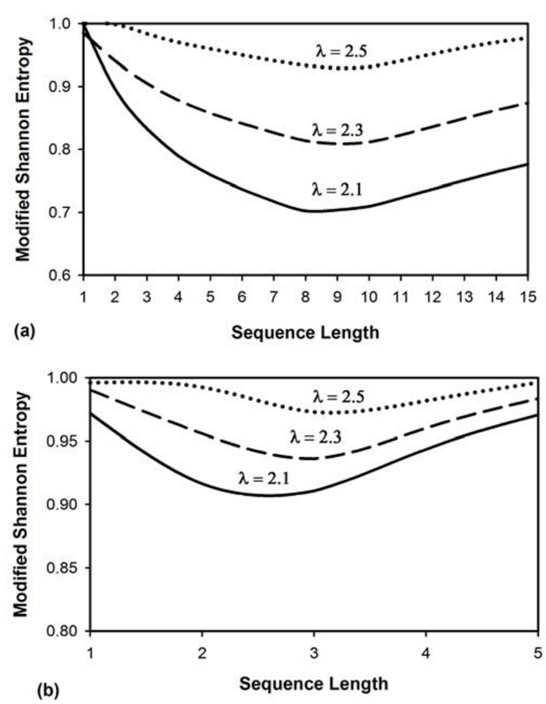


Figure 4. Modified shannon entropy variation for different λ at 1800 rpm using (a) binary and (b) octal partitions.

It can be noticed from figure 4 that H_s value vary depending on the symbol sequence length L. Finney *et al.* explained that minimum value of modified Shannon entropy (H_s) reflects the symbol sequence length, which best distinguishes the data from a random sequence [30]. This can be used as an optimum choice of sequence length for given data and for selected number of partitions. It can be observed from the figure 4a that minimum value of Shannon entropy is around the sequence length of 8 cycles for binary partition. This indicates that the influence of previous cycles on the CA_{50} extends back up to 8 previous cycles. For the octal partitioning (using 8 partitions), the minimum value is found for sequence length of 3 cycles. Therefore for HCCI engine combustion control, it should be advantageous for a controller to have information about more than just the immediate previous cycle.

RESULTS AND DISCUSSIONS

In this section, the experimental results of cyclic variation of combustion phasing in HCCI combustion engine running at different operating conditions are presented. The in-cylinder pressure history of 3000 consecutive cycles is measured and analyzed to calculate the combustion timings CA_{10} (crank angle for 10% heat release) and CA_{50} (crank angle for 50% heat release). Rate of heat release is calculated using the method described in experimental setup section. Cyclic variation in HCCI combustion can occur with a variety of patterns depending on the physics occurring inside the cylinder and pattern of charge variation [16]. One method to understand these patterns is to analyze the ignition timing ensemble formed by large number of consecutive ignition timings. Figures 5 and 6 show the ensemble of CA_{10} and CA_{50} timings at different λ for engine running at 1500 rpm and intake air temperature of 120°C. The thick red line indicates the normal probability density for combustion timings in each graph. It can be observed from the figure that CA_{10} and CA_{50} timings have similar distribution at each value of λ. It can also be noticed from the figures 5 and 6 that as mixtures become leaner, the combustion timing ensemble comes close to normal distribution.

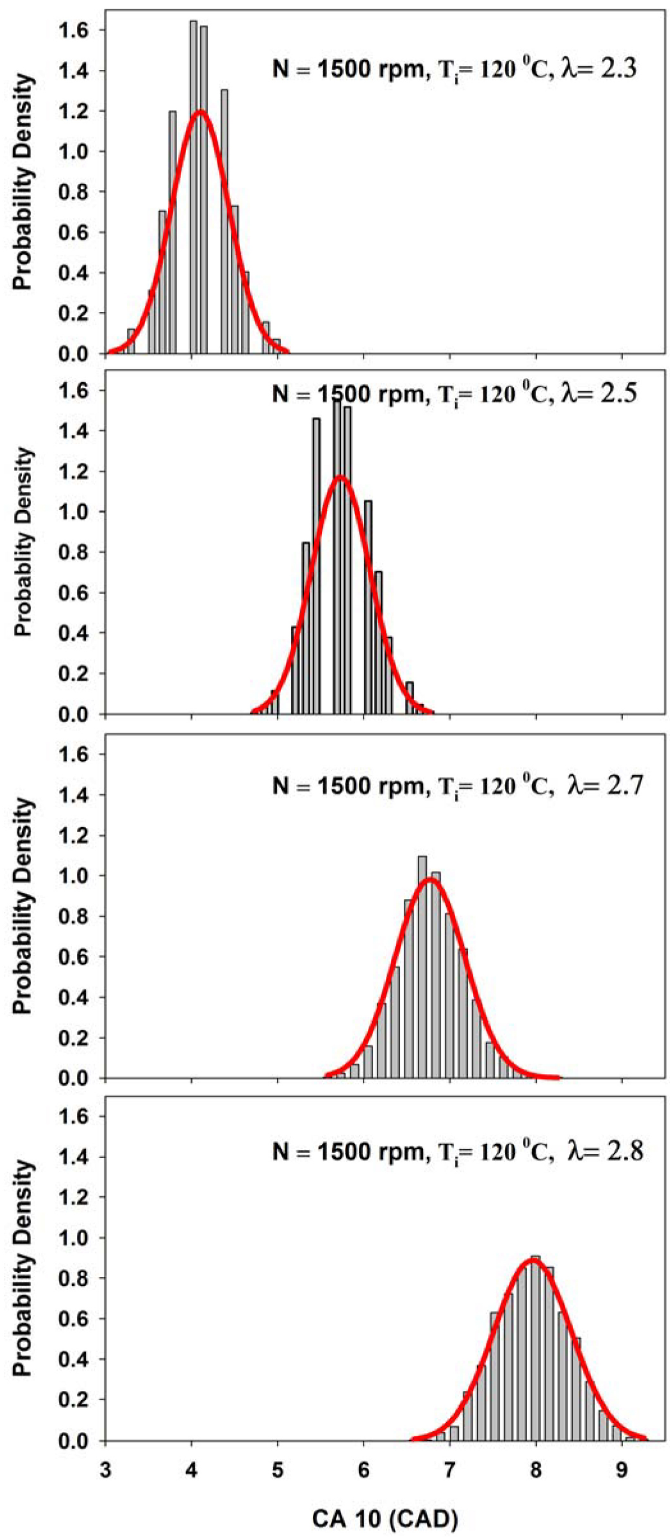


Figure 5. Probability density distribution of CA_{10} timing.

