Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

# An experimental study on cycle-to-cycle combustion variations at different speeds in a common-rail diesel engine

## Ortak hatlı bir dizel motorda farklı devirlerde çevrimden çevrime yanma değişimleri üzerine deneysel bir çalışma

*Ali ŞANLI[1]*, İlker Turgut YILMAZ[2]*

[1]Piri Reis Vocational and Technical Anatolian High School, İstanbul, Turkey.
phdalisanli@outlook.com
[2]Mechanical Engineering, Technology Faculty, Marmara University, İstanbul, Turkey.
ilker.yilmaz@marmara.edu.tr

Received/Geliş Tarihi: 17.12.2022 Revision/Düzeltme Tarihi: 15.08.2023 doi: 10.5505/pajes.2023.23565
Accepted/Kabul Tarihi: 12.09.2023 Research Article/Araştırma Makalesi



**Abstract**

*This study experimentally studies cyclic combustion variabilities in a four-cylinder automotive common-rail diesel engine at different engine speeds including 1600, 1800, and 2000 rpm. Purpose of the investigation is to evaluate the relative effects of speed shifting on the cyclic discrepancies in a modern diesel engine. 1000 sequential pressure related combustion parameters including peak combustion pressure (Pmax), peak pressure rise rate (PRRmax) and indicated mean effective pressure (IMEP) were analyzed in the experimental study. It was found that the cyclic fluctuations in combustion pressure versus crank angle in each speed mode were small, but detailed comparison for the parameters of Pmax, PRRmax, and IMEP revealed differences between the cycles studied. The COVs of IMEP and Pmax decreased with increasing the engine speed and each remained below 1% at all speeds, thus concluding that stable and regular combustion was maintained at high numbers of cycles in the engine. Pre-injection phase of fuel delivery system was recognized to be effective to first peak of the combustion pressure in individual cycles. It is concluded from this study that the common-rail diesel engine generates minor cyclic discrepancies under different engine speeds.*

**Keywords:** Cyclic variations, pressure related combustion parameters, common-rail diesel engine

*Öz*

*Bu çalışmada, dört silindirli ortak hatlı bir dizel motorda farklı devirlerde (1600, 1800, 2000 d/dak) çevrimden çevrime yanma değişimleri deneysel olarak incelenmektedir. Çalışmanın amacı, modern dizel motorda dönme sayısının çevrimsel farklılıklara etkisini değerlendirmektir. Maksimum yanma basıncı (SBmax), maksimum basınç artış oranı (BAOmax), ve ortalama indike basınç (OİB) parametrelerini kapsayan 1000 adet basınçla ilişkili yanma parametresi deneysel çalışmada analiz edildi. Sonuçlar göstermektedir ki, her bir motor hızında krank açısına göre silindir basıncındaki çevrimsel değişimler makuldür, ancak detaylı karşılaştırmada incelenen çevrimler arasında SBmax, BAOmax ve OİB'de farklar ortaya çıkmıştır. OİB ve SBmax için çevrimsel değişim katsayısı artan dönme sayısıyla birlikte azalmıştır ve tüm devir sayılarında %1'in altında kalmıştır, böylece yüksek çevrim sayılarında stabil ve düzenli yanmanın devam ettiği sonucuna varılmıştır. Yakıt sistemi ön enjeksiyon fazının her bir çevrimde yanma basıncı ilk pikinde etkili olduğu görülmüştür. Bu çalışmayla, ortak hatlı dizel motorun çeşitli devirlerde küçük çevrimsel farklılıklar meydana getirdiği anlaşılmaktadır.*

**Anahtar kelimeler:** Çevrimsel değişimler, basınca dayalı yanma parametreleri, ortak hatlı dizel motor

## 1 Introduction

Modern compression ignition (CI) engines are widely used today in transport and energy requirement facilities, such as modern automotive vehicles, maritime transport sector, and stationary generator applications. Their high thermal efficiency, better fuel economy, and lower emission aspects compared to earlier engine generations make them preferable devices. The limited knowledge of the inconsistencies in the phenomenon of combustion compels researchers to draw deeper insights and new conclusions. Therefore, a deeper understanding of in-cylinder process is required to make CI engines run more efficiently and cleanly.

One of the key aspects of the diesel cycle is the combustion process, which refers to the sequence of events that occurs within the engine during the power stroke. This process is critical to the performance of the engine, and can be affected through a number of factors, including the engine working parameters, the fuel injection system, and the injection timing.

