24TTC008 – BEng Project
(CW2 - Final Report)

Simulink based Hydrogen Internal Combustion Engine model

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By

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Eng (Hons) in Automotive Engineering

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Abstract

This project demonstrates how to employ Realis WAVE and Simulink to analyse and simulate a single-cylinder hydrogen internal combustion engine (H2ICE). The objective was to generate similar output profiles and evaluate Simulink's suitability for precisely simulating hydrogen combustion processes through the development of a control model. The study creates a solid modelling framework for hydrogen-fuelled engines by testing the model on both platforms, advancing sustainable combustion technology.

A reduced ECU system that dynamically modifies fuel mass in response to air mass flow and intake circumstances is incorporated into the final Simulink model, which has a control-oriented structure. Because of its modular construction, it can adjust important engine parameters like temperature and pressure in real time at different engine speeds. This method shows how useful Simulink is as a versatile tool for academic research as well as the creation of future hydrogen engine controllers.

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1. Introduction

The creation and verification of a control-based simulation model for a H2ICE is the main objective of this thesis. For precise engine behaviour prediction and real-time adaptability under changing operating conditions, control-oriented modelling is essential. The project's goals and objectives are initially stated in this introduction, which then goes on to discuss the report's format and the organisation of the paper. [1]

1.1 Project Aim and Objectives

Creating a control-based simulation model of a H2ICE in Simulink that accurately depicts combustion behaviour and reacts dynamically to shifting engine conditions is the primary objective of this project. The model can forecast how cylinder pressure and temperature change over the course of an engine cycle by altering variables like engine speed, air mass flow, and fuel input. This makes it possible to evaluate thermal properties and performance in real time, which aids in the creation of flexible control schemes for engines that run on hydrogen.

A list of objectives this project aims to complete are listed:

1. Develop an angle-based simulation model

Create a crank-angle-resolved model to simulate cylinder pressure, temperature, and heat transfer over the full engine cycle using hydrogen combustion.

2. Implement a control-based simulation framework

Integrate control elements such as start of injection (SOI), ignition timing, and load response into the Simulink model to enable transient operation and tuning flexibility.

3. Validate simulation accuracy against a benchmark virtual engine made in Realis

Ensure that key outputs (pressure, temperature, and heat transfer rate) from the Simulink model align with those from Realis WAVE, maintaining a deviation of less than 3%.

1.2 Control Based ICE Model

To simulate and modify engine behaviour in real time, control-based modelling is crucial to modern engine development. These models facilitate performance tuning and system adaptability by fusing physical equations with control techniques like fuel injection and ignition timing [2]. They are particularly helpful for assessing responsive drive techniques and sophisticated fuels.

Engineers can maximise engine performance under various loads, speeds, and environmental circumstances by using control-based models, which enable real-time modifications to critical operational parameters. This adaptability is necessary to guarantee the stability of new fuel technologies in dynamic, real-world driving situations, in addition to increasing efficiency.

1.3 Structure of the Report

The next section of this study reviews the body of research on internal combustion engine modelling and hydrogen combustion, emphasising the value of simulation and control modelling in the creation of next-generation powertrains. The baseline model developed in Realis WAVE is then presented, together with the theoretical foundation that was utilised to reproduce it in Simulink. The model architecture is described in full, along with its subsystem interactions and control-oriented characteristics. To verify model accuracy, important performance outcomes are then examined and contrasted with the Realis WAVE benchmark. A summary of the results and recommendations for further research into hydrogen-fuelled engines concludes this paper.

2. Literature Review

The purpose of this literature review is to establish a foundational understanding of hydrogen internal combustion engine modelling and to contextualise the methods used within this project. This review explores the various modelling techniques employed to simulate ICE behaviour, highlighting their respective strengths and limitations.

2.1 Types of ICE Models

1D Modelling Tools such as Realis WAVE and GT-Power are frequently utilised in both academic and industrial contexts for engine performance study [3, 4]. These platforms excel in capturing the overall thermodynamic behaviour of the engine, including pressure and temperature dynamics, flow rates, and combustion properties, all while preserving decent computing efficiency. Simple yet accurate modelling of intricate in-cylinder processes is made possible by the application of semi-empirical equations such as Woschni's correlation for heat transport and the Wiebe function for combustion [5]. These models are frequently used for engine calibration and cycle analysis under various operating situations, which means they are especially well-suited for system-level optimisation.

On the flip side, 3D Computational Fluid Dynamic (CFD) models provide extremely fine-grained spatial resolution of localised heat transfer, flow fields, turbulence, and flame propagation. [6] These models are computationally costly and less beneficial for real-time control integration or iterative design workflows, despite being effective for understanding fine-scale phenomena like knock or wall quenching. Therefore, rather than developing embedded control systems, their work is frequently restricted to research and validation.

To mimic the physics-based outputs of Realis WAVE in the context of this project, a block-based Simulink model was selected, which also offers the flexibility to interact with possible control schemes. Simulink supports both the future deployment of model-based control and the real-time adjustment of combustion parameters by providing a balance between control-oriented modularity and physical precision [7]. This control integration becomes crucial for hydrogen ICEs, where heat management and quick flame propagation are crucial, to maintain efficiency and dependability under a variety of load and speed conditions.