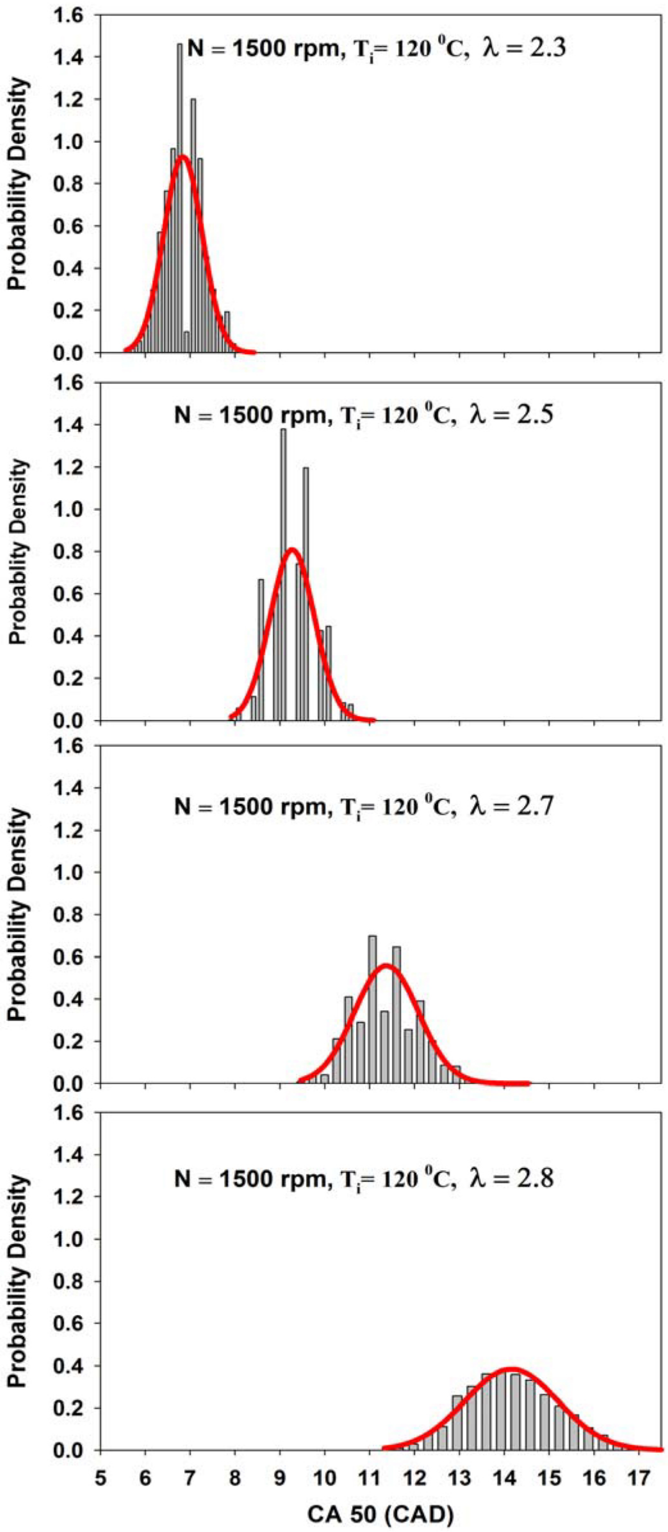


Figure 6. Probability density distribution of CA_{50} timing.

CA_{10} timing is often regarded as marker for start of combustion in engines [35]. In HCCI combustion engine, start of combustion depends on chemical kinetics purely and it depends on the pressure-temperature history in the combustion chamber. A robust combustion phasing parameter is required for feedback alternative HCCI combustion control, which creates the need of improved understanding of combustion timing variation. It can be noticed from above figures (5,6) that, for richer mixture (lower λ), CA_{10} have large deviation from normal distribution line as compared to CA_{50} timings. It can also be observered from the experimental data points (figures 5 and 6) that CA_{10} and CA_{50} have large deviation from the normal distribution line as mixtures become richer (toward stoichiometric mixture). Assuming a normal distribution for the random component of data, deviation from normal distribution are indicative of deterministic component in the data [36-37]. This indicated higher deterministic pattern in the CA_{10} and CA_{50} timings as mixtures becomes richer. Knowledge of CA_{50} distribution can provide valuable information to find high cyclic variation regime for HCCI combustion engines. Several reserchers have used CA_{50} timing for HCCI combustion control [37-38]. The information about distribution of combustion timing can be utilized for designing HCCI combustion controllers. To find more details of deterministic structure in data points, symbol sequence statistics method is used.

Figures 7,8,9 show the symbol sequence histograms of CA_{50} for different λ at intake air temperature of 120°C using octal partition and sequence length of 3 for three different engine speeds of 1200, 1500 and 1800 rpm. Symbol sequence histograms for binary partition for the all the operating is also provided in the appendix. The thick red line indicates the frequency for random gaussian data points. Frequency above this line indicates the determinism in the data points. The symbol sequence numbers having higher frequency indicates that these patterns are repeated more number of times in experimental data points. It is observed from the figures that the frequency of sequence number increases more above the red line as mixture become richer (lower λ) for each engine speed. This indicates the inherent determinitic structures as mixtures becomes richer. It can also be noticed from figures that at higher engine speeds, the frequency of sequence numbers increses with increase in engine speed. Which show that deterministic pattern increases with increase in engine speed. The sequence code occurs more frequently with higher frequency are 0, 8, 16, 64, 128, 276 and 511. These numbers when converted from decimal to octal number corresponds to sequence 0-0-0, 0-1-0,0-2-0, 1-0-0, 2-0-0, 4-2-4 and 7-7-7. The two sequences 0-0-0 and 7-7-7 represent steady behaviour of combustion timing. Other patterns indicate that advanced-to-retard and retard-to-advanced timing combustion events are dominant. Similar trend is demonstrated by the binary partition with sequence length 8 as shown in appendix (figure 16,17,18).

Table 3 shows the changes in modified Shannon entopy with different engine operating conditions for both binary partition with sequenc length (2-8) and octal partition with sequence length (8-3). Shannon entropy decreases with decrease in λ values or with increase in engine speed, which indicates the deterministic behaviour. The decrease in shannon entropy implies that a controller should have greater effect at these operating conditions with lower entropy values as compared to higher entropy values, where more randon nature is expected.

Table 3. Shannon entropy variation with different engine operating conditions.

Speed (rpm)	T_i (^{0}C)	λ	2-8	8-3
1200	120	2.3	0.932	0.974
		2.5	0.958	0.977
		2.7	0.956	0.978
		2.8	0.958	0.975
1500	120	2.3	0.804	0.934
		2.5	0.923	0.945
		2.7	0.938	0.962
		2.8	0.913	0.963
	130	2.7	0.888	0.92
	140		0.768	0.903
	150		0.777	0.868
1800	120	2.1	0.702	0.917
		2.3	0.813	0.936
		2.5	0.933	0.973

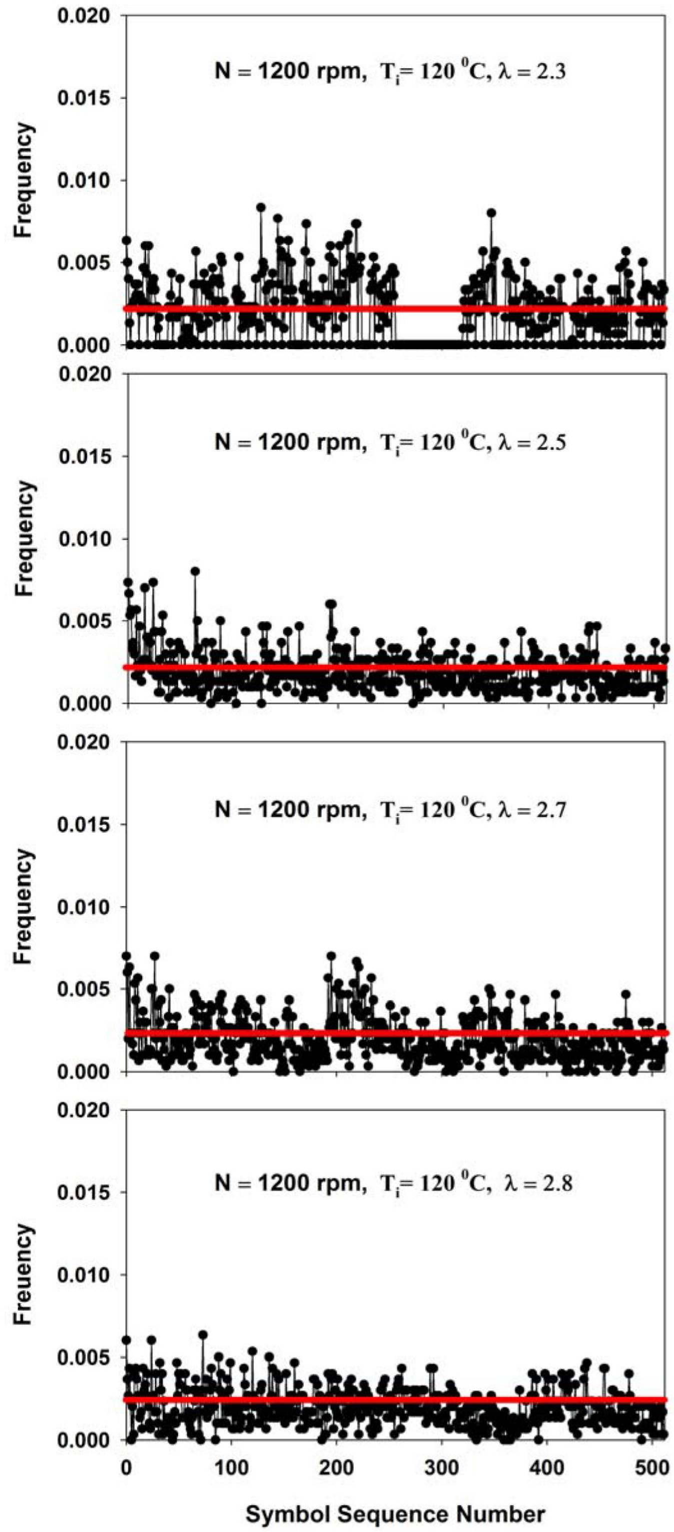


Figure 7. Symbol sequence histograms of CA_{50} for different λ at 1200 rpm using octal partition and sequence length 3.