Cycle-to-cycle variabilities in CI engines are mainly responsible for sensible vibration formation. Unstable and vibrational operations in CI engines are closely related to cycle-to-cycle combustion differences. During sequential regional air-fuel mixture discrepancies in combustion chamber, residual gas concentration mixed with the new fresh air, rich or lean combustion zones in the combustion chamber, early flame development conditions, ignition delay, fuel type and injection characteristics are main causes of cycle-to-cycle variabilities [1, 2]. Engine output, combustion noise, and emissions are always affected by the cyclic variations [3]. Engine thermal efficiency can be significantly enhanced when the cyclic variability is reduced [4]. Also, idling reduces fuel consumption; but this is limited to cycles where the lowest IMEP values are produced.

In a CI engine, the charge is ignited through the high pressure and temperature generated through the compression of the air. However, the exact point at which the fuel ignites can vary in cylinder, resulted in differences in the rate and intensity of the combustion. This can result in variations in the amount of

*Corresponding author/Yazışılan Yazar

power generated by the engine and the efficiency of the combustion process [5].

Different engine parameters have a significant impact on cyclic variabilities in internal combustion engines. Hamai et al. [6] investigated effects of main operation parameters on cyclic variations of spark ignition (SI) engine. They revealed that air/fuel ratio (A/F) was strongly correlated with the IMEP and heat releasing delay over 50 cycles. That is, the richer the mixture near the spark plug, the higher the IMEP and the lower the heat releasing delay in individual cycles. Yu et al. [7] executed experimentally a study in a SI engine with 10% hydrogen ($H_2$) fraction under $H_2$ direct injection mode for lean burn. They found that coefficient of variation in indicated mean effective pressure increased with increment of excess air ratio, and cyclic variations were reduced and combustion stability was aroused notably with $H_2$ supplement. Shere and Subramanian [8] conducted some tests in a single cylinder common-rail direct injection (CRDI) engine at 2200 rpm and full load. The authors investigated effects of fuel type and different injection timings which are 12° and15° before top dead center (TDC) in the engine fuelled with dimethyl ether (DME). In the study, cyclic variations of Pmax, PRRmax, and IMEP for 100 consecutive cycles were reported. For only diesel operation at different injection timings it was found that COV of Pmax values were between 2.7% and 3.2%, and COV of IMEP values were between 1.86% and 1.52%. In addition, they also showed that fuel type had a strong effect on cyclic variability. Gürbüz et al. [9] reported that hydrogen usage in SI engine provided more stable engine operation, by decreasing the COV of IMEP. Yasin et al. [10] investigated 200 cyclic cylinder pressures and IMEP variations in a diesel engine fueled with biodiesel and alcohol blends. COV of IMEP value of about 2% with diesel operation was lower than the results obtained with biodiesel and alcohol blends. Ceviz et al. [11] reported that biodiesel presence in diesel fuel led to reduce in COVs of Pmax and IMEP at different engine speeds. On the other hand, it was found that biodiesel presence increased COV of Pmax at low engine speeds. Sen et al. [12] investigated the variations of IMEP in a diesel engine at different engine speeds. They found that under different engine speeds strong periodicities appear in low-frequency bands and may continue over many cycles, whereas the intermittency may continue at higher frequencies.

Since various engine parameters have different impacts on the cycle-to-cycle variations, it can be aroused different problems on combustion stability and drivability conditions; therefore, more detailed investigations are required. In addition, in the light of above literature studies few studies on the effect of engine speed on cyclic combustion variations were found. In this regard, this study investigates and discusses the relationship between degree of cyclic variations and engine speed in a common-rail diesel engine.



## 2 Material and Methods

In this study, a commercial turbocharged CI engine (K9K 700) was used. The EGR system was disabled so as not to affect the test results. A Cussons, model P8602 dynamometer is used in order to load the test engine. Cylinder and fuel line pressure sensors together with a crank encoder were integrated onto the test engine. Schematic illustration of the test bench is given in Fig. 1. Main specifications of the test engine end the pressure sensors can be respectively seen at Table 1 and Table 2. Kistler charge amplifier (model 4067 C2000S) was used to amplify the fuel line pressure signals. Diesel fuel purchased from the Petrol Ofisi gas station was used in the tests.

