Airo International Journal
Peer-Reviewed
Multidisciplinary

ISSN: 2320-3714
Volume: 1 Issue: 2
February 2026
Impact Factor: 10.2
Subject: Engineering

ANALYZING ENGINE PERFORMANCE USING DIGITAL TWIN–BASED VALVE MODELING IN INTERNAL COMBUSTION ENGINES

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ABSTRACT

Improved fuel efficiency, reduced emissions, and improved reliability of internal combustion engines have promoted the use of high monitoring and simulation technology. The paper introduces a digital twin-based model of the valve modeling that can be used in the analysis of internal combustion engine performance. Virtual replica of the engine valve train is created through the combination of real-time sensor data and mathematical models of physics that describe the processes of valve lift, timing and gas exchange. The model predicts engine behavior at different speed and load conditions and compares the important performance parameters such as brake power, torque, brake thermal efficiency and specific fuel consumption. The results of simulations suggest that the valve timing and lift of the engine are optimized to a great extent, which not only enhances the amount of volumetric efficiency and overall engine performance but also results in some efficiency loss that could be perceived. The digital twin allows also early wear detection of the valves and timing errors and facilitates predictive maintenance and mitigates the threat of mechanical failure. The results reveal that digital twin-based models of valves can be used as a useful tool to make predictions of real-time performances, engine optimization, and intelligent maintenance planning, which will help to create an efficient and sustainable internal combustion engine system.

Keywords: *Digital Twin, Internal Combustion Engine, Valve Modeling, Engine Performance, Predictive Analysis.*

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1. INTRODUCTION

It is still true that internal combustion engines (ICEs) are still common in cars, farm machinery, power production, and industry because of their reliability, high energy density, and infrastructure. Nevertheless, the emission regulations and fuel economy have made more efficient engine systems and engine systems which are intelligently controlled more essential. The main problem in the engineering of the present-day mechanical world has thus been to improve engine performance as well as to cut down the amount of fuel used as well as the amount of exhaust gas.

The traditional techniques of engine analysis primarily rely on the work of dynamometer testing and numerical models of one-dimensional gas dynamics and computational fluid dynamics (CFD). Experimental testing is also expensive and time consuming and simulation models might not necessarily reflect actual operating conditions due to uncertainty like wear and environmental changes although useful. Therefore, an approach that aids in the combination of actual operating information and calculational modeling is needed.

The digital twin technology is one such solution by producing a dynamic virtual copy of a real engine that continuously communicates real-time information using sensors. This allows monitoring, performance forecast and controlled optimum without disruption to engine operation. The valve train is a particularly important engine subsystem since the timing and lift of the valves directly influence air intake and exhaust flow which affect volumetric efficiency, combustion quality, power production, fuel consumption, and emissions. The slightest irregularities of valve action may result in a detectable loss of performance.

1.1.Objectives of the Study

The objectives of the research are:

- To develop a digital twin–based valve model for an internal combustion engine.
- To study the effect of valve timing and lift on engine performance parameters.
- To assess real-time performance prediction and predictive maintenance capability.

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2. LITERATURE REVIEW

Matulić (2020)created a framework of building a digital twin of a combustion engine with a goal of real-time diagnostic systems. To provide continuous monitoring of the operational parameters, the study had combined sensor measurements with a model of a computational engine. It had shown that the digital twin was able to identify abnormal engine behavior and anticipate possible faults before failure took place. It was noted in the work that the combination of physical engine data and mathematical modeling is essential to enhance reliability and lower the time of maintenance.

Altosole et al. (2022) used a digital twin in the diagnosis of a marine diesel engine. They had used operational data provided by onboard sensors to develop a virtual environment of the engine to be used in condition monitoring. The outcomes had established that the digital twin was able to detect performance deterioration such as inefficiencies in combustion and wear of the components. The authors had established that digital twin technology could be useful in enhancing the maintenance planning and operational safety, and particularly in large marine propulsion systems.

Tran, et al. (2023) provided the review of digital twin applications in the internal combustion engines. Their work had reviewed the recent advances in modeling, monitoring and optimization of engines with the help of virtual replicas. They had stated that the digital twins allowed the real-time prediction of performance, estimation of emissions, and fault diagnosis. The review however also had pointed out that the majority of current studies were done on general engine performance with little detailed subsystem modelling, especially valve train modelling.

Bondarenko and Fukuda (2020) created a digital twin of a diesel engine to forecast the dynamics of the propulsion system. The scientists had developed a physics model of simulation that was matched with actual working data. Their research had demonstrated that the digital twin was able to forecast engine dynamic behavior with accurate predictions in different load conditions. The research had also pointed out that real-time synchronization between the physical engine and virtual model enhanced the accuracy of prediction and proactive maintenance strategies.