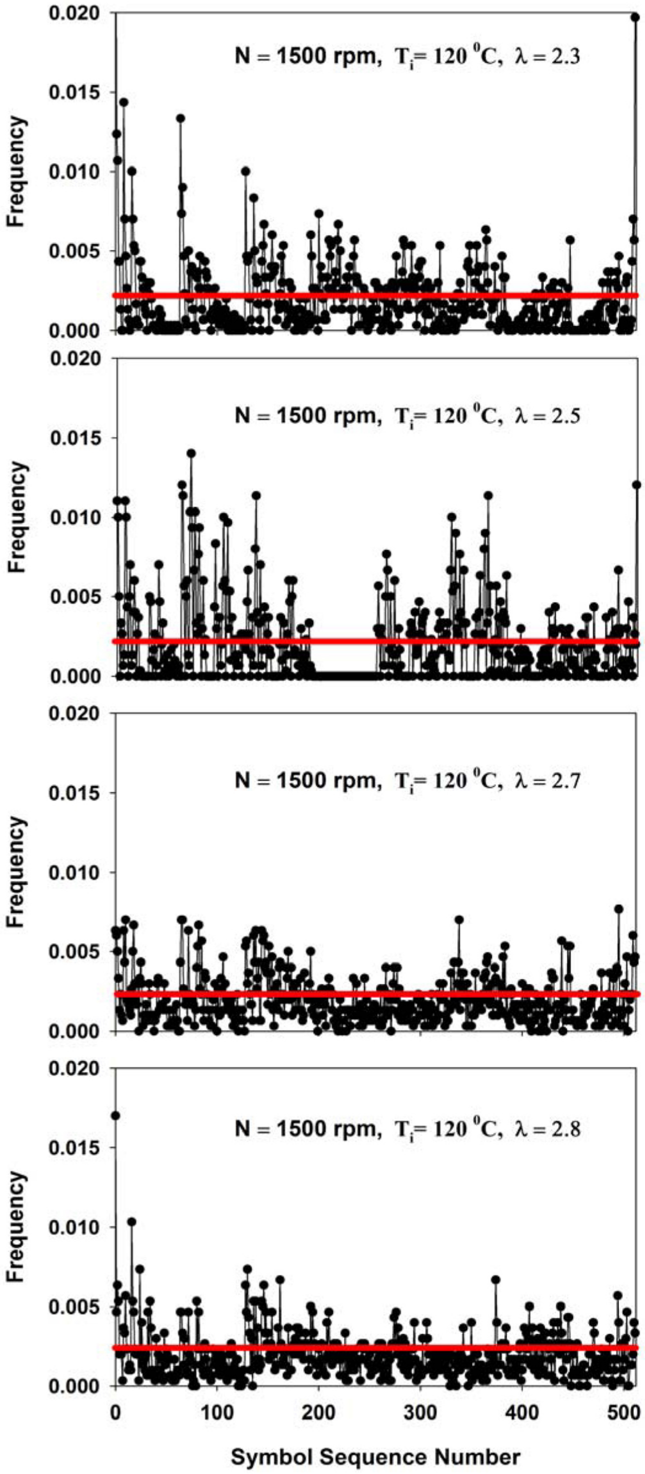


Figure 8. Symbol sequence histograms of CA_{50} for different λ at 1500 rpm using octal partition and sequence length 3.

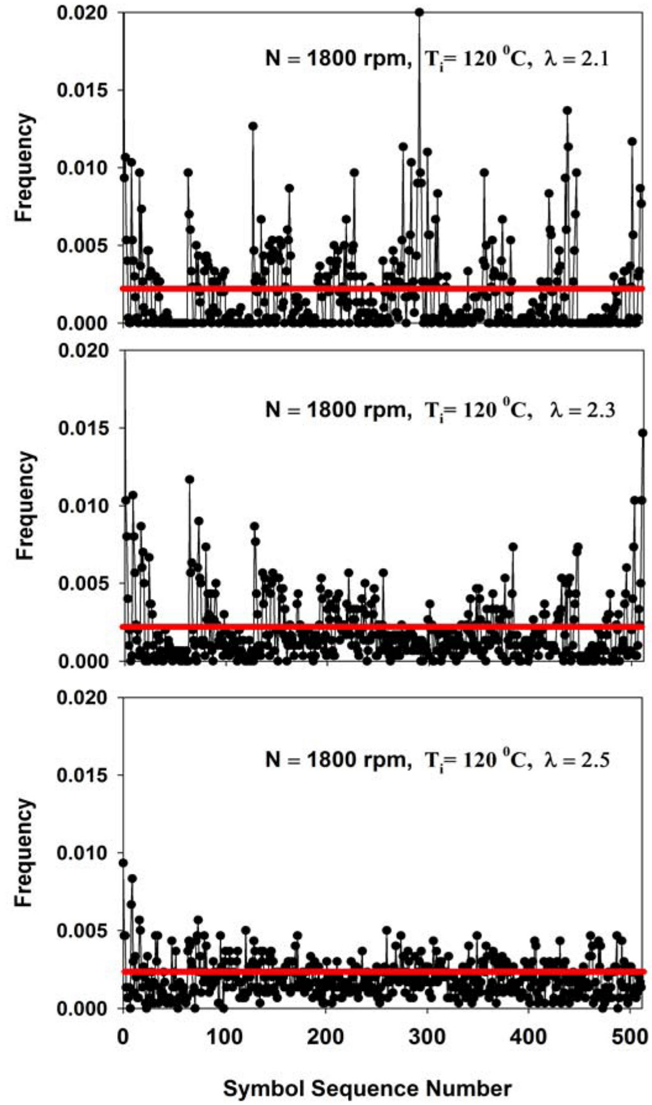


Figure 9. Symbol sequence histograms of CA_{50} for different λ at 1800 rpm using octal partition and sequence length 3.

Figures 10-11 show the symbol sequence histograms of CA_{50} and CA_{10} for intake air temperature of 120-150°C at contant λ using octal partition and sequence length of 3 for engine speed of 1500 rpm. The thick red line indicates the frequency for random gaussian data points. Frequency above this line indicates the determinitic behavior in the combustion timing data points. In both cases, several peaks rise above this line. It can be noticed from these figures that the frequency of sequence number increases more above the red line as intake air temperature increses for both CA_{50} and CA_{10}. This indicates that deterministic behavior increases with increase in temperature at constant λ. This shift in behavior is also confirmed by decrease in modified Shannon entropy (Table 3) with increase in intake air temperature. Both measures of combustion timing CA_{50} and CA_{10} have similar pattern with increase in intake air temperature like on increasing temperature on intake manifold sequence numbers having higher frequency increases.

