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Effects of Valve Overlap, Lift, and Duration on Spark Ignition Engine Performance

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Research Article

Abstract

This study aims to investigate the effects of valve motion characteristics on the performance of spark-ignition engines. The impact of valve timing, valve lift, and valve duration on the full-load performance characteristics of the engine was analyzed through modeling. For this purpose, the WAVE simulation program, one of the one-dimensional gas dynamics simulation tools, was used. The Taguchi experimental design method was applied for the simulation design of the variables. An analysis of variance (ANOVA) was conducted to examine the relationship between engine performance and valve motion characteristics. A total of 125 simulations were conducted, with 25 solutions for each engine speed. Brake torque, brake thermal efficiency, and volumetric efficiency were chosen as engine performance parameters. Based on the ANOVA, the optimal valve motion characteristics that maximize these three engine performance parameters simultaneously were determined. The results showed that valve overlap and intake valve duration were the most influential parameters affecting engine performance. Moreover, compared to the reference engine's original configuration, increasing valve overlap and reducing intake valve duration improved engine performance. A comparison was made between the optimized values and the original values of the reference engine. While the original configuration of the reference engine performed better at high engine speeds, a significant improvement in engine performance was observed at low and medium engine speeds. Specifically, for low and medium speeds, improvements of 8.1% in brake power and brake torque, 1.5% in brake thermal efficiency, and 6.8% in volumetric efficiency were observed.

Keywords: Engine performance, Spark ignition engine, Valve motion, Valve characteristic

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1. Introduction

Internal combustion engines (ICEs) are among the most essential technologies in the modern world, serving as a primary power source across various sectors, including transportation, energy production, agriculture, industry, and defense. Their widespread applications, ranging from automobiles and aircraft to generators and ships, have made them integral to daily life and critical to industrialization and global trade [1]. Despite the growing prominence of hybrid and electric vehicles, ICEs remain indispensable, particularly in high-power-demand applications [3]. Consequently, understanding the principles governing their operation and optimizing their design is of significant importance from both an engineering and technological perspective.

A defining feature of ICEs is that the energy conversion process occurs directly within the combustion chamber, where the air-fuel mixture is ignited in a controlled manner to produce mechanical motion. This energy conversion is essential for engine power output. However, achieving efficient operation requires precise control over various parameters. Among the key processes influencing engine performance, the intake and exhaust cycles play a pivotal role in determining overall efficiency. To optimize combustion efficiency, factors such as homogeneous air-fuel mixture distribution, in-cylinder fluid dynamics, and gas exchange processes must be carefully controlled [1,3,4].

In theoretical engine cycles, heat rejection is often assumed to occur at constant volume, and intake-exhaust processes may be disregarded. However, in real-world engines, these processes can be modeled through energy equations, with the timing of intake and exhaust valve operations being a critical factor. Innovations such as the Atkinson cycle and fuel-efficient six-stroke engines have emerged by optimizing these processes [5-7].

The gas exchange process in a four-stroke engine is primarily controlled by the valve system. The intake system includes components such as the air filter, air ducts, throttle valve, intake manifold, and fuel injectors, while the exhaust system consists of the exhaust manifold, exhaust pipe, catalytic converter, and muffler. Pressure losses occur during the intake process, with significant drops observed in the intake port and valve [1-3,8].

Modern ICEs feature a variable camshaft mechanism, enabling adjustable valve timing. This allows real engines to deviate from theoretical valve timing to enhance volumetric efficiency. In these engines, the exhaust valve opens before Bottom Dead Center (BDC) and closes after Top Dead Center (TDC), while the intake valve opens before TDC and closes after BDC, creating valve overlap [1,2].

At partial load, exhaust pressure exceeds intake pressure, leading to backflow from the exhaust to the intake and reducing volumetric efficiency. At full load, the intake pressure is higher, resulting in fuel escaping into the exhaust and lowering performance. In high-performance engines, valves remain open longer to accommodate faster piston speeds. Early exhaust valve opening reduces the expansion ratio but also decreases pumping losses. Variable Valve Timing (VVT) technology optimizes valve timing based on engine speed and load conditions, improving volumetric efficiency, torque, and power. VVT systems adjust valve overlap, reducing it at idle and enhancing torque by closing intake valves earlier at low speeds, while closing them later at higher speeds to optimize volumetric efficiency [2,8].

Over the years, numerous studies have explored the impact of valve motion characteristics on engine performance and emissions, emphasizing the importance of valve parameters in optimizing engine efficiency. An experimental study examining the effects of valve lift found that increasing valve lift allows for greater air intake, enhancing power output [9]. Similarly, an increase in intake valve lift has been shown to improve volumetric efficiency, which in turn positively affects indicated power and combustion efficiency [10]. Research on valve timing has highlighted that the duration of intake and exhaust valve openings directly impacts charge purity and torque, with optimization leading to significant performance improvements [11,12]. In HCCI engines, variable cam mechanisms have been found to extend the operational range and enhance combustion stability, leading to lower emissions [13]. Moreover, a negative valve overlap strategy has been shown to enable knock-free operation in HCCI engines, improving their efficiency [14]. Research on methanol/gasoline blends has suggested that reducing valve lift prolongs the combustion process, enhancing fuel economy and thermal efficiency [16]. Additionally, a study on hydrogen-diesel dual-fuel operation found that increasing the hydrogen energy ratio and valve lift significantly reduced soot and CO emissions [17]. Continuously variable valve lift (CVVL) systems have also been shown to reduce pumping losses and substantially lower fuel consumption by increasing the maximum lift amount [18]. These findings underscore the potential of optimizing valve motion parameters—such as valve lift, timing, overlap duration, and opening duration—to improve engine performance while reducing fuel consumption and emissions. The integration of variable valve timing and lift systems holds significant promise for enhancing both conventional and alternative fuel engines.

This study aims to investigate the effects of valve motion characteristics on the performance of spark-ignition engines. The study models variables such as valve timing, valve lift, and valve opening duration using the one-dimensional gas dynamics simulation tool WAVE to assess their impact on full-load engine speed characteristics. The simulation design is then systematically analyzed through the Taguchi experimental design method to evaluate how these variables influence engine performance.