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3. DIGITAL TWIN FRAMEWORK FOR VALVE MODELING

The digital twin system created in this paper is a coordinated communication between the physical internal combustion engine and the virtual one. This system is based on gathering working information on the physical engine and feeding it into communication networks, which then update a high-fidelity model of computation. This real time interaction allows monitoring, prediction and optimization of engine performance. The framework consists of three main components, namely the physical system, the virtual valve model and the data communication and integration layer.

3.1. Physical System

The physical system comprises of four stroke internal combustion engine that is fitted with sensors to record actual operating conditions. There are sensors in strategic positions close to the valve train, intake manifold, exhaust manifold and crankshaft to check the engine behavior.

The measurements obtained are as follows:

- Valve lift (valve lift sensor or LVDT)
- Crankshaft position and crank angle (crank angle encoder)
- Out-cylinder pressure (pressure transducer)
- The temperature of intake and exhaust gas (thermocouples)
- Engine speed (tachometer)
- Airflow rate (mass airflow sensor)

Such sensors deliver real-time running data when engines are in operation like when at idling, partial load and full load. The information that is gathered are the boundary conditions and input validation to the virtual model.

3.2. Virtual Valve Model

A mathematical model of the valve train and gas exchange mechanism is the virtual valve model, which is a physics-based mathematical model. It is used to simulate the kinematic movement of the cam-follower-valve system and predicts the entering and leaving airflow into and out of the combustion chamber.

Valve lift is determined as a function of angle of cam rotation:

$$L(\theta) = L_{max} \sin \left(\frac{\pi(\theta - \theta_o)}{\theta_c - \theta_o}\right)$$

where:

- $L(\theta)$= valve lift at crank angle θ
- L_{max}= maximum valve lift
- θ_o= valve opening angle
- θ_c= valve closing angle

Compressible flow relations are used to model the flow of air through the valve:

$$\dot{m} = C_d A_v \sqrt{2\rho(P_{in} - P_{cyl})}$$

where:

- $\dot{m}$= mass flow rate
- C_d= discharge coefficient
- A_v= effective valve flow area
- ρ= air density
- P_{in}= intake manifold pressure
- P_{cyl}= cylinder pressure

The virtual model is thus predictive of volumetric efficiency, quality of combustion, and performance production. The model also considers the valve spring stiffness, the inertia forces and damping to have a dynamic valve behavior at various engine speeds.

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3.3. Data Communication and Integration Layer

The physical engine is interconnected to the virtual model via the communication layer that gives a real-time data exchange system. A sensor feed is sent to a data acquisition (DAQ) unit into a computational platform where the digital twin is run. There are communication protocols like CAN bus or internet of things-based networks which can constantly transfer operational data.

The sensor information obtained is received and utilized to perform a change in the model parameters such as pressure, temperature, engine speed and valve position. This is the process of updating which is called synchronization. By means of the synchronization, the virtual engine acts like the actual engine at any given moment.

The digital twin carries out the following functions:

- Prediction of real-time engine performance.
- Abnormal valve functioning identified.
- Efficiency losses estimation.
- Maintenance requirement prediction.

The system is able to predict the performance of the system even in untested operating conditions through sensor data integration with simulation models, without the need to make use of extensive experimental trials.

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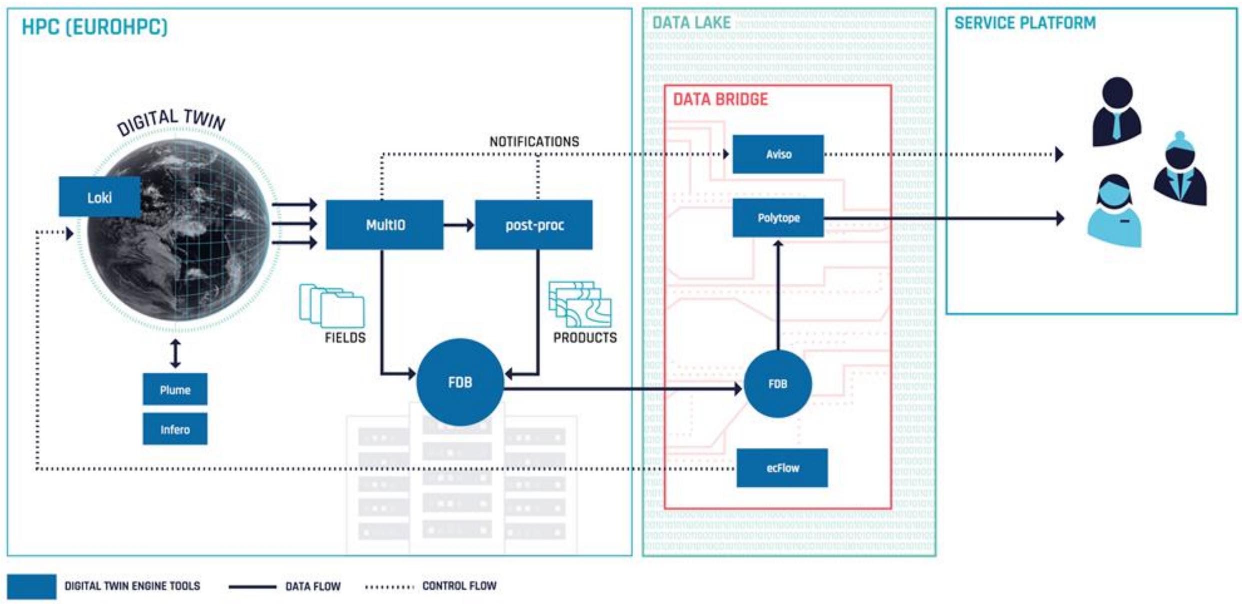