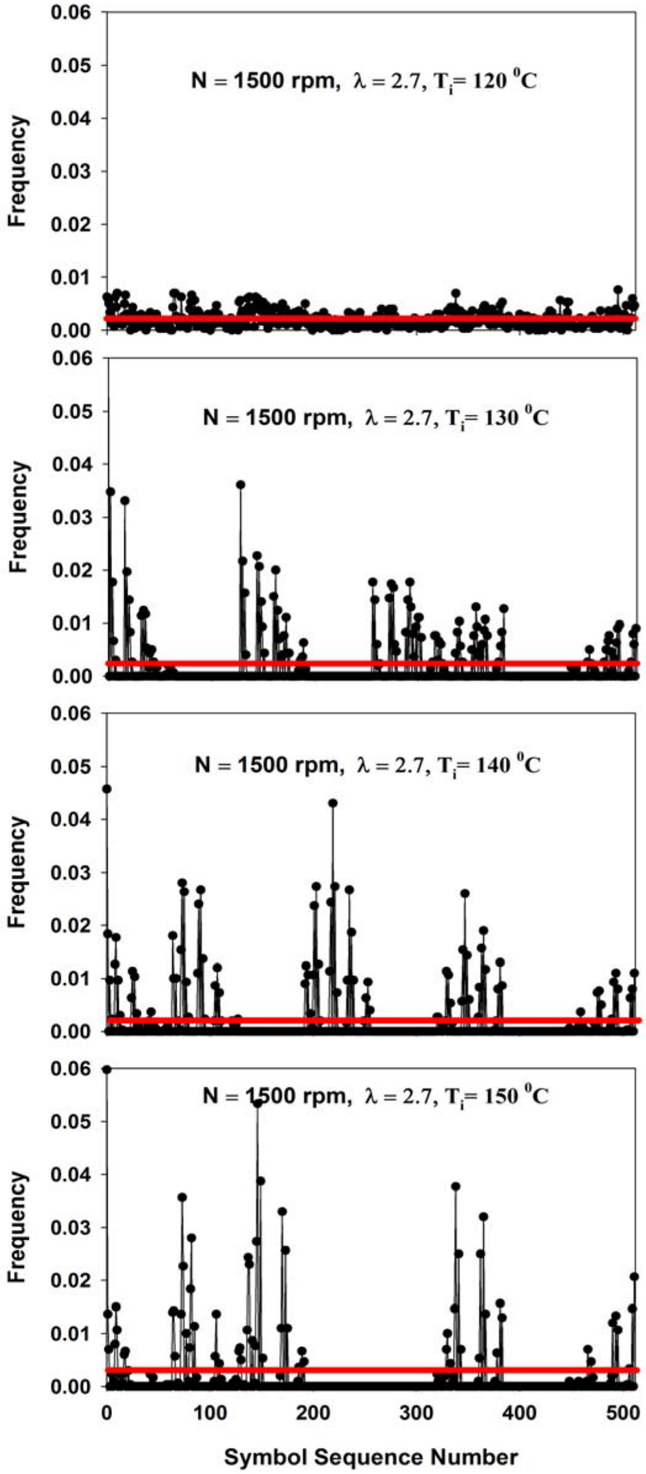


Figure 10. Symbol sequence histograms of CA_{50} for different T_i at 1500 rpm using octal partition and sequence length 3.

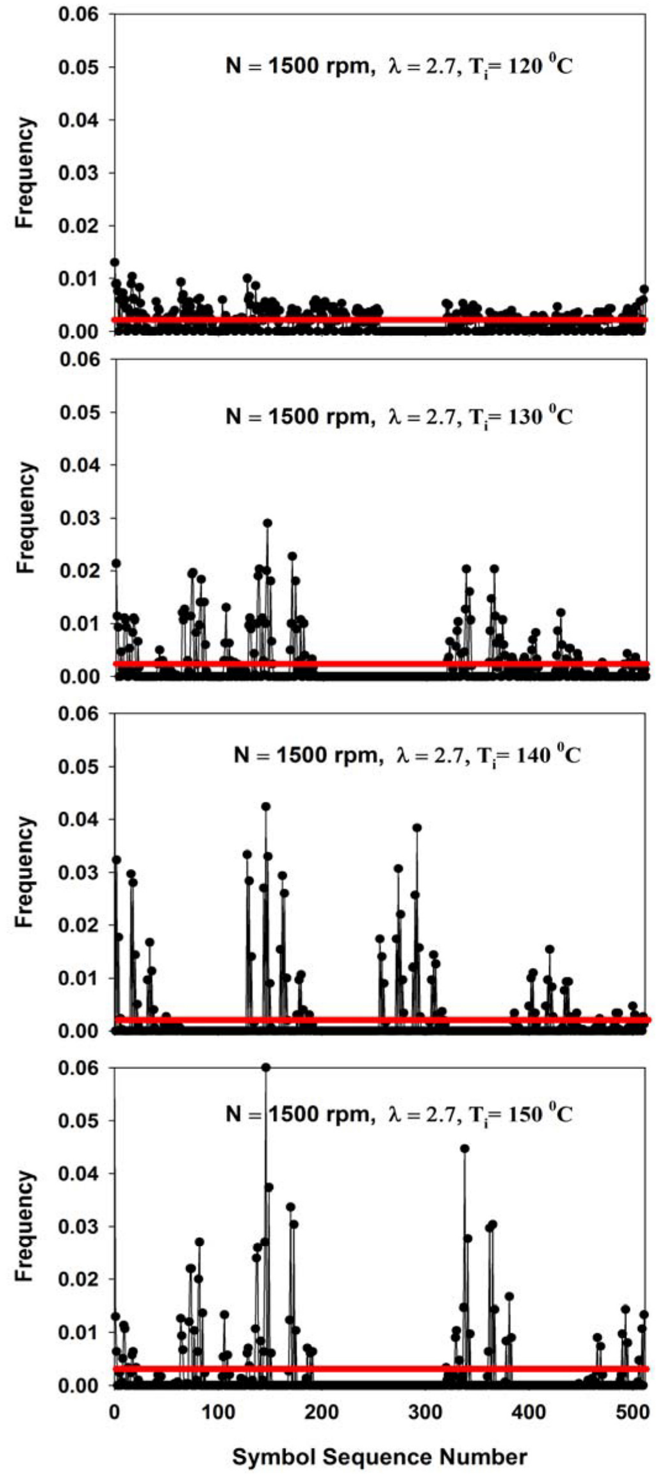


Figure 11. Symbol sequence histograms of CA_{10} for different T_i at 1500 rpm using octal partition and sequence length 3.

An alternate method for examining inherent interactions between cycles of combustion events is to plot return maps [24]. Return maps describe the correlation between each individual pair of events in the data set without averaging. This can be advantageous in some cases, because return maps may reveal strong but rarely occurring correlations which are overwhelmed in spectral densities by the signals from weaker but more frequently occurring correlations. Return maps have additional advantage that they reveal any time asymmetry which may exist in the correlation [26, 39]. Return map is a good tool to check the probable interaction between parameters of each cycle with its next consecutive cycle. For random time series, consecutive cycles are uncorrelated and the return map shows an unstructured cloud of data points gathered around a fixed point. With deterministic coupling between points, the return map shows more structure such as dispersed data points about a diagonal line [40]. Figures 12,13,14 show return maps based on 3000 consecutive engine cycles for different λ at 1500 rpm with the lag of one cycle. To plot the return map of time series data, first, the time series is converted to (x, y) pairs of data like each CA_{50} value (except the last one) paired with the CA_{50} value for the following event (3000 events yield 2999 pairs). These pairs of experimental data points are plotted as (x, y) pairs on a scatter plot (Figures 12, 14).

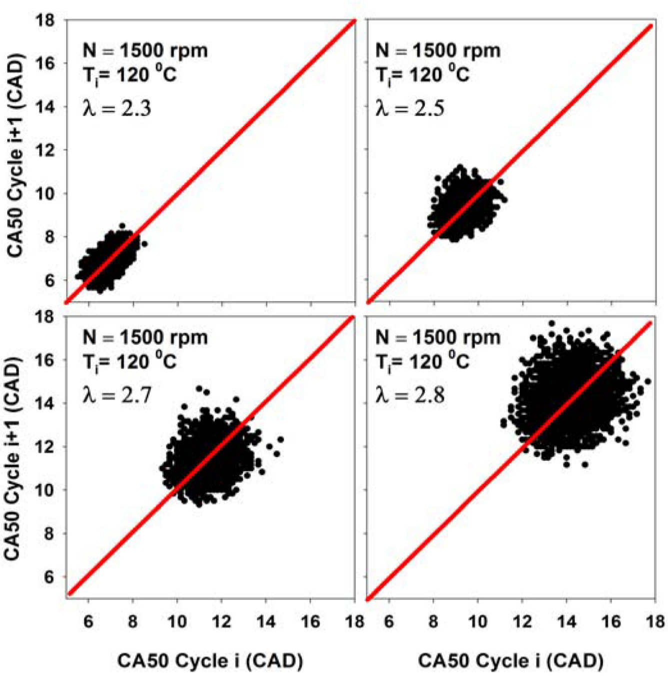


Figure 12. Return maps for CA_{50} for different λ at 1500 rpm with lag of one cycle