Ultimately, the selection of an ICE modelling approach depends on the desired trade-off between fidelity, computational load, and control integration. This project offers a solid and scalable framework for real-time behaviour analysis of hydrogen engines thanks to the hybrid usage of Simulink for simulation and possible control system compatibility and Realis for reference data. [8]

2.2 Control Models for Engine Optimization

Modern engine models rely heavily on control systems, which allow for the real-time manipulation of critical parameters to optimum efficiency, performance, and emissions compliance. The Engine Control Unit (ECU), which is at the centre of this control structure, is essential in figuring out the fuel load depending on changing air mass, engine speeds, and other input variables. By modifying the injection of hydrogen fuel in accordance with the intended air-fuel ratio, the ECU in this type oversees guaranteeing effective combustion under various operating conditions.

By incorporating such control logic, the model may react dynamically to modifications in engine inputs, simulating how actual engines adjust to variations in load and speed. In addition to improving simulation accuracy, this responsiveness paves the way for future control-oriented advancements. [9]

Advanced control techniques like Model Predictive Control (MPC) offer significant potential for additional optimisation beyond the capabilities of a typical ECU [10]. MPC works effectively for controlling combustion timing, torque delivery, and thermal behaviour, especially in hydrogen-fuelled engines, by forecasting future engine states and resolving optimisation issues in real time [11]. Prior to being used in actual engine testing, these controllers can be fine-tuned using simulation data, which enables extensive testing and optimisation under a variety of operating circumstances. This guarantees dependable performance in real-world applications and expedites the transfer from simulation to physical implementation.

2.3 The Role of Engine Mapping in Control Applications

In the development of contemporary ICEs and the design of control systems, engine mapping is essential. Engine maps offer an organised method of predicting and optimising engine behaviour in real time by aggregating important performance data, including torque, fuel consumption, thermal efficiency, and emissions, over a matrix of engine speeds and loads. Control systems can easily refer to pre-calculated outputs without having to solve intricate physical models on the spot thanks to these maps, which are frequently represented as multi-dimensional lookup tables. [12]

Furthermore, as discussed, integrating engine maps becomes significantly more streamlined when paired with advanced control strategies such as Model Predictive Control (MPC). MPC predicts future system behaviour over a specified horizon, which enables it to make optimal decisions in real time. Supported by engine maps, MPC may make better predictions and optimise outputs by using pre-calculated performance data, including torque curves or fuel consumption measurements. As such, incorporating engine mapping remains a valuable potential enhancement for future iterations of the model, particularly as control complexity increases. [13]

2.4 Summary of Literature Review

Based on the literature review the required model should have the following specification: it must accurately capture the thermodynamic behaviour of hydrogen combustion, including pressure, temperature, and heat transfer rate, while remaining computationally efficient. [14] To enable the integration of control systems, especially an ECU that can adjust fuel load in response to shifting engine speeds and conditions, the model should offer modularity. For future optimisation, it is also preferable to have the flexibility to integrate sophisticated control techniques, like Model Predictive Control. To enable hybrid modelling approaches that strike a balance between physical correctness and real-time responsiveness, the model should lastly be organised to support the possible insertion of engine maps or lookup tables.

Employing a virtual model built in Realis WAVE, the following section investigates the actual application of these findings, building on the theoretical framework given in the literature. By using this model as the project's simulation benchmark, key performance indicators may be assessed. The control-oriented Simulink model's further development and calibration are guided by these findings.

3. Virtual Engine

The Realis WAVE model for simulating a single-cylinder hydrogen internal combustion engine is shown in this section. Pressure, temperature, and heat transfer rate are the main outputs that are utilised for comparison and form the basis of the Simulink model. A quick evaluation of the model's setup, assumptions, and performance creates a baseline for the subsequent validation step.

3.1 Overview of Realis Model

The Realis WAVE model used in this project was pre-built and served primarily as a reference and testing environment for the development of the Simulink H2ICE model. It provided a validated simulation platform to study key combustion behaviours such as pressure, temperature, and heat transfer rate throughout the engine cycle [15]. Rather than being modified extensively, the Realis model was used to extract engine data, validate simulation outputs, and establish performance benchmarks. The overall structure of the model is shown in Figure 3.1, illustrating the complete engine cycle from intake to exhaust.