2. Materials and Methods

In this study, the WAVE simulation program, a one-dimensional gas dynamics simulation tool, was utilized to model and analyze the engine performance. WAVE is widely recognized and employed across a broad range of industrial sectors globally, including land transportation, railways, motorsports, maritime, and power generation. Its versatility makes it an invaluable tool for optimizing various engine systems. The program is capable of performing detailed performance and acoustic analyses for virtually any intake, combustion, and exhaust system configuration, providing engineers with crucial insights into system behavior and optimization opportunities [19].Furthermore, WAVE is built on the foundation of solving the one-dimensional form of the Navier-Stokes equations, which govern the mass, momentum, and energy transfer within compressible gas flows. This allows for the accurate simulation of fluid dynamics in complex flow environments. Additionally, the program includes advanced sub-models that specifically address combustion processes, fuel consumption, and emission formation, making it particularly useful for assessing the environmental impact of engine systems [8,20]. By incorporating these specialized models, WAVE can simulate real-world operating conditions with high precision, helping to optimize performance while minimizing negative emissions and fuel consumption.

A model of a single-cylinder direct injection engine, is shown in Figure 1, was utilized in this study. For this purpose, a pre-validated engine model available within the program was taken as a reference.

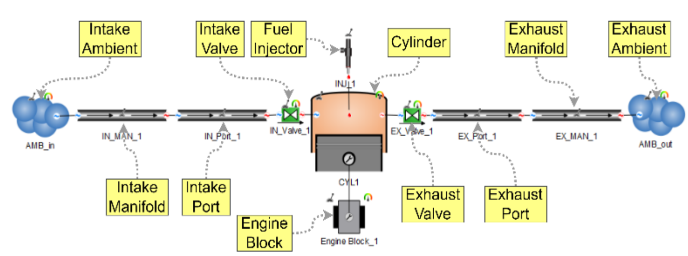

Figure 1. Simulation model created for a single-cylinder engine

Various dimensional specifications of the engine are presented in Table 1. Within the scope of this study, the duration, timing, and maximum lift values of the intake and exhaust valves were selected as independent variables. Additionally, engine speed was also considered an independent variable. The variations in key engine performance parameters were analyzed based on these independent variables. The specifications in Table 1 were used as control variables.

Table 1. Key dimensional characteristics of the engine used in the simulation model

Specification	Value
Stroke	82 mm
Cylinder Bore	78.1 mm
Connecting Rod Length	150 mm
Compression Ratio	10:1
Displacement	393 cm³
Intake Port Diameter	35 mm
Exhaust Port Diameter	28 mm
Intake Duration	280° CA
Exhaust Duration	300° CA
Intake Valve Opening	330° CA
Exhaust Valve Opening	100° CA
Intake Valve Clearance	0.15 mm
Exhaust Valve Clearance	0.20 mm
Maximum Intake Valve Lift	8.89 mm
Maximum Exhaust Valve Lift	8.64 mm
Rocker Arm Ratio	1:1
Injection Start	-100° CA
Injection Duration	20° CA
Injection Pressure	20 bar

In the simulation framework, mechanical friction losses were accounted for using the Chen–Flynn friction model, which provides a semi-empirical approach to estimating engine friction mean effective pressure (FMEP). The model decomposes total friction into components such as constant losses, speed-dependent losses, and load-dependent effects, allowing for a realistic representation of frictional behavior across varying engine conditions. This formulation is particularly effective in capturing the contribution of hydrodynamic lubrication and piston assembly friction. For combustion modeling, the Wiebe function was employed to simulate the rate of heat release, while heat transfer between in-cylinder gases and chamber walls was described using the original Woschni correlation.

The intake and exhaust valve motion curves of the reference engine were approximated using a cosine function to enable parametric analysis. The valve motion data of the reference engine were normalized within the range (-1,1).

$$x_{\mathrm{n}} = 2\left(\frac{x - \min x}{\max x - \min x}\right) - 1 \quad (1)$$

$$f(x_{\mathrm{n}}) = \cos\theta = s_{\mathrm{n}} = \cos(x_{\mathrm{n}}\pi) \quad (2)$$

The instantaneous velocity and acceleration values for the valves can be calculated as follows:

$$v_{\mathrm{n}} = -\omega\pi\sin(x_{\mathrm{n}}\pi)\,1 \quad (3)$$

$$a_{\mathrm{n}} = -\omega^2\pi^2\cos(x_{\mathrm{n}}\pi) \quad (4)$$

Figure 2 presents a comparison of the reference values, and the lift values obtained using the cosine function. Here, the coefficient of determination for the intake and exhaust valves is approximately 1.

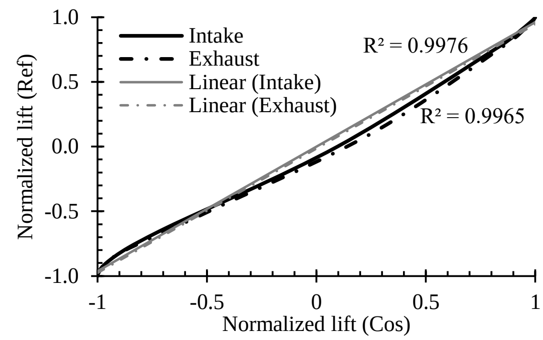

Figure 2. Comparison of Lift Values

The lift, velocity, and acceleration characteristics for the normalized values obtained using the cosine function are shown in Figure 3.

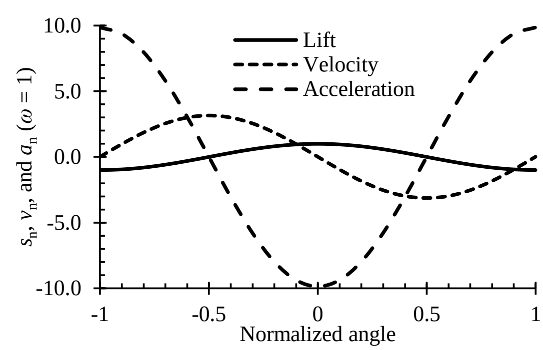

Figure 3. Normalized motion characteristics of the cosine function based on the normalized angle

Here, the normalized values have been converted to actual values for clarity. Figure 4 presents a comparison of the reference values and those obtained using the cosine function for the intake valve. This comparison highlights the consistency and accuracy of approximation. A similar trend is observed for the exhaust valve, confirming the reliability of the results for both valves.