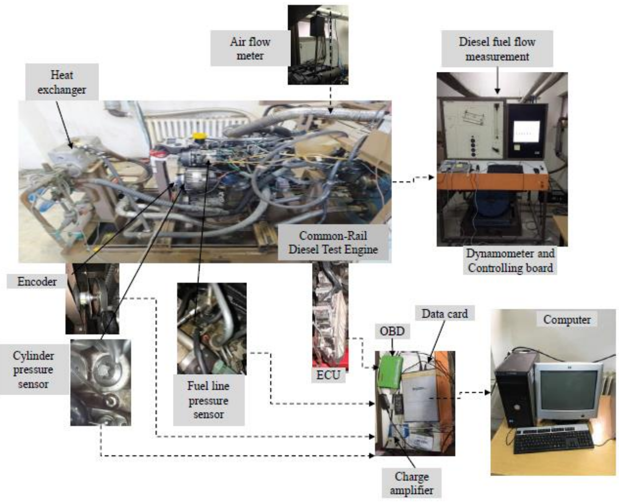


Figure 1. Schematic illustration of the test system.

Table 1. Specifications of test engine.

| | |
|---|---|
| Type | Inline, four stroke, turbocharged |
| Cylinder volume | 1461 $cm^3$ |
| Number of cylinders | 4 |
| Maximum power | 48 kW (4000 rpm) |
| Maximum torque | 160 Nm (1750 rpm) |
| Compression ratio | 18.25 |
| Fuel injection | Common-rail |

A National Instruments 6343 model data collecting card is used to acquire fuel line and cylinder pressure data over 1000 cycles. All tests were conducted at revolutions of 1600, 1800 and 2000 r/min at a constant load of 60 Nm. The experiments were performed at around 80 ±5 °C. Temperatures at different points on the test engine were measured via K-type thermocouples.

Table 2. Specifications of sensors.

| | Cylinder Pressure Sensor | | Fuel Line Sensor | |
|---|---|---|---|---|
| Brand/Model | Optrand | 33288 GPA | Kistler | C6533 A11 |
| Range | bar | 0-200 | bar | 0-2000 |
| Linearity | % FSO | ±1 | % FSO | <±0,5 |
| Operating Temperature | °C | -40-300 | °C | 20 - 120 |
| Output signal | V DC | 0,5-4,5 | mA | 4-20 |
| Natural frequency | kHz | >120 kHz | kHz | >100 |
| Overload | bar | 400 | bar | 2 500 |

In analyzing of the cycles, coefficient of variation (COV) is computed from Equation (1).

$$COV\_X = \frac{\sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}}}{\bar{X}}100 \qquad (1)$$

Where $n$ symbolizes number of cycles, $X_i$ is value of random combustion parameter (Pmax or IMEP in this study) in $i^{th}$ cycle, and $\bar{X}$ denotes the mean value of $n$ combustion parameters. Pmax was determined from the experimental data, and IMEP is defined by using instantaneous combustion pressure ($P$) and volume ($V$), and displacement volume ($V_d$) presented in Equation (2).

$$IMEP = \frac{\oint P.dV}{V_d} \tag{2}$$

## 3 Results and Discussion

Combustion pressure measurement is one of the main tools used to study the fundamental burning characteristics in today's test engines. Fig. 2 presents sequential combustion pressure traces versus crank angle during 1000 cycles for different speeds. It is clear from the Fig. 2 that similar cycle-to-cycle cylinder pressures were produced at a constant speed. However, considering the average value of the cylinder pressure, it raised when the crank revolution improved, which is probably owing to increasing fraction of the pilot injection which affects the first peak of cylinder pressure in whole cycles. The test engine has two fuel injection phases. These are pre-injection and main injection [13], [14], [15]. With increasing engine speed, the engine management system would advance the fuel injection timing. Otherwise, combustion may be delayed due to an increase in the mean piston speed, resulting in poor combustion efficiency. CI engines generally give regular combustion results. However, the SI engines do not produce cyclic combustion variations satisfactorily. For instance, Chen et al. [16] reported substantial fluctuations in the cylinder pressure over 100 consecutive cycles under lean burn conditions in the engine fuelled with natural gas and methanol. They documented remarkable cylinder pressure fluctuations for each fuel operation. Similarly, Gupta and Mittal [17] demonstrated that the cylinder pressure traces in methane-fuelled SI engine unstably varied during 120 consecutive cycles. They reported that the cyclic pressure fluctuations were diminished with increasing the compression ratio.