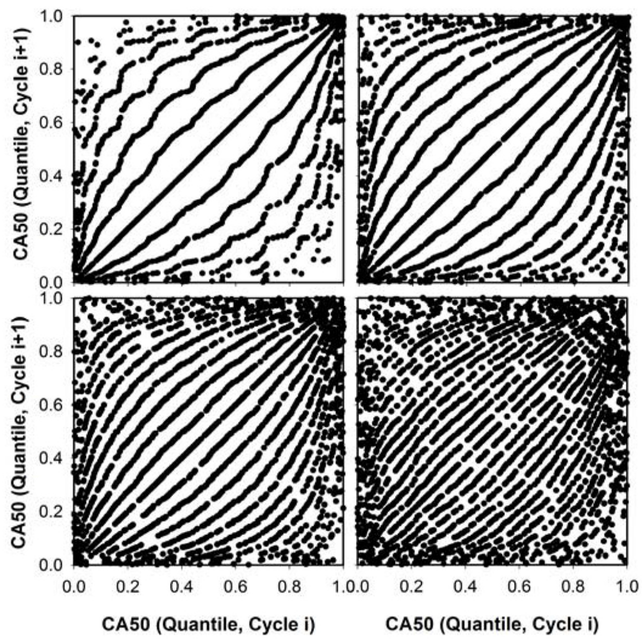


Figure 13. Return maps for CA_{50} for different λ at 1500 rpm with lag of one cycle, CA_{50} values converted to quantiles

The return maps in figure 12 show a circular cloud for leaner mixtures, and as charge become richer, the combustion timings distribution becomes flat along the diagonal line. It is difficult to say about the correlation by these graphs. Wagner *et al.* found that circular return map indicates primarily stochastic behavior [25]. Interpretation of return maps is often complicated by the fact that skewed distributions may produce dispersed data points, even in the absence of correlations. The other problem is the difficulty of finding an objective test to determine whether a statistically significant degree of correlation is present [39].

A widely applicable solution to these problems is to construct return maps of quantile values of combustion timing instead of CA_{50} timing values. For a data set containing N values of CA_{50} measurements, the quantile values for data set are generated by replacing the smallest CA_{50} value with the number 1/N, the next smallest with the number 2/N, etc. The process is continued to whole data set up to the largest CA_{50} timing value, which is replaced with the number N/N, or 1. In this quantile conversion process, whole data set is converted in values between 0 and 1. Also in this process, neither the rank order nor the sequence of the data is changed in the quantile conversion. The advantage of converting the points from CA_{50} to quantile space is that a highly skewed distribution is converted to a uniform distribution, where the values are evenly distributed between 0 and 1 [39]. An uncorrelated time series will fill the return map with an even density of points, while correlations will appear as areas of higher and lower densities of points [39].

Return maps of quantile combustion timing are shown in figures 13 and 15 at 1500 rpm. It is observed from the figure 13 that for leaner mixtures, the data points are distributed in the whole plot space, as mixture strength increases the points are distributed with uneven density distribution of areas of higher and lower densities points. This indicates the increase in deterministic behavior as mixture becomes richer.

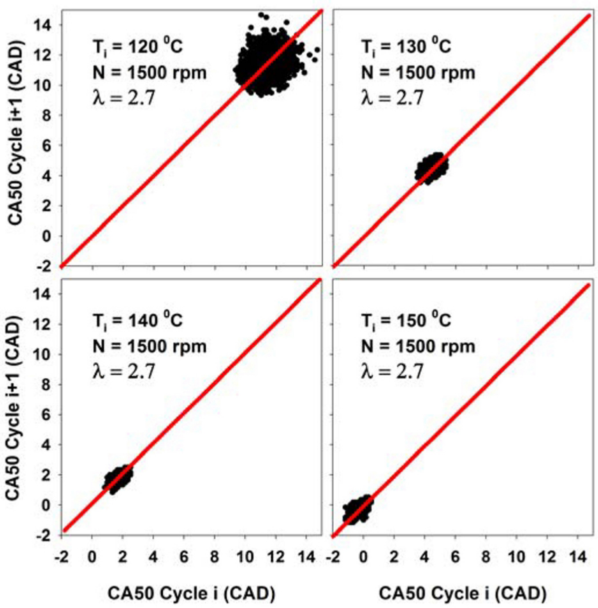


Figure 14. Return maps for CA50 for different T_i at 1500 rpm with lag of one cycle.

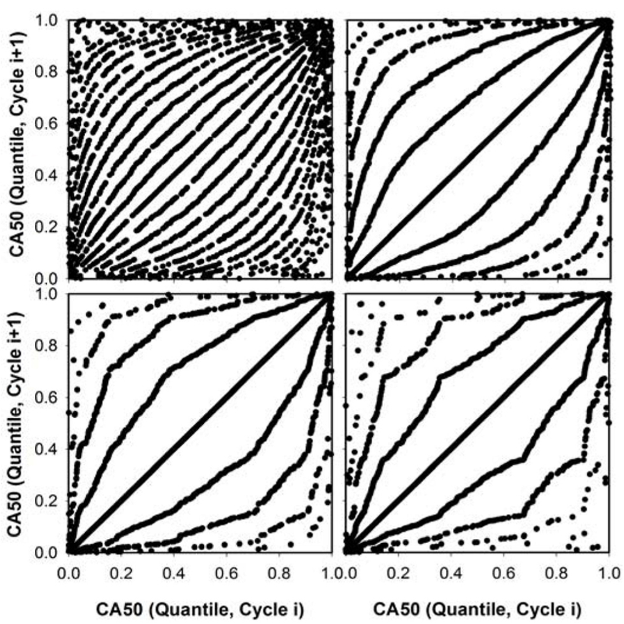


Figure 15. Return maps for CA50 for different T_i at 1500 rpm with lag of one cycle, CA50 values converted to quantiles.

It can also be noticed from the figure 15 that for lower intake air temperatures, the data points are distributed in the whole plot space, and as the intake air temperature increases, the points are distributed with uneven density distribution of areas of higher and lower densities points. This indicates an increase in deterministic behavior as mixture becomes intake air temperature increases. The general inherent relationship of combustion phasing between the current cycle and the next cycle has been shown in Figure 15. This return map clearly shows a deterministic dependency on previous cycles as intake air temperature increases.

SUMMARY/ CONCLUSIONS

The cycle-to-cycle variations in combustion phasing of HCCI combustion were investigated on a modified transportation diesel engine. The inlet air was supplied at 120, 130, 140 and 150°C temperature and the engine was operated at different engine speed of 1200, 1500 and 1800 rpm, with port fuel injection of gasoline in HCCI combustion mode. Analysis for determinism in consecutive cyclic variation is analyzed through statistic and chaotic method. It is found that distribution of combustion timing deviates largely from normal distribution as mixture becomes richer (lower λ). Using symbol sequence statistics method, it is observed that cyclic variations of combustion timing experiences clear shift from stochastic to deterministic behavior as λ decreases for all test speeds. The similar shift in the behavior is observed at constant λ with increasing intake air temperature. Return maps of combustion timings also confirms the shift from stochastic to deterministic behavior, when CA_{50} values are converted to quantiles. It was found that minimum value of modified Shannon entropy is around the sequence length of 8 cycles for binary partition. This indicates that the influence of previous cycles on the CA_{50} extends back up to 8 previous engine cycles. For the octal partitioning (using 8 partitions), the minimum value is found for sequence length of 3 cycles. Hence for HCCI engine operation, it should be beneficial for a controller to have information about more than just the immediate previous cycle. In summary, return maps, modified Shannon entropy and symbol sequence statistics are very useful tools for understanding nonlinear cyclic combustion dynamics.

REFERENCES

1. Zhao, H., "Homogeneous charge compression ignition(HCCI) and controlled auto ignition (CAI) engines for the automotive industry", Woodhead Publishing Ltd, UK, ISBN 978-1420044591, 2007.