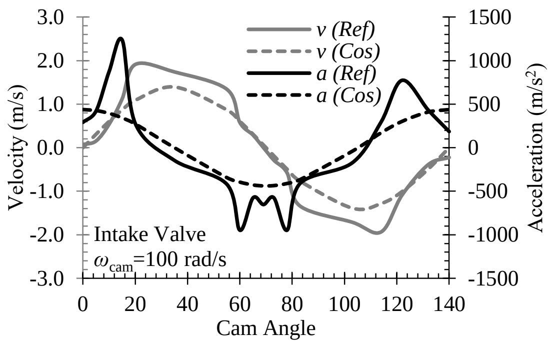

Figure 4. Velocity and acceleration curves for the intake valve

The large angular steps in reference valve motion data caused significant errors in the velocity and acceleration curves, hindering accurate engine performance analysis. However, by approximating the valve motion data using a cosine function, the velocity and acceleration profiles became smoother, improving the accuracy of the data and making the performance analysis more reliable.

In this study, a Design of Experiments (DoE) approach was employed to systematically assess the effects of independent variables on engine performance. A total of six independent variables were identified, with five distinct levels defined for each factor. Five of these variables were specifically related to the valve motion characteristics, including parameters such as valve duration, timing, lift, overlap, and the exhaust intake valve dynamics. The sixth variable, engine speed, was treated as a separate factor due to its direct influence on the gas exchange process and its interaction with valve motion characteristics. Given the inherent relationship between valve motion and engine speed, it was recognized that engine speed indirectly influences engine performance by modifying the pressure conditions during intake and exhaust cycles.

The primary objective of this study was to examine the individual and combined effects of valve motion characteristics on engine performance metrics, such as brake power, brake torque, volumetric efficiency, and brake-specific fuel consumption (BSFC). Consequently, the experimental design was focused on optimizing the five valve motion characteristics, excluding engine speed from the core analysis to allow for a more direct investigation of valve-related parameters. Table 2 presents an overview of the factor levels and how each variable's variation is expected to impact engine performance.

Table 2. Variables planned to be used for experimental design

Variable (Factors)	Values (Levels)	Unit
Engine Speed ($\omega = 2\omega_{\text{cam}}$)	100, 200, 300, 400, 500	rad/s
Valve Overlap Duration (α_{vol})	40, 55, 70, 85, 100	°CA
Max. Valve Lift (max s) (In)	7.5, 8.2, 8.9, 9.6, 10.3	mm
Valve Duration (α_{dur}) (In)	240, 260, 280, 300, 320	°CA
Max. Valve Lift (max s) (Ex)	7.2, 7.9, 8.6, 9.3, 10.0	mm
Valve Duration (α_{dur}) (Ex)	260, 280, 300, 320, 340	°CA

By narrowing the focus to valve motion characteristics, the study aimed to provide a clearer understanding of how these factors influence engine efficiency and overall performance.

Accordingly, for each engine speed, a total of $5^5 = 3125$ experiments would have been required. However, instead of conducting such many experiments using a traditional orthogonal array table, the Taguchi method, also known as a "robust" design method, was adopted. The Taguchi method is a widely used statistical approach in engineering that minimizes the number of required experiments while reliably analyzing the effects of independent variables on dependent variables. By applying this method, the required number of experiments was reduced from 3125 to only 25, allowing for the statistical determination of the effects of valve motion characteristics on engine performance and facilitating the identification of optimal design parameters. The Taguchi experimental design was conducted using Minitab statistical data analysis software. The L25 orthogonal array Taguchi experimental design created for each engine speed is presented in Table 3.

Table 3. Taguchi design

Valve Overlap	Intake Valve		Exhaust Valve	
	Maximum Lift (mm)	Duration (°CA)	Maximum Lift (mm)	Duration (°CA)
40	7.5	240	7.2	260
40	8.2	260	7.9	280
40	8.9	280	8.6	300
40	9.6	300	9.3	320
40	10.3	320	10.0	340
55	7.5	260	8.6	320
55	8.2	280	9.3	340
55	8.9	300	10.0	260
55	9.6	320	7.2	280
55	10.3	240	7.9	300
70	7.5	280	10.0	280
70	8.2	300	7.2	300
70	8.9	320	7.9	320
70	9.6	240	8.6	340
70	10.3	260	9.3	260
85	7.5	300	7.9	340
85	8.2	320	8.6	260
85	8.9	240	9.3	280
85	9.6	260	10.0	300
85	10.3	280	7.2	320
100	7.5	320	9.3	300
100	8.2	240	10.0	320
100	8.9	260	7.2	340
100	9.6	280	7.9	260
100	10.3	300	8.6	280

The simulation values presented in Table 3 were applied to each engine speed, generating a comprehensive set of 125 distinct solutions. This approach allowed for a thorough analysis of the impact of various valve motion characteristics on engine performance across different operating conditions.

3. Results and Discussion

The reference engine characteristics, including brake power, brake torque, brake specific fuel consumption (BSFC), and volumetric efficiency, were analyzed to provide a comprehensive evaluation of engine performance. In the initial phase of the study, the performance of the reference engine was compared with that of an engine where the valve motion had been modified using a cosine function. This comparison aimed to assess how changes in the valve motion function affected overall engine performance.

At a constant engine speed, the effects of key valve configuration parameters—such as duration, lift, and overlap—on brake power, brake torque, BSFC, and volumetric efficiency were thoroughly examined. The influence of valve timing on the combustion process and gas exchange efficiency was carefully assessed, with a focus on how various configurations contributed to overall engine performance.

In the subsequent phase of the study, Analysis of Variance (ANOVA) was applied to identify the most efficient operating conditions and determine the optimal valve configuration. This statistical analysis evaluated the impact of different valve parameters on engine performance and provided valuable insights into the most effective configurations. The results emphasize the significant role of the valve motion function in optimizing engine performance, offering important guidance for future engine design and valve timing optimization.