Fig. 3 illustrates cycle-by-cycle variabilities of Pmax at the same speeds, and also indicates mean values of Pmax. It was seen that the Pmax values varied significantly from cycle to cycle at a constant speed. Maximum and minimum values of the peak cylinder pressures were detected between 92.35 bar with 388th cycle and 89.01 bar with 197th cycle at 1600 rpm, and between 93.77 bar with 775th cycle and 90.67 bar with 14th cycle at 1800 rpm, and 95.80 bar with 917th cycle and 93.89 bar with 108th cycle at 2000 rpm. Fig. 3 also indicates that the mean value of Pmax is elevated by the engine speed, which is consistent with the literature study [18]. It can be emphasized that with increasing the engine speed, air movement in the cylinders and injection pressure increase. This means that the sprayed fuel droplets are more evenly distributed in the cylinder [19]. Clearly, it was resulted in stronger diesel combustion, thus leading to higher peak pressures with increasing the speed.

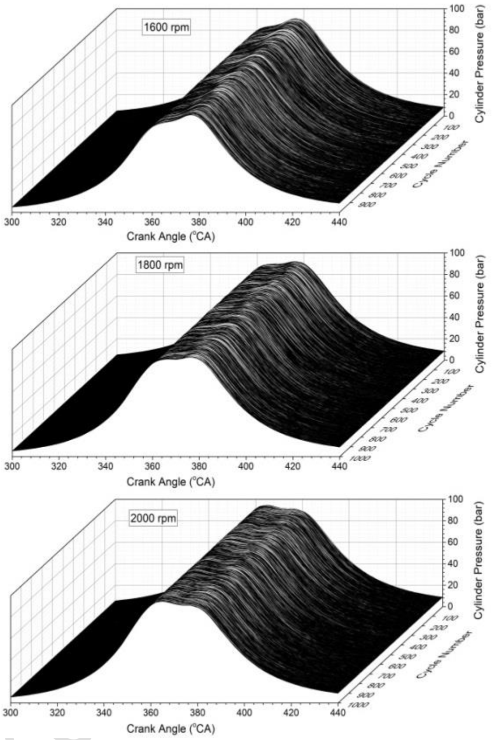


Figure 2. Sequential variabilities of cylinder pressure curves over 1000 cycles for different engine speeds.

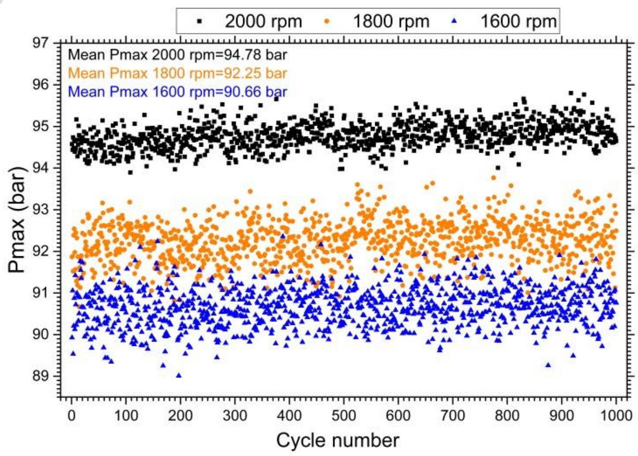


Figure 3. Cyclic variations of Pmax over 1000 individual cycles for different engine speeds.

Fig. 4 exhibits relationship between Pmax values and corresponding crank angles at different engine speeds. As indicated earlier, peak values of the cylinder pressure increased with enhanced engine speed. At low and medium speeds, the highest values of the cylinder pressure were achieved at 16-18 °CA after TDC. At high speed, they were as close as 4-5 °CA to the TDC. These results may be due to the dynamic injection strategy of the engine management system. At higher engine speeds, the injection process starts earlier, and more fuel is needed to improve the crank revolution. The increase in the amount of pilot fuel shifts the first peak pressure nearer TDC. As raising the crank revolution, the heat loss to the jacket water decreases, thus increasing the compression pressure. COV of Pmax, presented in Fig. 5, is observed to be reduced notably with increasing the engine speed. When the crank revolution was increased from 1600 r/min to 2000 r/min, COV of Pmax was diminished from 0.52% to 0.33%, meaning that cyclic fluctuations could be decreased with elevated speed.

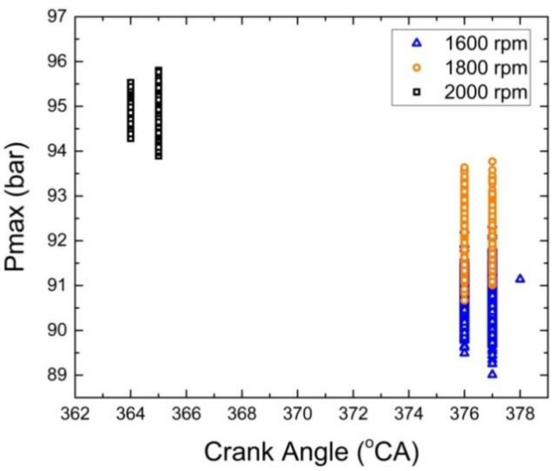


Figure 4. Pmax and CA locations for different engine speeds.