2. Zhao, F., Asmus, T. W., Assanis, D. N., Dec, J. E., Eng, J. A., and Najt, P. M., "Homogeneous Charge Compression Ignition (HCCI) Engines," PT-94, SAE International, Warrendale, PA, ISBN 978-0-7680-1123-4, 2003.

3. Homogeneous charge compression ignition technology - A report to the U.S. Congress. Technical report, Office of

Transportation Technologies, US Department of Energy, April 2001.

4. Fritz, D., "GM moves closer to market with HCCI", Automotive Engineering (SAE International), 22, February 2007.

5. Christensen, M., Johansson, B., Einewall, P., "Homogeneous Charge Compression Ignition (HCCI) Using Isooctane, Ethanol and Natural Gas - a Comparison with Spark Ignition Operation," SAE Technical Paper 972874, 1997, doi: 10.4271/972874.

6. Maurya, R.K., Agarwal, A.K., "Experimental investigation of the effect of the intake air temperature and mixture quality on the combustion of a methanol- and gasoline-fuelled homogeneous charge compression ignition engine", *Journal of Automobile engineering Proc. IMechE Part D* **223**(11):2041-2991, 2009.

7. Stanglmaier, R. H. and Roberts, C. E., "Homogeneous Charge Compression Ignition (HCCI): Benefits, Compromises, and Future Engine Applications," SAE Technical Paper 1999-01-3682, 1999, doi: 10.4271/1999-01-3682.

8. Kelly-Zion, P. L. and Dec, J. E., "A computational Study of the effect of the Fuel-Type on the Ignition Time in HCCI Engines", *Proceedings of Combustion Institute* **28**:1187-1194, 2000.

9. Sjöberg, M. and Dec, J. E., "Combined Effects of Fuel-Type and Engine Speed on Intake Temperature Requirements and Completeness of Bulk-Gas Reactions for HCCI Combustion", SAE Technical Paper 2003-01-3173, 2003, doi:10.4271/2003-01-3173.

10. Shaver, G. M., Roelle, M. J., and Gerdes, J. C., "Modeling cycle to cycle dynamics and mode transition in HCCI engines with variable valve actuation", *Journal of Control Engineering Practice* **14**: 213-222, 2006.

11. Matsuoka, S., Yamaguchi, T. and Umemura, Y., "Factors Influencing the Cyclic Variation of Combustion of Spark Ignition Engine," SAE Technical Paper 710586, 1971, doi: 10.4271/710586.

12. Galloni, E., "Analyses about parameters that affect cyclic variation in a spark ignition engine", *Applied Thermal Engineering* **29**: 1131-1137, 2009.

13. Xingcai, L., Libin, J., Junjun, M., and Zhen, H., "Experimental study on the cycle-by-cycle variations of homogeneous charge compression ignition combustion using primary reference fuels and their mixtures", Proc. *IMechE, Part D: J. Automobile Engineering* **221**(7): 859-866, 2007.

14. Kalghatgi, G. T. and Head, R. A., "Combustion limits and efficiency in a homogeneous charge compression ignition engine", *Int. J. Engine Res.* **7**(3):215-236, 2006.

15. Koopmans, L., Backlund, O., and Denbratt, I., "Cycle to Cycle Variations: Their Influence on Cycle Resolved Gas Temperature and Unburned Hydrocarbons from a Camless Gasoline Compression Ignition Engine," SAE Technical Paper 2002-01-0110, 2002. doi:10.4271/2002-01-0110.

16. Shahbakhti, M. and Koch, C.R., "Characterizing the cyclic variability of ignition timing in a homogeneous charge compression ignition engine fuelled with n-heptane/iso-octane blend fuels", *International Journal of Engine Research* **9** : 361-397, 2008.

17. Sjoberg, M., Dec, J. E., Babajimopoulos, A., and Assanis, D., "Comparing Enhanced Natural Thermal Stratification Against Retarded Combustion Phasing for Smoothing of HCCI Heat-Release Rates," SAE Technical Paper 2004-01-2994, 2004, doi:10.4271/2004-01-2994.

18. Persson, H., Pfeiffer, R., Hultqvist, A., Johansson, B. and Strom, H., "Cylinder-to-Cylinder and Cycle-to Cycle Variations at HCCI Operation with Trapped Residuals," SAE Technical Paper 2005-01-0130, 2005, doi: 10.4271/2005-01-0130.

19. Maurya, R.K. and Agarwal, A.K., "Experimental Investigation of Cycle-by-Cycle Variations in CAI/HCCI Combustion of Gasoline and Methanol Fuelled Engine," SAE Technical Paper 2009-01-1345, 2009, doi: 10.4271/2009-01-1345.

20. Maurya, R.K. and Agarwal, A.K., "Experimental Investigation of cycle-by-cycle variation of Heat release parameters in HCCI combustion of Methanol and gasoline fuel", International conference and Exhibition on Advances in Energy Research, IIT Bombay India, 9-11th December, 2009.

21. Daw, C. S., Wagner, R. M., Edwards, K. D., and Green, J. B.Jr., "Understanding the transition between conventional spark-ignited combustion and HCCI in a gasoline engine" *Proc. Combust. Inst.* 31: 2887-2894, 2007.

22. Ozdor, N., Dulger, M., and Sher, E., "Cyclic Variability in Spark Ignition Engines: A Literature Survey," SAE Technical Paper 940987, 1994, doi: 10.4271/940987.

23. Martin, J.K., Plee, S.L., and Remboski, D.J., "Burn Modes and Prior-Cycle Effects on Cyclic Variations in Lean-Burn Spark-Ignition Combustion," SAE Technical Paper 880201, 1988, doi: 10.4271/880201.

24. Daw, C.S., Finney, C.E.A., Green, J.B., Kennel, M.B., and Thomas, J.F., "A Simple Model for Cyclic Variations in a Spark Ignition Engine," SAE Technical Paper 962086, 1996, doi: 10.4271/962086.

25. Wagner, R. M., Drallmeier, J. A. and Daw, C. S., "Prior-Cycle Effects in Lean Spark Ignition Combustion - Fuel/Air Charge Considerations," SAE Technical Paper 981047, 1998, doi: 10.4271/981047.

26. Green, J. B., Daw, C. S., Armfield, J. S., Finney, C. E. A., et al., Time Irreversibility and Comparison of Cyclic-

Variability Models," SAE Technical Paper 1999-01-0221, 1999, doi:10.4271/1999-01-0221.

27. Kaul, B.C., Vance, J. B., Drallmeier, J. A., and Sarangapani, J., "A method for predicting performance improvements with effective cycle-to-cycle control of highly dilute spark ignition engine combustion" *Proc. IMechE Vol. 223 Part D: J. Automobile Engineering* **223**(3): 423-438, 2009.

28. Indian Oil Corporation Limited India, "Gasoline specification", http://www.iocl.com/Products/GasolineSpecifications.pdf. Dec. 2010.

29. Heywood, J. B., "Internal combustion engine fundamentals", McGraw-Hill, New York, 1988.

30. Finney, C. E. A., Green, J. B.Jr., and Daw, C. S., "Symbolic Time-Series Analysis of Engine Combustion Measurements," SAE Technical Paper 980624, 1998, doi: 10.4271/980624.

31. Ghazimirsaied, A., Shahbakhti, M., Koch, C. R., "HCCI Engine Combustion Phasing Prediction Using a Symbolic-Statistics Approach", *Journal of Engineering for Gas Turbines and Power* **132** (8), 2010.

32. Daw, C., Finney, C. and Kennel, M., "A symbolic approach for measuring temporal irreversibility", *Physical Review E* **62** (2):1912-1921,2000.

33. Crutchfield, J. P. and Packard, N. H., "Symbolic dynamics of noisy chaos", Physica D, 7: 201-223, 1993.

34. Tang, X. Z., Tracy, E. R., Boozer, A. D., DeBrauw, A., and Brown, R., "Symbol sequence statistics in noisy chaotic signal reconstruction", Phys. Rev. E 51:3871-3889,1995.

35. Christensen, M., Hultqvist, A., Johansson, B., "Demonstrating the Multi Fuel Capability of a Homogeneous Charge Compression Ignition Engine with Variable Compression Ratio," SAE Technical Paper 1999-01-3679, 1999, doi:10.4271/1999-01-3679.