3.1. Performance characteristics of the reference engine

In Figure 5, the fundamental performance parameters of the reference engine (Ref) and the engine with the valve motion modified using a cosine function (Cos) are compared.

In terms of brake power, both the reference engine and the engine modified with the cosine function exhibited comparable performance, with the difference in their maximum values being less than 1%. This suggests that altering the valve motion using the cosine function has a negligible effect on the engine's power output. However, when evaluating brake torque, the reference engine produced a maximum torque of approximately 32.5 Nm, while the engine with the cosine-modified valve motion achieved a maximum torque of around 30.5 Nm. This represents a 6.15% reduction in torque, with the reference engine demonstrating a 5-7% higher torque, particularly at lower and medium engine speeds.

Regarding brake-specific fuel consumption (BSFC), the reference engine's minimum specific fuel consumption was approximately 0.245 kg/kWh, while the engine with the cosine-modified valve motion exhibited a minimum BSFC of 0.255 kg/kWh. This indicates a 4-5% increase in fuel consumption for the engine with the modified valve motion, suggesting a slight reduction in fuel efficiency compared to the reference engine.

In terms of volumetric efficiency, the reference engine reached a maximum volumetric efficiency of around 0.91, whereas the engine with the cosine-modified valve motion attained a maximum volumetric efficiency of 0.86. This results in a 5-6% reduction in volumetric efficiency, indicating that the modification to the valve motion led to less efficient gas exchange during the intake and exhaust processes.

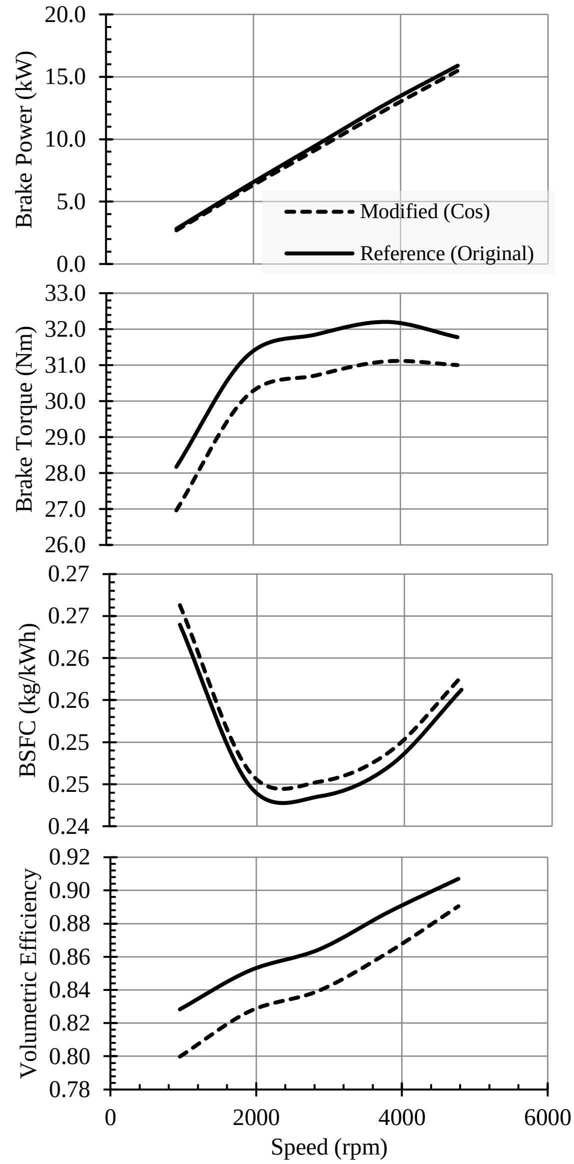

Figure 5. The effect of the valve motion on engine performance

When the valve motion curves of the reference engine were adapted to a cosine function, the resulting changes in engine performance characteristics were considered an important parameter for analyzing the effects of valve configuration. In this study, these performance variations were treated as a constant error and evaluated accordingly in the analysis. The impact of changes in the valve motion function on power output, torque characteristics, fuel consumption, and volumetric efficiency was examined in detail. The findings provide valuable insights for optimizing valve timing and improving overall engine performance.

3.2. The effects of valve motion configuration on engine performance characteristics

Engine performance varies directly depending on engine speed. Therefore, this section examines in detail the effect of valve timing configuration on engine performance at a constant engine speed. In the analyses conducted at a constant engine speed, an intermediate value of 2868 rpm (≈300 rad/s) was arbitrarily selected. A comprehensive evaluation for all engine speeds was not conducted in this section. Instead, a detailed discussion on the optimal configuration, including all engine speeds, is provided in the following section.

The effect of valve configuration on brake torque at a constant engine speed is shown in Figure 6. The analyses indicate that, except for one configuration, the brake torque varies within the range of 22-33 Nm across different configurations. The configuration that produces the maximum brake torque features an overlap of 85 degrees, an intake valve lift of 8.9-10.3 mm, an exhaust valve lift of 9.3-10 mm, an intake valve duration of 240-260 degrees, and an exhaust valve duration of 280-300 degrees. Examination of trend lines suggests that increasing overlap while reducing other parameters is advantageous for achieving higher brake torque.

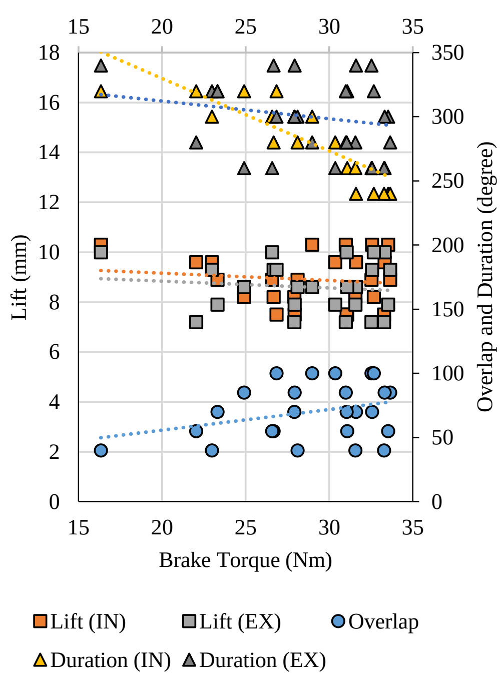

Figure 6. The effect of valve configuration on brake torque

A similar trend is observed for brake power as well. The effect of valve configuration on brake power at a constant engine speed is shown in Figure 7. Since brake power is a function of brake torque and engine speed, it follows the same trend as brake torque under constant-speed conditions. The analyses indicate that, except for one configuration, brake power varies within the range of 6.5-10 kW. The highest brake power is obtained in the configuration that also generates the maximum brake torque. These findings highlight the significant influence of valve timing and geometric parameters on overall engine performance.