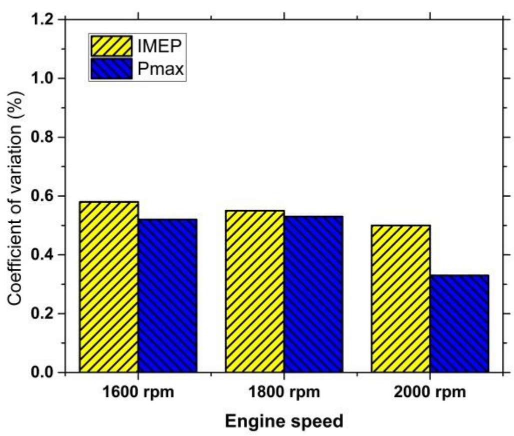


Figure 5. COV of IMEP and Pmax variations under various engine speeds.

Fig. 6 shows pressure fluctuations in fuel line in each cycle at the speed of 2000 r/min. It is emphasized that one of the key issues contributing to cyclic fluctuations in diesel burning is the fuel injection process [1], [20]. In a CI engine, fuel is introduced directly into the cylinder and is ignited by the charge with high temperature. However, the fuel injection process, as shown in Fig. 6, is not always uniform among the sequential cycles. This can result in differences in the fraction and timing of fuel injection for each working cycle, thus leading to variances in the combustion pressure and the generation of power [21].

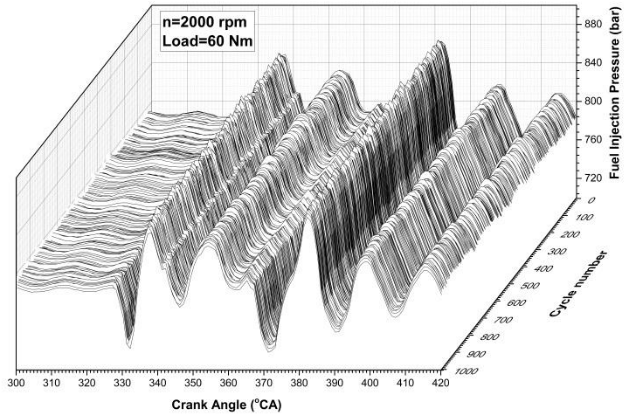


Figure 6. Individual pressure variabilities in fuel line over 1000 cycles for 2000 r/min.

Pressure rise rate is an important tool used for determination of engine knock characteristics. It is calculated from instantaneous cylinder pressure traces. Its peak value in each cycle is evaluated in this study and presented in Fig. 6. It was found that as increasing the engine speed, cyclic peak values of the pressure rise rate showed a significant increase. Mean values of pressure rise were found 3.36 bar/°CA at 2000 r/min, 3.19 bar/°CA at 1800 r/min, and 2.98 bar/°CA at 1600 r/min. At high speed, boosted turbulence intensity and air movement raise the mixture formation degree of the charge. Consequently, burning spreads promptly. This can build up the high combustion pressure leading to significant variations in instantaneous pressure rises. Lastly, the highest value among the peak pressure rise rates in entire operation conditions was found 3.46 bar/°CA at 2000 r/min, which implies no knocking cycle existed during the tests based on the literature [5].

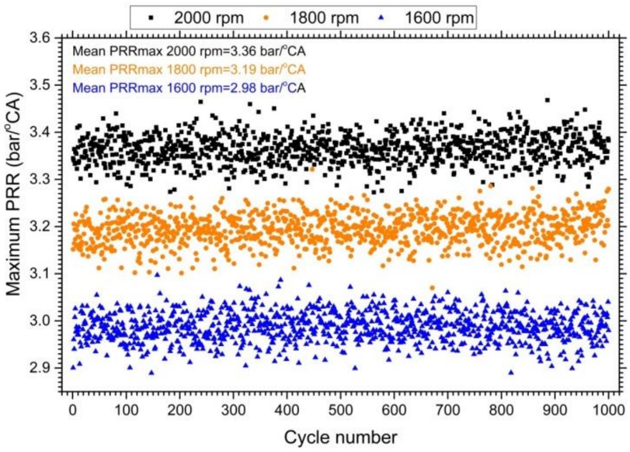


Figure 7. Sequential variations of maximum PRR over 1000 cycles for different engine speeds.