Figure 1: Digital twin architecture for internal combustion engine valve modeling.

4. RESEARCH METHODOLOGY

The analysis is based on simulation-based methodology, combined with actual engine parameters to analyze the engine performance on a digital twin model of a valve based on digital twin. The methodology primarily involves construction of the model, engine working simulation and performance analysis.

4.1. Model Development

Internal combustion engine geometry and operating data are first used to build a digital twin of the engine. Cylinder bore; stroke length, compression ratio, and valve timing are some of the parameters that are included in the computational model. The crank-slider system is modeled to obtain piston position and instantaneous cylinder volume that are needed in calculating the pressure and combustion.

4.2. Integration of Valve Timing and Lift

The digital twin is then incorporated with the valve train behavior. The functions of crank angle are the intake and exhaust valve opening and closing and the lift profiles. These traits define the

ISSN: 2320-3714
Volume: 1 Issue: 2
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inlet of air into the cylinder and the elimination of exhaust gases and are directly related to volumetric efficiency and quality of combustion.

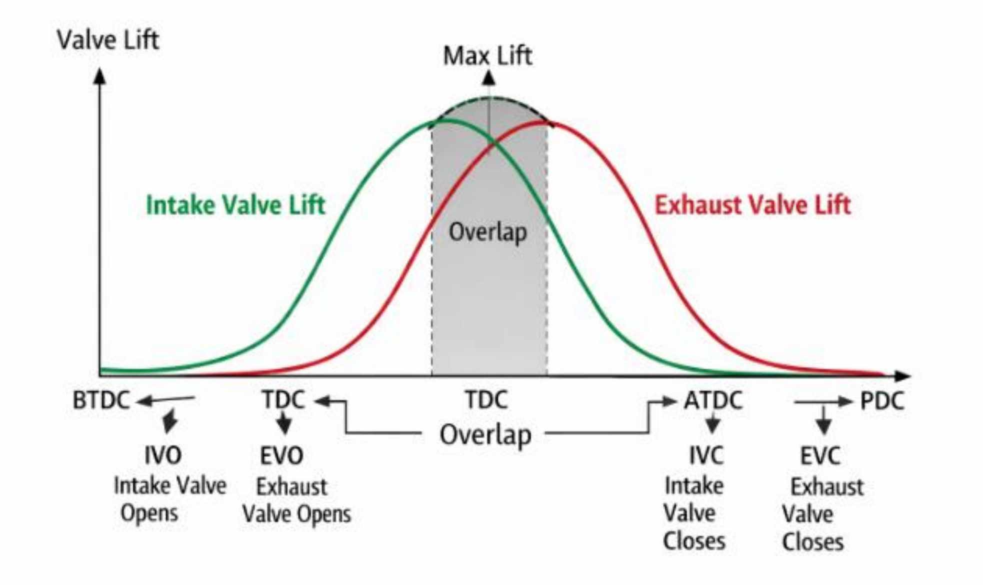

Figure 2: Valve timing and lift characteristics used in the digital twin model

4.3. Simulation of Engine Operation

The digital twin developed is simulated at varying engine speed levels (1500 rpm, 2000 rpm and 2500 rpm) and load levels. The model gives predictions on the cylinder pressure, airflow rate, and behavior of combustion taking into account the valve dynamics and flow resistance.

4.4. Performance Evaluation

The performance of the engine is measured on the usual parameters of brake power, torque, brake thermal efficiency, and brake specific fuel consumption. The results of the digital twin are compared with predicted engine behavior to determine efficiency losses and potential problems with valves.

5. RESULTS AND DISCUSSION

The digital twin-based valve model was developed to test the performance of the internal combustion engine. Measurement of standard engine performance was also taken into

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Volume: 1 Issue: 2
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consideration so as to identify the efficiency of the engine to convert the chemical energy of the fuel into some useful mechanical energy as well as to observe how the valve behavior affects the overall performance.