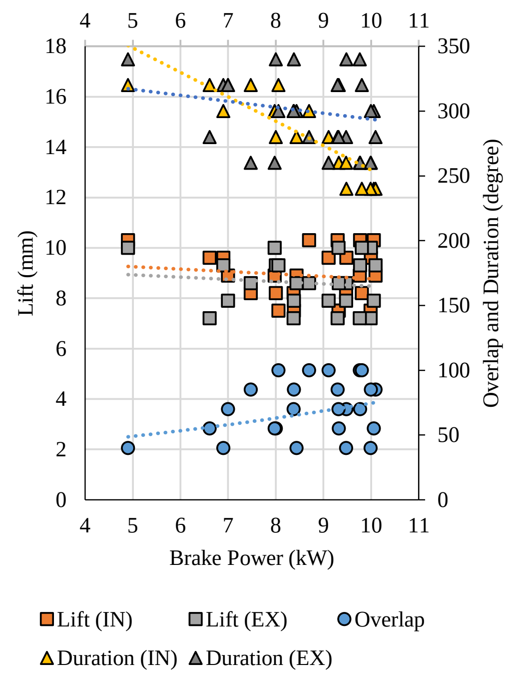

Figure 7. The effect of valve configuration on brake power

The effect of valve configuration on brake specific fuel consumption (BSFC) at a constant engine speed is illustrated in Figure 8. BSFC is a crucial parameter that represents the fuel efficiency of an engine, as it quantifies the amount of fuel consumed per unit of power output. Lower BSFC values indicate improved combustion efficiency and more effective energy conversion. The analysis reveals that minimum BSFC is achieved when the valve timing and lift parameters fall within specific ranges. In particular, the overlap is in the range of 85-100 degrees, the intake valve lift is between 8.9-9.6 mm, the exhaust valve lift falls within 9.3-10 mm, the intake valve duration is between 240-260 degrees, and the exhaust valve duration ranges from 280-300 degrees. These values suggest that a well-balanced valve timing strategy plays a critical role in optimizing fuel consumption while maintaining effective engine performance. Examining the trend lines, it is evident that increasing overlap while reducing other parameters contributes to a lower BSFC, thereby enhancing fuel economy under constant engine speed conditions. This implies that an optimized valve configuration can reduce pumping losses, improve charge dilution, and enhance the scavenging process, leading to better air-fuel mixing and more complete combustion. Consequently, fine-tuning valve events can significantly impact engine efficiency and fuel consumption, reinforcing the importance of precise valve timing control in engine design and calibration.

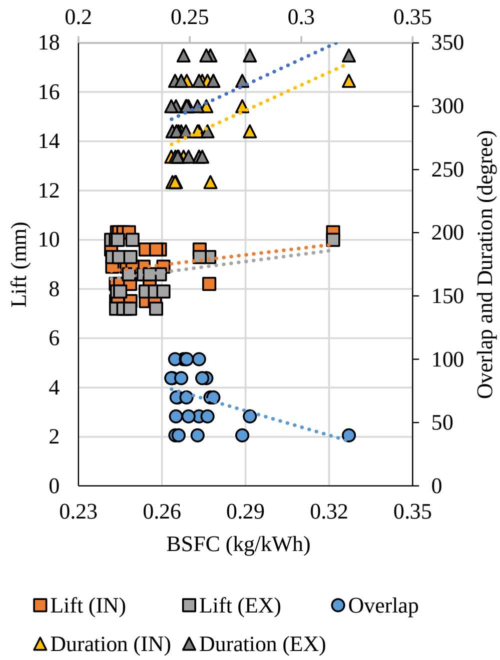

Figure 8. The effect of valve configuration on BSFC

Figure 9 illustrates the effect of valve configuration on volumetric efficiency at a constant engine speed. Volumetric efficiency is a critical parameter that represents the ratio of the actual air-fuel mixture intake to the theoretical maximum capacity of the cylinder. A higher volumetric efficiency allows the engine to take in more air, leading to improved combustion efficiency and increased power output. The analysis indicates that minimum volumetric efficiency occurs when specific valve timing and lift parameters are applied. In particular, overlap is within the range of 55-70 degrees, intake valve lift is between 9.6-10.3 mm, exhaust valve lift falls within 7.9-8.6 mm, intake valve duration is set at 240 degrees, and exhaust valve duration ranges between 300-340 degrees. These values highlight the significant influence of valve timing and lift on volumetric efficiency.

Examining the trend lines, it is evident that achieving maximum volumetric efficiency is favored by increasing the overlap while reducing other parameters. An increase in overlap enhances cylinder filling by allowing a greater volume of fresh air-fuel mixture to enter, while reducing other parameters helps prevent excessive exhaust gas retention in the cylinder, leading to a more efficient combustion process. This underscores the importance of optimized valve timing and lift strategies, particularly in high-performance engine applications, to maximize volumetric efficiency and improve overall engine performance.