36. Shahbakhti, M., Ghazimirsaied, A. and Koch, C.R, "Predicting the distribution of combustion timing ensemble in an HCCI engine", Proceedings of ASME internal combustion division, ICES 2009-76007, 2009.

37. Shahbahkti, M., "Modeling and Experimental Study of an HCCI Engine for Combustion Timing Control", Phd Thesis, University of Alberta, 2009.

38. Bengtsson, J., Strandha, P., Johansson, R., Tunestål, P., Johansson, B., "Hybrid modelling of homogeneous charge compression ignition (HCCI) engine dynamics-a survey", *International Journal of Control*, **80** (11): 1814-1847, 2007.

39. Scholl, D. and Russ, S., "Air-Fuel Ratio Dependence of Random and Deterministic Cyclic Variability in a Spark-Ignited Engine" SAE Technical Paper 1999-01-3513, 1999, doi:10.4271/1999-01-3513.

40. Wagner, R.M., Daw, C.S., and Green, J.B., "Characterizing lean spark ignition combustion instability in terms of a low-order map", Second Joint Meeting of the US Sections of the Combustion Institute, USA, March 25-28, 2001.

CONTACT INFORMATION

Dr Avinash K Agarwal
Associate Professor and Devendra Shukla Research Fellow
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur-208016 India
akag@iitk.ac.in
www.iitk.ac.in/erl
Tel:+91 512 2597982(O)
FAX: +91 512 2597982, 2597408 (O)

About the authors:

Rakesh Kumar Maurya (rakesh@iitk.ac.in) is doctoral research student under the supervision of Dr. A. K. Agarwal. He has completed his dual degree M.Tech./B.Tech. program in mechanical engineering from IIT Kanpur under the supervision of Dr A K Agarwal in 2006. His areas of current interest are HCCI Combustion and control, instrumentation, combustion and emission control of IC engine, alternative fuels.

Dr. Avinash Kumar Agarwal (akag@.iitk.ac.in) is currently faculty of mechanical engineering at IIT Kanpur since March 2001. His areas of current interest are combustion phenomenon study in IC engines, automotive emission control, biodiesel development and characterization, laser diagnostic techniques, PIV, lubricating oil consumption reduction, lubricating oil tribology, development of micro sensors, and alternative fuels for diesel engines.

ACKNOWLEDGMENTS

The authors would like to express their sincere appreciation of the help extended by Mr. D. D. Pal, Technical Superintendent, Virtual Instrumentation Laboratory, Department of Electrical Engineering at Indian Institute of Technology Kanpur for his assistance in LabVIEW Programming. The Engine Research Laboratory staff Mr. Roshan Lai and Mr. Ravi Singh also helped during the experimental setup and experiments.

DEFINITIONS/ABBREVIATIONS

CAD
crank angle degree

CA_{10}
crank angle for 10% heat release

CA_{50}
crank angle for 50% heat release

DICI
direct injection compression ignition

FPGA
field programmable gate array

HCCI
homogeneous charge compression ignition

LabVIEW
laboratory virtual instrument engineering workbench

RIO
reconfigurable input output

ROHR
rate of heat release

SI
spark ignition

TDC
top dead center

λ
relative air fuel ratio

N
engine speed

n_{part}
number of partition

T_i
intake air temperature

APPENDIX

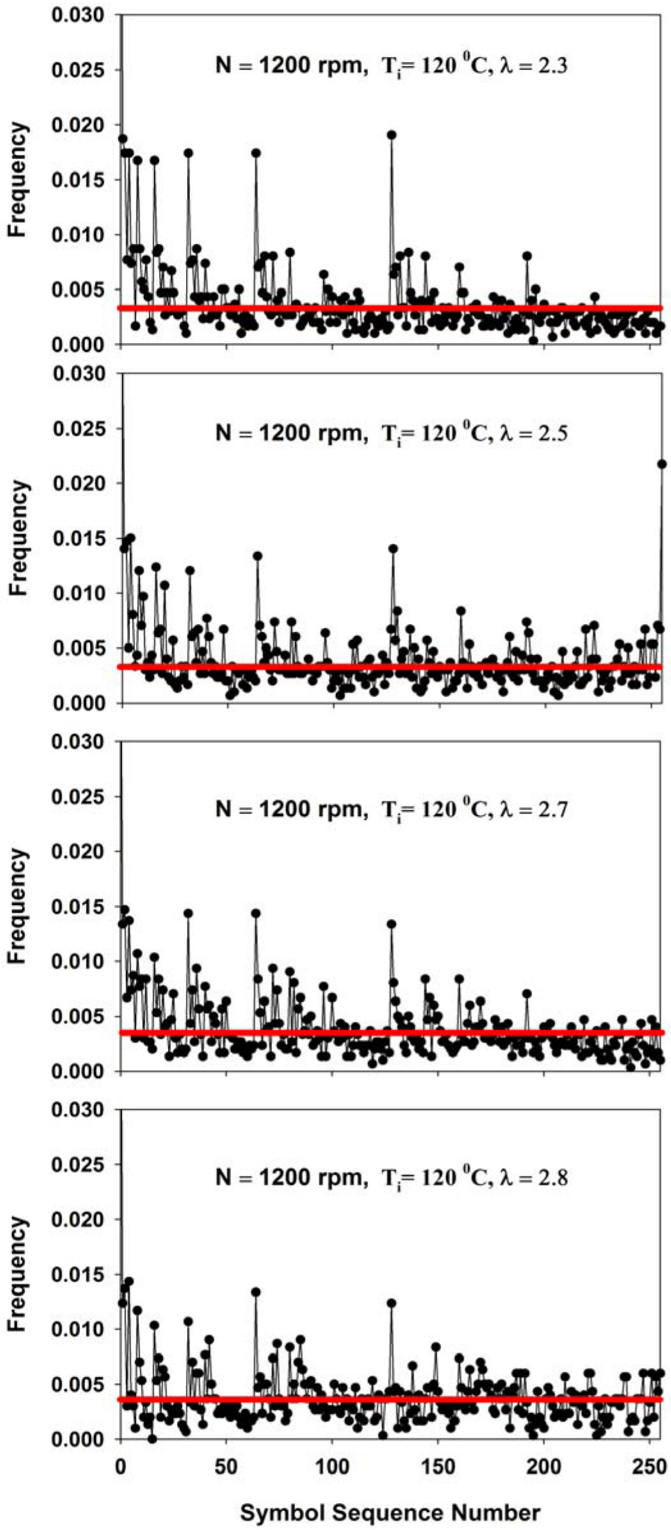


Figure 16. Symbol sequence histograms of CA_{50} for different λ at 1200 rpm using binary partition and sequence length 8