IMEP is the mean effective pressure determined by cylinder pressure traces over the engine cycle. It is used to assess the cyclical burning variabilities, and its coefficient of variation is a valuable magnitude of cyclic variability [22]. Fig. 8 represents the impact of engine speed on cyclic discrepancies in IMEP. As can be seen, IMEP significantly varied from one cycle to another. It is clear from the Fig. 8 that IMEP values at 1800 rpm were higher than those at 1600 and 2000 rpms due to probably operating at the best torque revolution obtained in 1750 rpm.

At the close speed conditions to the maximum best torque, the best engine performance is obtained due to operating at better volumetric efficiency and minimal fuel consumption. As a result, the combustion process can be significantly improved, and IMEP at 1800 rpm is obviously expected larger than others.

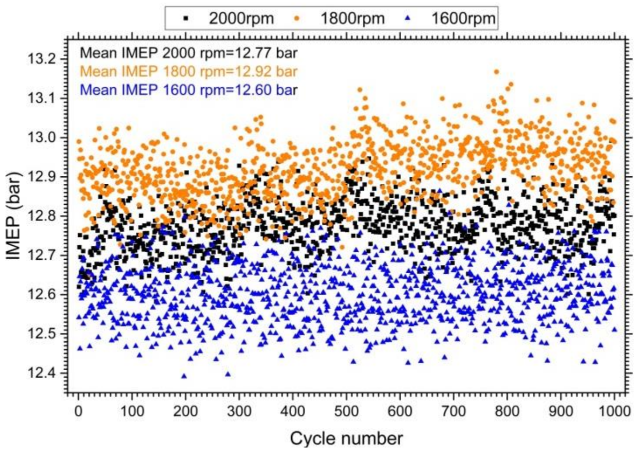


Figure 8. Sequential variations of maximum PRR over 1000 cycles at various crank revolutions.

It was shown during 1000 cycles that some of the cycles adopt an important rise in IMEP, while some of them do conversely. Maximum and minimum values of IMEP and their corresponding cycle number were respectively found as 12.99 bar in 994th cycle and 12.58 bar in 145th cycle at 2000 rpm, and 13.17 bar in 780th cycle and 12.65 bar in 22nd cycle at 1800 rpm, and 12.86 bar in 673th cycle and 12.39 bar in 197th cycle at 1600 rpm. This corresponds to respective IMEP differences of 0.41, 0.52, and 0.47 bar at the speeds of 2000, 1800, and 1600 r/min. As raising the crank revolution, turbulent movement of the air at intake and compression strokes significantly increases the phenomena of tumble and squish. Whereas, as increasing the engine speed intake phenomenon in the intake manifold weakens partly due to increasing the friction losses inside the intake channels originated from the accelerated air, as a result of which mass of air drawn into the cylinders decreases and makes an opposite influence on cycle efficiency. Thus it can be resulted in a decrease in IMEP with increased crank revolution. COV of IMEP was decreased as increasing the crank revolution, as shown in Fig. 5. When raising the speed from 1600 rpm to 2000 rpm, COV of IMEP was diminished from 0.58% to 0.50%. Faster crank revolution provided more stable operation over the combustion cycles of the engine. These values are well coincided with studies performed by Ghadikolaei et al. [23] and Ozkan [24]. It is also expected that COV of IMEP does not exceed 10% that interprets the poor drivability [5], [25]. However, such COV of IMEP and Pmax behavior with engine revolution was not observed before in the literature studies conducted on CI engines fuelled with various fuels. On the contrary, Wang et al. [26] found in a NG run SI engine that COVs of peak pressure and IMEP enhanced with increasing engine speed. Besides, COV of IMEP was over 1% while COV of Pmax was upper than 6%. Karvountzis-Kontakiotis et al. [27] documented similar results related to COV of IMEP and Pmax in an SI engine. Also, they obtained the lowest deviance and COV of IMEP in the case of maximum best torque. Accordingly, this study also supports the general conclusion of that the CI engines produce rather steady cyclic variations in comparison to SI engines [3], [26], [28], [29].

## 4 Conclusions

Common rail diesel engine was run under different engine speeds to analyze cycle-to-cycle combustion variations. It may be concluded below results from this study.