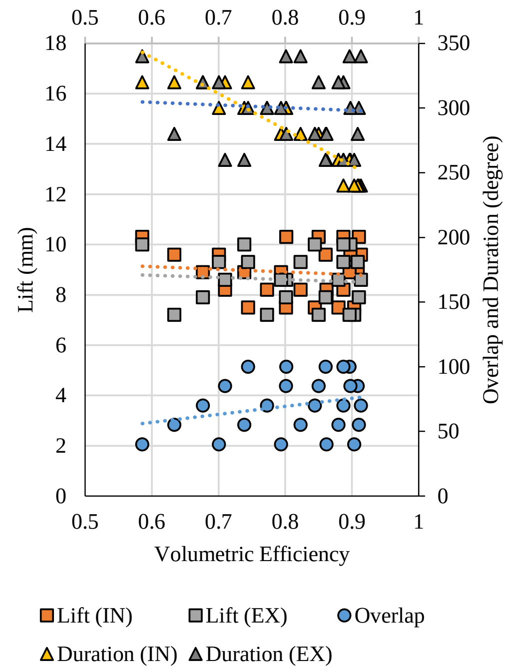

Figure 9. The effect of valve configuration on volumetric efficiency

The required valve overlap, duration, and lift values for achieving maximum power, maximum torque, minimum BSFC, and maximum volumetric efficiency are shown in Figure 10. For engine performance optimization, an overlap of 85 degrees is generally considered appropriate. This value serves as a suitable starting point to ensure efficient engine operation, enhancing both torque and power output. However, it is challenging to assign a single value to the other valve parameters, as their interrelationships and the operating conditions of the engine directly influence performance.

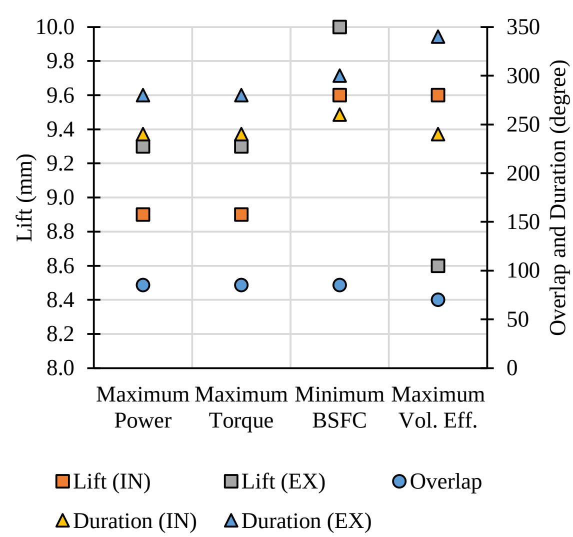

Figure 10. Valve configurations based on engine characteristics

The analysis for minimum BSFC and maximum volumetric efficiency reveals that the lift and duration values need to be higher than those selected for maximum power and maximum torque. This indicates that increasing valve lift and duration is advantageous for achieving better air-fuel mixture intake and combustion efficiency. Higher duration and lift values allow more air-fuel mixture to enter the cylinder, which enhances combustion efficiency and contributes to greater energy production. However, increasing these values may also impact fuel consumption and exhaust emissions, so an optimal balance must be achieved.

Therefore, optimizing the valve configuration parameters and carefully selecting them based on various engine performance criteria is crucial for enhancing engine performance.

3.3. Determination of the optimum valve configuration

In this study, Taguchi experimental design was applied for each engine speed to investigate the effects of various valve parameters on engine performance (see Table 2 and Table 3). For instance, at an engine speed of 100 rad/s (954 rpm), independent variables such as valve overlap, intake valve lift, intake valve duration, exhaust valve lift, and exhaust valve duration were considered to maximize dependent variables, including brake torque (performance indicator), brake thermal efficiency (economy indicator), and volumetric efficiency (quality indicator). The Signal-to-Noise Ratio (SNR) values, which evaluate the contribution of each parameter to engine performance, were recorded for this case. The results are presented in Table 4, demonstrating the interaction between different parameters and how optimizing each one affects engine efficiency.

The "Larger-is-better" criterion was selected in this study due to its suitability for maximizing engine performance. This criterion assumes that larger response values are better, making it ideal for situations where the goal is to increase performance indicators such as brake torque, brake thermal efficiency, and volumetric efficiency. As these dependent variables increase, the engine is considered to be operating more efficiently and performing better. Therefore, the "Larger-is-better" criterion was chosen to optimize the valve parameters in a way that enhances the overall performance, economy, and quality of the engine.

$$\mathrm{SNR} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{5}$$

In this Eq. 5 for the Signal-to-Noise Ratio (SNR) used in the “Larger-is-better” criterion, the variables are defined as follows: n denotes the number of experimental repetitions or trials, reflecting the number of times the experiment is conducted to ensure more reliable and consistent results. y_i represents the observed value of the response variable for the i-th trial, which corresponds to the measured value of the dependent variable (e.g., brake torque, brake thermal efficiency, volumetric efficiency) for each individual experiment. The SNR itself is a measure used to assess the quality of the experimental response. In the context of the “Larger-is-better” criterion, a higher SNR signifies that the response is closer to the desired target and less influenced by variability or noise. The formula evaluates the impact of the experimental parameters on the response, with a higher SNR indicating an optimal performance where the desired outcome is maximized, and variability is minimized.

In Table 4, the Delta value represents the significance (effect) of each factor. A higher Delta value indicates that the factor is more influential. The Delta value (ΔSNR) is defined as the difference between the maximum and minimum SNR values.

$$\Delta\mathrm{SNR} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{6}$$

It is observed that the intake valve angular open duration is more effective than the other factors in achieving maximum values for the dependent variables—brake torque, brake thermal efficiency, and volumetric efficiency. The levels at which the SNR values are highest indicate the optimum settings necessary for the best engine performance. According to Table 4, the level configuration selected for 954 rpm (highlighted in bold) is 5-1-1-2-3.