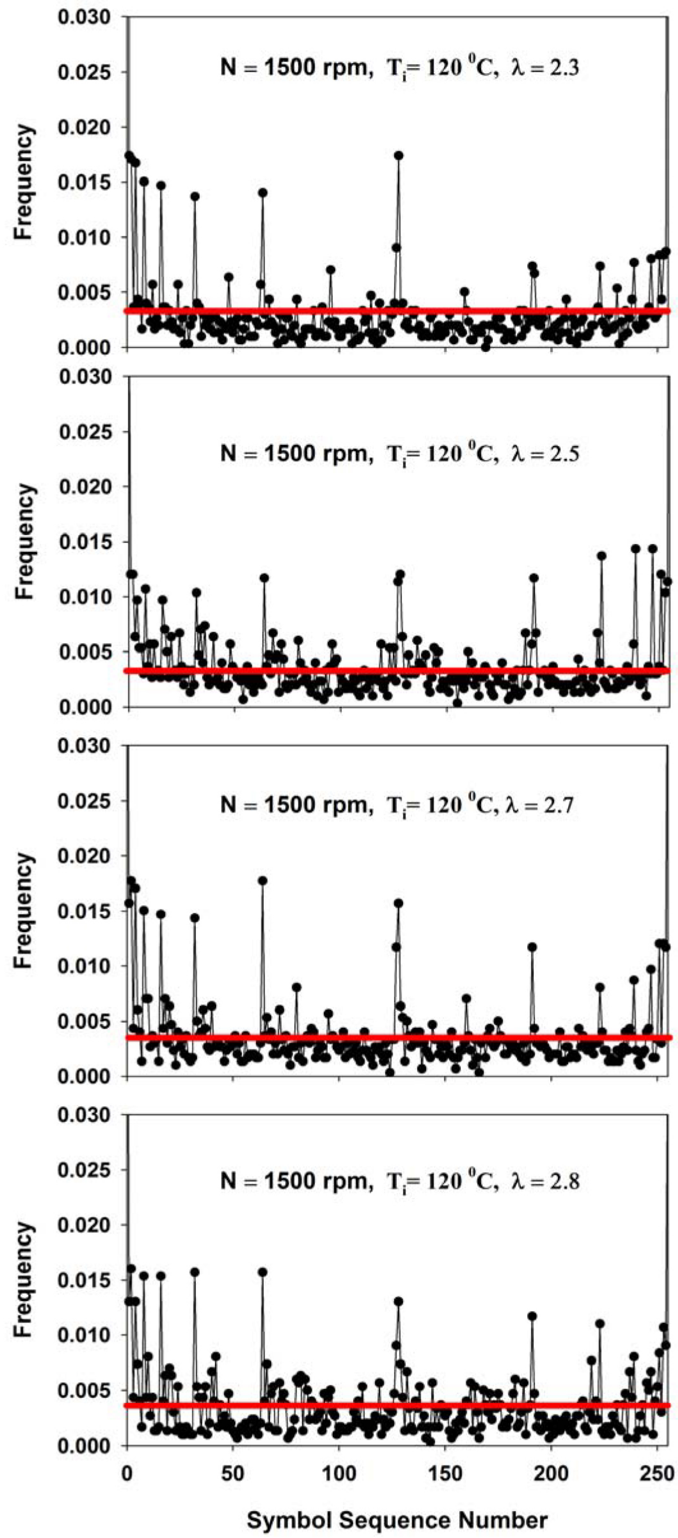


Figure 17. Symbol sequence histograms of CA_{50} for different λ at 1500 rpm using binary partition and sequence length 8

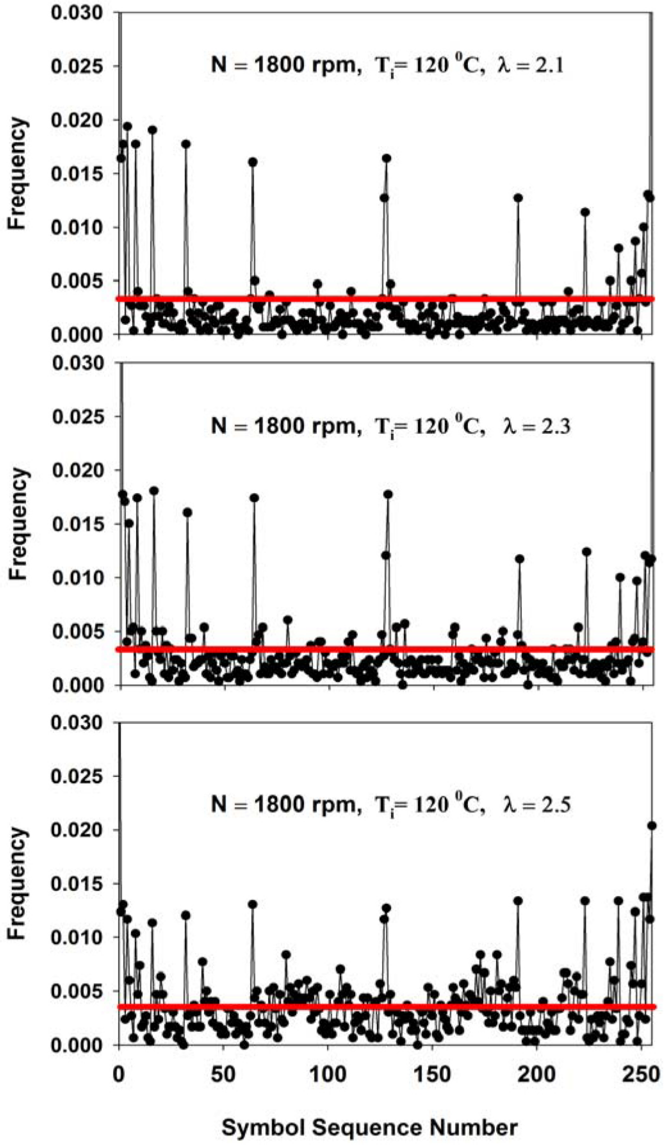


Figure 18. Symbol sequence histograms of CA_{50} for different λ at 1800 rpm using binary partition and sequence length 8

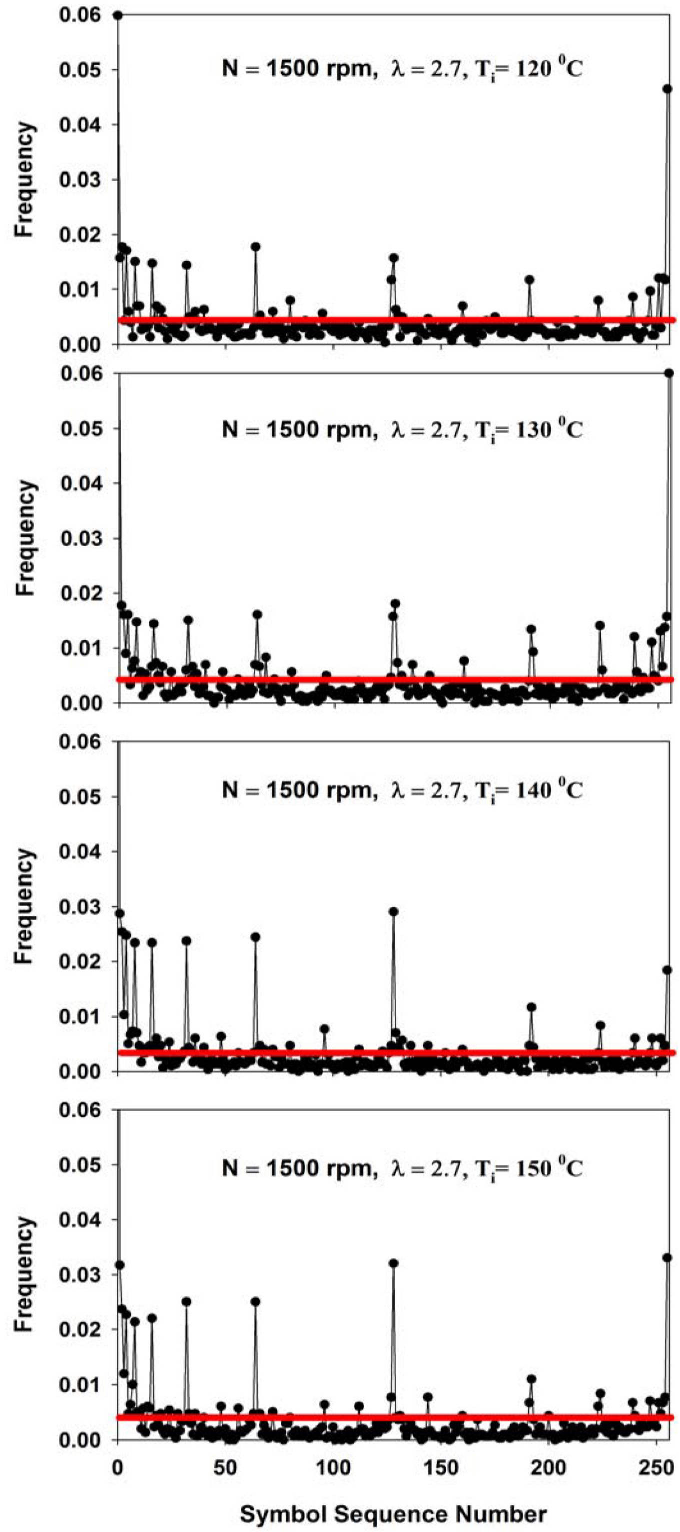


Figure 19. Symbol sequence histograms of CA_{50} for different T_i at 1500 rpm using binary partition and sequence length 8

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

SAE Customer Service:
Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org
Printed in USA

SAE International™