Mean cylinder pressure enhanced as increasing the engine speed. Cyclic Pmax values during 1000 cycles were found to remarkably vary. Corresponding crank angles of the Pmax in each cycle was found quite close to each other, and with increasing speed they were advanced due to effectiveness of pre-injection event in the common rail fuel system. COV of Pmax reduced with the engine speed. PRR values in each cycle remained below the diesel-knock limit. With increasing speed, mean PRRmax values increased.

COV of IMEP values were obtained as 0.41, 0.52, and 0.47 bar at 1600, 1800, and 2000 rpm speeds, respectively. The highest mean IMEP value was obtained at 1800 rpm, and then followed by 2000 rpm and 1600 rpm, with the corresponding IMEP values of 12.92 bar, 12.77 bar and 12.60 bar.

Overall, the presented results revealed that engine speed had minimal effect on the cyclic combustion variations of CRDI, and stable and regular burning regarding the pressure related combustion parameters was preserved under different engine speeds.

## 5 Symbols and nomenclature

| | |
|---|---|
| A/F | Air-fuel ratio |
| TDC | Top dead center |
| $COV$ | Coefficient of variation |
| SI | Spark ignition |
| rpm | revolution per minute (r/min) |
| $IMEP$ | Indicated mean effective pressure (bar) |
| $n$ | Number of cycles |
| $Pmax$ | Peak combustion pressure (bar) |
| $PRRmax$ | Peak rate of pressure rise (bar/°CA) |
| $V_d$ | Displacement volume ($m^3$) |
| $\bar{X}$ | Average of random combustion parameter |

## 6 Ethics committee approval and conflict of interest statement

There is no need for permission from the ethics committee for the article prepared. There is no conflict of interest with any person or institution in the article prepared.

## 7 Author contribution statements

In this study, Author 1 involves in conceptualization, methodology, literature review, analyzing the data, writing and visualization, and Author 2 involves in supervising, experimental study, validating the results, and reviewing the writing, spell-check and editing.

## 8 References


[1] Kyrtatos P, Brückner C, Boulouchos K. "Cycle-to-cycle variations in diesel engines". *Applied Energy,* 171, 120-132, 2016.

[2] Bozza F, De Bellis V, Minarelli F, Cicciatore D. "Knock and cycle by cycle analysis of a high performance V12 spark ignition engine. Part 2: 1D combustion and knock

modelling". *Society of Automotive Engineering International Journal of Engines*, 8(5), 2002-2011, 2015. https://doi.org/10.4271/2015-24-2392.

[3] Selim MYE. "Effect of engine parameters and gaseous fuel type on the cyclic variability of dual fuel engines". *Fuel*, 84(7-8), 961-971, 2005.

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

[5] Heywood JB. Internal Combustion Engine Fundamentals. 1st ed. USA, McGraw-Hill Press, 1988.

[6] Hamai K, Kawajiri H, Ishizuka T, Nakai M. "Combustion fluctuation mechanism involving cycle-to-cycle spark ignition variation due to flow motion in S.I. engines". *21st symposium (International) on Combustion*, 21(1), 505-512, 1988.

[7] Yu X, Wu H, Du Y, Tang Y, Liu L, Niu R. "Research on cycle-by-cycle variations of an SI engine with hydrogen direct injection under lean burn conditions". *Applied Thermal Engineering,* 109, 569-581, 2016.

[8] Shere A, Subramanian KA. "Experimental investigation on effects of fuel injection timings on dimethyl ether (DME) energy share improvement and emission reduction in a dual-fuel CRDI compression ignition engine". *International Journal of Automotive Science and Technology*, 6(2), 98-112, 2022.

[9] Gürbüz H, Buran D, Akçay İH. "An experimental study on performance and cyclic variations in a spark ignition engine fuelled with hydrogen and gasoline". *Journal of Thermal Science and Technology* 33(1), 33-41, 2013.

[10] Yasin MHM, Mamat R, Yusop AF, Abdullah AA, Othman MF, Yusrizal ST, Iqbal ST. "Cylinder pressure cyclic variations in a diesel engine operating with biodiesel-alcohol blends". *Energy Procedia*, 142, 303-308, 2017.

[11] Ceviz MA, Koncuk F, Küçük Ö, Gören AC, Yüksel F. "Analysis of combustion stability and its relation to performance characteristics in a compression ignition engine fueled with diesel-biodiesel blends". *Energy Souces Part A: Recovery, Utilization, and Environmental Effects*, 33(10), 990-1003, 2011.