5.1. Indicators of Engine Performance

Table 1 presents the main performing parameters that were examined in the research.

Table 1: Engine performance parameters considered in the study

Parameter	**Description**
Brake Power (BP)	Useful power output available at the crankshaft
Brake Torque (T)	Rotational force produced at the crankshaft
Brake Thermal Efficiency (BTE)	Ratio of brake power to the fuel energy supplied
Specific Fuel Consumption (SFC)	Fuel consumed per unit brake power output

Brake power is the real mechanical power of the engine, and it was computed as in below:

$$BP = \frac{2\pi NT}{60}$$

where $N$is engine speed (rpm) and $T$is brake torque (N·m).Brake thermal efficiency was a measure of the ratio of the energy converted to fuel to mechanical work:

$$BTE = \frac{BP}{\dot{m}_f \times CV}$$

Increased BTE meant better combustion and effective exchange of gases as a result of the intake and exhaust valves.Specific fuel consumption was used to measure fuel economy:

$$SFC = \frac{\dot{m}_f}{BP}$$

Poor timing of valve timing diminished the amount of air entering, led to the partial combustion experienced and consequently led to high consumption of the fuel.

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5.2. Simulation Performance Results

The digital twin concept was emulated on three operating speeds, that is, 1500 rpm, 2000 rpm, and 2500 rpm. Table 2 demonstrates the influence of valve timing and valve lift on the engine performance.

Table 2: Effect of valve modeling on engine performance

Engine Speed (rpm)	Brake Power (kW)	Brake Thermal Efficiency (%)
1500	18.2	28.5
2000	24.6	30.1
2500	29.8	31.4

These findings suggested that the power of the brakes was proportional to the speed of the engine since a greater amount of air-fuel mixture was pushed into the cylinder in a given period of time. Adequate valve lift and proper duration of valve opening enhanced the efficiency of the volumetric capacity and this led to improved combustion and increase in force. This also helped to improve brake thermal efficiency as engine speed was increased because of further complete combustion. Lower velocities resulted in delayed opening of the valves, limiting air to enter the cylinder, lowering the power output and the pressure of combustion.

During increased speed, the loss of charge due to the improper closing of the valves occurred and led to the mixing of the exhaust gases, which resulted in low efficiency. These changes were continuously tracked by the digital twin and forecasted performance fluctuations before severe degradation of performance took place.

5.3. Predictive Maintenance and Optimization

A significant measure of the digital twin framework was that it facilitated predictive maintenance. Constant checking of data provided by the real engine and the simulated behavior helped to identify the presence of abnormal valve functioning at the initial stage.

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Table 3: Predictive maintenance indicators using digital twin analysis

Maintenance Indicator	Digital Twin Output
Valve Wear	Gradual reduction in valve lift
Timing Deviation	Phase shift in valve opening/closing
Performance Drop	Predicted decrease in brake power

As an example, the valve seat wear caused slow but consistent decrease in the effective valve lift, thereby decreasing the flow of air into the cylinder. The digital twin noticed this decrease and forecasted the decrease of brake power and efficiency. On the same note, the wear on the camshaft or chain elongement led to a change in the opening and closing angle of the valves, which the digital twin was able to detect right away.

Consequently, maintenance would be done in advance before mechanical failure was experienced. This strategy avoided sudden failures, minimized downtime of the operations and enhanced engine performance. Also, the system enabled optimization of the valve timing and operating conditions, which ensured that the engine ran at its full efficiency. In general, the outcomes showed that the development of the digital twin-based valve modeling contributed to much better performance monitoring, the opportunity to detect potential faults early, and intelligent engine control and the further sustainability of operational efficiency.

6. CONCLUSION

The research examined the use of a digital twin-based framework of valve modeling to analyze and optimize internal combustion engine performance. The developed digital twin could predict engine performance at various speeds and operating conditions and cruise conditions through the combination of real-time sensor information and a physics-based virtual representation of the valve train, enabling it to calculate the main performance parameters which include brake power, torque, brake thermal efficiency and specific fuel consumption. It was found that an adequate valve timing and lift considerably increases the volumetric efficiency and combustion quality, which translates to improved power output and fuel economy and that any deviation due to wear or improper adjustment yields performance that is quantifiable. The digital twin also exhibited the ability to identify abnormal valve behaviour early and anticipate maintenance needs, which minimized the potential of having an unexpected failure and unplanned downtimes. Altogether, the work confirms that digital twin-based valve modeling is a quality and effective tool of real-time monitoring, predictive maintenance and performance optimization that will help to increase the smartness, efficiency, and sustainability of the internal combustion engine systems.

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ISSN: 2320-3714
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