Table 4. SNR values and importance ranking for 954 rpm speed

Level	Overlap	Intake Valve		Exhaust Valve	
		Lift	Duration	Lift	Duration
1	1.8443	**2.6927**	**3.8217**	2.3275	2.4698
2	2.0955	2.4328	3.4551	**2.5016**	2.3416
3	2.4287	2.2412	2.7688	2.4996	**2.5330**
4	2.6904	2.1596	1.6746	2.3878	2.2304
5	**2.8696**	2.2424	0.0484	2.0521	2.1938
Delta	1.1852	0.5330	3.7733	0.4495	0.3391
Rank	2	3	1	4	5

It is observed that the least influential parameters for achieving the highest values of brake torque, brake thermal efficiency, and volumetric efficiency are the exhaust valve-related factors. To verify the reliability of the SNR values, an ANOVA was conducted. Additionally, when examining the significance level (P-value) and importance value (F-value), it was determined that the intake valve duration and valve overlap factors are the most influential, while exhaust-related factors are the least effective. The SNR (Signal-to-Noise Ratio) delta is a quantitative metric used within the Taguchi method to evaluate the relative impact of each control factor on the system output. The term “delta” refers to the difference between the average SNR values obtained at different levels of a given factor. This difference indicates the magnitude of the factor’s effect on the performance of the system. In essence, the larger the delta value, the more significant the influence of that factor. Therefore, SNR delta analysis is utilized in the design of experiments to rank and prioritize factors based on their importance for optimization. Table 5 presents the SNR delta values.

The delta SNR helps identify the influence of individual factors on performance. Among all engine speeds analyzed, the Intake Valve Duration exhibits the highest delta SNR values, indicating that it is the most significant parameter affecting engine performance. However, its influence tends to decrease as engine speed increases. The Overlap parameter has a more prominent effect at lower speeds, while its impact diminishes at higher rpm. In contrast, the Exhaust Valve Duration gains prominence at higher speeds, reaching its highest delta value at 4774 rpm, highlighting its importance in high-speed engine performance. Intake and exhaust valve lifts show relatively lower delta SNR values, indicating they are less influential compared to other parameters. These results demonstrate that different valve timing parameters become more influential depending on engine speed, suggesting that such variability should be considered in optimization strategies.

Table 5. ΔSNR values

Speed (rpm)	Overlap	Intake Valve		Exhaust Valve	
		Lift	Duration	Lift	Duration
954	1.18524	0.53309	3.77332	0.44958	0.33919
1909	0.94540	0.47250	3.03030	0.40950	0.30880
2864	0.82900	0.42500	2.63800	0.39900	0.29600
3819	0.77300	0.46100x	2.30200	0.48800	0.38400
4774	0.72800	0.42000	1.85800	0.55400	0.44000

Important results of the ANOVA for other engine speeds are presented in Figure 11.

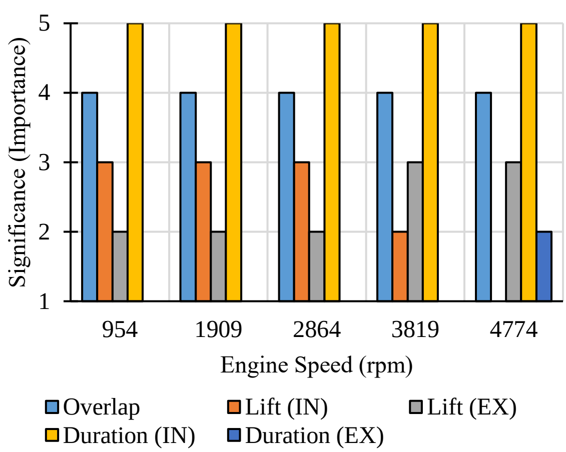

Figure 11. Results of the ANOVA

The most influential factor for achieving the highest brake torque, brake thermal efficiency, and volumetric efficiency is the intake valve lift duration. Determining the intake valve lift duration is critical for each engine speed. Additionally, valve seating is another important factor for optimizing engine performance. The importance of the intake valve maximum lift decreases at higher engine speeds, while the significance of the exhaust valve maximum lift increases with higher engine speeds. The factor with the least effect on engine performance is the exhaust valve lift duration.

Table 6 presents the factor levels determined to achieve optimal engine performance at various engine speeds, separately for each engine. These values represent the optimum conditions based on previously defined factors and their respective levels. If the optimization had been conducted separately for brake torque, brake thermal efficiency, and volumetric efficiency, the resulting values might have been different. However, since the primary objective of this study is to identify the optimal conditions under which all three parameters are simultaneously high, separate performance evaluations for each parameter were not carried out.

Table 6. Optimal parameter levels

Speed (rpm)	Overlap	Intake Valve		Exhaust Valve	
		Lift	Duration	Lift	Duration
954	100	7.5	240	7.9	300
1909	100	7.5	240	8.6	300
2864	100	7.5	240	7.9	300
3819	85	7.5	240	8.6	300
4774	85	7.5	260	7.9	300

In Figure 12, a comparison of engine performance is made between the optimum values presented in Figure 11 and the original values of the reference engine.

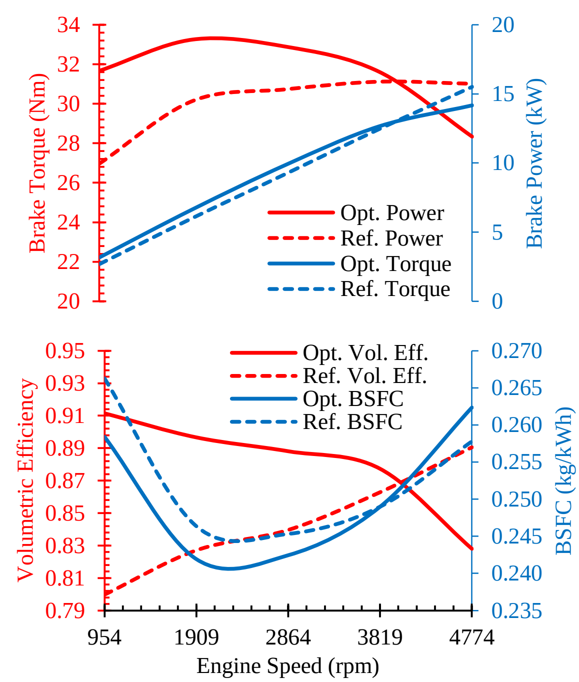

Figure 12. Engine performance for the optimum values and the original values of the reference engine

At higher engine speeds, the reference engine's original values exhibited better performance. However, at low and medium engine speeds, a significant improvement in engine performance is observed. Specifically, at these speeds, an 8.1% improvement in brake power and brake torque, a 1.5% improvement in brake thermal efficiency, and a 6.8% improvement in volumetric efficiency are observed. Achieving optimal values for volumetric efficiency, brake thermal efficiency, and brake torque simultaneously is challenging. However, as shown in the graphs of Figure 12, it is possible to achieve a suitable valve motion configuration to enhance overall engine performance.