[12] Sen AK, Longwic R, Litak G, Gorski K. "Analysis of cycle-to-cycle pressure oscillations in a diesel engine". *Mechanical Systems and Signal Processing*, 22(2), 362-373,2008.

[13] Şanlı A, Gümüş M. "Investigation of heat transfer in combustion chamber of a direct injection diesel engine under different compression ratios and engine torques". *Pamukkale University Journal of Engineering Sciences*, 28(1), 91-103, 2022.

[14] Şanlı H. "Investigation of waste animal fat based biodiesel fuels' usage in a common rail direct injection diesel engine: performance and combustion characteristics". *Pamukkale University Journal of Engineering Sciences*, 25(4), 396-402, 2019.

[15] Yılmaz İT, Yavuz M, Gümüş M. "The effect of diesel fuel amount on emissions in a diesel-biogas dual-fuel engine". *Pamukkale University Journal of Engineering Sciences*, 26(4), 683-688, 2020.

[16] Chen Z, He J, Chen H, Geng L, Zhang P. "Experimental study on cycle-to-cycle variations in natural gas/methanol bi-fueled engine under excess air/fuel ratio at 1.6". *Energy*, 224, 120233, 2021.

[17] Gupta SK, Mittal M. "Effects of compression ratio on the performance and emission characteristics, and cycle-to-cycle combustion variations of a spark-ignition engine fueled with bio-methane surrogate". *Applied Thermal Engineering*, 148, 1440-1453, 2019.

[18] Shi J, Wang T, Zhao Z, Wu Z, Zhang Z. "Cycle-to-cycle variation of a diesel engine fuelled with fischer-tropsch fuel synthesized from coal". *Applied Sciences,* 9(10), 2032, 2019.

[19] Geng L, Li S, Xiao Y, Xie Y, Chen H, Chen X. "Effects of injection timing and rail pressure on combustion characteristics and cyclic variations of a common rail DI engine fuelled with F-T diesel synthesized from coal". *Journal of Energy Institute*, 93(6), 2148-2162, 2020.

[20] Henein NA, Lai M-C, Singh IP, Zhong L, Han J. "Characteristics of a common rail diesel injection system under pilot and post injection modes". *Society of Automotive Engineering Technical Paper,* 2002. https://doi.org/10.4271/2002-01-0218.

[21] Zhong L, Singh IP, Han J, Lai M-C, Henein NA, Bryzik W. "Effect of cycle-to-cycle variation in the injection pressure in a common rail diesel injection system on engine performance". *Society of Automotive Engineering Technical Paper*, 2003. https://doi.org/10.4271/2003-01-0699.

[22] Ali OM, Mamat R, Masjuki HH, Abdullah AA. "Analysis of blended fuel properties and cycle-to-cycle variation in a diesel engine with a diethyl ether additive". *Energy Conversion Management,* 108, 511-519, 2016.

[23] Ghadikolaei MA, Cheung C, Yung KF, Wong PA. "Impact of fueling methods on the combustion and cyclic variability in a compression ignition engine". *International Journal of Green Energy*, 18(5), 474-489, 2021.

[24] Ozkan M. "Comparative study of the effect of biodiesel and diesel fuel on a compression ignition engine's performance, emissions, and its cycle by cycle variations". *Energy & Fuels,* 21, 3627-3636, 2007.

[25] Ozdor N, Dulger M, Sher E. "Cyclic variability in spark ignition engines a literature survey". *Society of Automotive Engineering Technical Paper*, 1994. https://doi.org/10.4271/940987.

[26] Wang S, Li Y, Fu J, Liu J, Dong H, Tong J. "Quantitative investigation of the effects of EGR strategies on performance, cycle-to-cycle variations and emissions characteristics of a higher compression ratio and heavy-duty NGSI engine fuelled with 99% methane content". *Fuel*, 263, 116736, 2020.

[27] Karvountzis-Kontakiotis A, Ntziachristos L, Samaras Z, Dimaratos A. "Experimental investigation of cyclic variability on combustion and emissions of a high-speed SI engine". *Society of Automotive Engineering Technical Paper,* 2015. https://doi.org/10.4271/2015-01-0742.

[28] Ozdor N, Dulger M, Sher E. "An experimental study of the cyclic variability in spark ignition engines". *Society of Automotive Engineering Technical Paper*, 1996. https://doi.org/10.4271/960611.

[29] Öner İV, Ceviz MA, Güner E, Köksal H. "Cyclic variability in spark ignition engines". *Ordu University Journal of Science and Technology*, 4(1), 27-35, 2014.