4. Conclusion

This study explores the intricate relationship between valve motion characteristics and engine performance in spark ignition engines, specifically focusing on the direct injection spark ignition (DISI) engine model incorporated into the WAVE simulation program. The model used was rigorously validated for accuracy, ensuring reliable results throughout the experimentation. Initial performance tests were conducted using the engine's original valve motion profiles, which were then modified by approximating them to a cosine function for easier analytical solvability. A comparison of performance outcomes between the original and modified valve motion profiles revealed a slight reduction of approximately 3% in overall performance following the modifications.

The primary objective of this research was to identify how various valve motion characteristics affect engine performance. To achieve this, five independent variables were carefully chosen based on valve motion dynamics: valve seat contact, intake valve lift, exhaust valve lift, and their respective durations. These factors were analyzed separately for a fixed engine speed of 200 rad/s to determine their individual impacts on engine performance. The results showed that increasing valve seat contact time by 42% led to an improvement of approximately 5.5% in engine performance. Conversely, a 15.7% reduction in intake valve lift resulted in a modest performance improvement of 0.6%. A 14.3% reduction in intake valve duration led to a significant performance increase of approximately 10.2%. However, modifications to exhaust valve lift and duration, whether increased or decreased, consistently reduced engine performance.

The findings indicated that modifying valve motion characteristics alone does not provide an optimal solution for engine design, as it fails to account for other essential factors influencing engine performance. Therefore, the study incorporated the Taguchi experimental design methodology, resulting in a total of 125 solutions, with 25 solutions per engine speed. Three distinct engine performance parameters—brake torque, brake thermal efficiency, and volumetric efficiency—were selected for evaluation. Brake torque was considered the primary performance parameter, brake thermal efficiency as the economic indicator, and volumetric efficiency as a measure of engine quality. The goal was to optimize all three parameters to be as high as possible, balancing performance, fuel economy, and engine quality.

Variance analysis revealed that valve seat contact and intake valve duration were the most influential parameters in improving engine performance. Specifically, increasing valve seat contact time and reducing intake valve duration produced the most significant improvements when compared to the reference engine with its original configuration. Interestingly, exhaust valve characteristics had a more pronounced effect on engine performance at higher engine speeds, indicating that their influence becomes more important in high-speed conditions.

The determination coefficients calculated from the variance analysis consistently exceeded 95%, ranging from 99.19% to 95.39% depending on the engine speed. This high level of statistical confidence further supports the importance of valve motion characteristics in optimizing engine performance.

Despite the valuable insights gained from this study, its scope is inherently limited to the effects of valve motion characteristics alone. As is well-established in internal combustion engine design, three critical aspects must be considered: performance, economy, and environmental impact. While this research primarily focused on performance, the environmental implications—particularly exhaust emissions—were not addressed. Given the study's reliance on a simplified engine model based on several assumptions, the results might not fully represent real-world conditions.

To gain a more comprehensive understanding of engine behavior, real-world testing is necessary to validate the findings. Furthermore, employing advanced simulation methods, such as three-dimensional computational fluid dynamics (CFD), would provide more detailed and accurate predictions, offering deeper insights into how different valve motion configurations can impact engine performance, fuel efficiency, and emissions.

Building on the findings of this study, future research should extend the focus beyond performance improvements resulting from modifications to valve motion characteristics, incorporating the broader impacts on engine efficiency and environmental sustainability. One potential avenue for future work involves investigating exhaust emissions and their relationship to changes in valve motion. Understanding how modifications to valve motion influence pollutant formation—such as NOx, CO_2, and particulate matter—would offer valuable insights into the environmental trade-offs of optimizing engine performance.

Future studies should also explore the effects of more complex valve motion profiles, such as those involving variable valve timing (VVT) and valve lift modulation. These techniques, which allow for dynamic adjustments to valve timing and lift throughout the engine's operation, have the potential to yield substantial improvements in both performance and fuel economy. Investigating the synergy between these advanced valve motion strategies and the optimized configurations identified in this study could lead to more versatile and efficient engine designs.

Another important direction for future research is the application of advanced simulation methods, including three-dimensional CFD, to model the internal combustion process in greater detail. By incorporating finer details of the flow dynamics and heat transfer mechanisms within the engine, CFD simulations could provide deeper insights into the interaction between valve motion characteristics and the combustion process, thereby facilitating the development of more accurate predictive models. Moreover, integrating multi-physics simulations that combine CFD with structural analysis and thermal modeling could provide a more holistic understanding of engine performance and reliability.

Real-world validation through experimental testing is also critical. While this study relied on a simplified engine model, future research should validate the findings using prototype engines equipped with the modified valve motion profiles. Such experimental validation would ensure that the theoretical benefits observed in simulations translate into tangible improvements in real-world engine performance.

Finally, future studies should focus on investigating the long-term durability and reliability of engines with modified valve motion characteristics. Prolonged operation under varying conditions will provide a clearer picture of potential trade-offs in terms of component wear and overall engine life, which are crucial considerations in any engine design process.

In conclusion, while this study has provided valuable insights into the relationship between valve motion characteristics and engine performance, further research is needed to explore the broader implications of these modifications, particularly in terms of exhaust emissions, environmental impact, and real-world engine performance. Utilizing more advanced simulation techniques and real-world experimental data is crucial for achieving more accurate and reliable results, paving the way for the development of more efficient and environmentally friendly engine designs.

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Nomenclature

CA	: crank angle
R^2	: coefficient of determination
a_n	: normalized instantaneous acceleration
s_n	: normalized instantaneous lift
v_n	: normalized instantaneous velocity
ANOVA	: analysis of variance
BSFC	: brake specific fuel consumption (kg/kWh)
EX	: exhaust valve
IN	: intake valve
SNR	: signal to noise ratio

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Şule Akar: Conceptualization, Writing-original draft, Supervision,
Emre Arabacı: Conceptualization, Supervision, Validation,

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