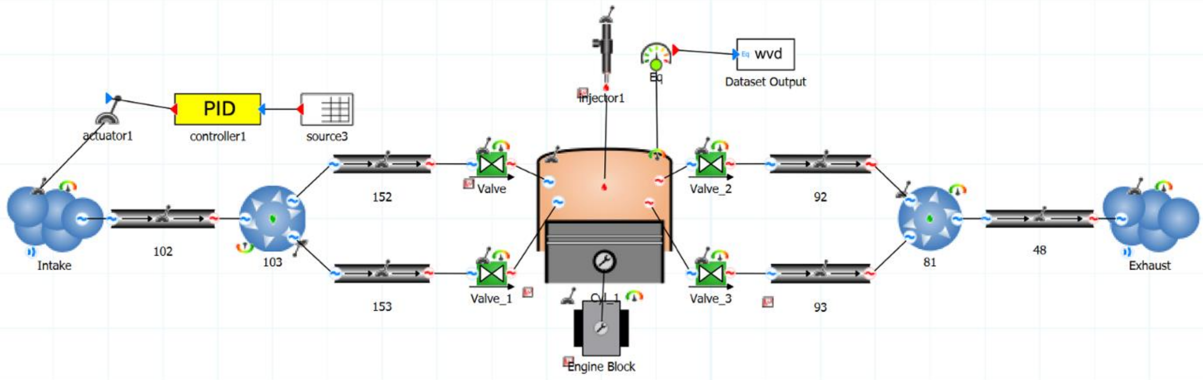

Figure 3.1: Realis WAVE Model

Key components include the intake and exhaust systems, a single-cylinder engine block, and control elements like actuators and valves. A PID controller is used to manage airflow, simulating real-time engine control. This setup mirrors the logic later used in the Simulink model for regulating the air-fuel mixture and timing.

3.2 Realis Engine Dimensions and Operating Parameters

The Realis model ran under a set of preset parameters that replicate the behaviour of ordinary hydrogen-fuelled engines in order to guarantee consistency and physical realism in the simulations. These operating circumstances served as the foundation for assessing Realis WAVE's performance as well as that of the later Simulink model.

Precise depiction of engine geometry is equally important since it directly affects the cylinder's airflow and thermodynamic properties. In order to preserve alignment between the two models, the dimensional inputs utilised in the Realis model—which covered crucial elements like cylinder configuration and valve design—were meticulously replicated in the Simulink platform.

The key engine geometry parameters and operating conditions used in the Realis WAVE and Simulink models are summarised in Table 3.2.

Group	Parameter	Value	Unit
Cylinder Dimensions	Crank Radius	79	mm
	Bore Diameter	131	mm
	Connecting Rod Length	230	mm
Valve Dimensions	Valve Lift (Max)	14	mm
	No of Intake Valves	2	-
	Valve Diameter	39.4	mm
Operating Parameters	Air Fuel Ratio	64.09	-
	Compression Ratio	11.8	-
	Lower Heating Value	114	MJ/kg
	Initial Mass of Air	2.24e-04	kg

Table 3.2: *Engine Dimensions and Operating Parameters*

3.3 Primary Comparison Criteria

To evaluate the accuracy of the Simulink model, three key outputs from the Realis WAVE model—cylinder pressure, temperature, and heat transfer rate—were selected as comparison benchmarks. These parameters are critical for capturing the core combustion behaviour of a hydrogen-fuelled engine.

Since it serves as the basis for determining the engine cycle's temperature and heat transfer rate, cylinder pressure is the most important output to duplicate [16]. Since the energy release and timing of hydrogen's rapid burn characteristics are highly sensitive, precise pressure simulation—especially close to TDC —is crucial for verifying the Simulink model.

To evaluate thermal efficiency, forecast emissions, and guarantee realistic combustion behaviour, cylinder temperature is crucial. To ensure that the combustion and energy conversion processes are well depicted, H2ICEs must appropriately reflect the anticipated high peak temperatures. Since the Ideal Gas Law is used to determine temperature from pressure, the precision of the temperature is intrinsically linked to that of the pressure profile.

Efficiency and thermal stress on engine components are directly impacted by the heat transfer rate, which tells you how much thermal energy is lost to the cylinder walls. Given the high combustion temperatures involved, this is especially crucial in hydrogen engines. Wall interactions, combustion duration, and the cooling dynamics anticipated in real-world operation can all be evaluated by comparing heat transfer patterns. To better understand and replicate these behaviours in Simulink, the next section outlines the theoretical models underpinning the simulation.

4. Theoretical Analysis

To verify the correctness of the formula presented in the preparation report, the theoretical analysis for this thesis is essential. Each model subsystem's pertinent formula will be reproduced in the section that follows.

4.1 Instantaneous Cylinder Volume

The instantaneous cylinder volume at any crank angle, θ, is a function of the engine's bore, stroke, and connecting rod length. The formula for calculating this volume is:

$$V_\theta = V_c + \frac{\pi B^2}{4}\left(L + \frac{S}{2} - \left(\frac{S}{2}\cos\theta + \sqrt{L^2 - \left(\frac{S}{2}\sin\theta\right)^2}\right)\right) \quad (1)$$

Where: V_θ is the instantaneous cylinder volume at crank angle θ (m³); V_C is the clearance volume, which is the minimum volume at TDC (m³); B is the bore diameter of the cylinder (m); L is the connecting rod length (m); S is the stroke length of the piston (m); θ is the crank angle from TDC (rads).

This equation accounts for the changing position of the piston within the cylinder as the crankshaft rotates, providing an accurate volume calculation at each crank angle and remains the same as the one identified in the preparation report.

4.2 Estimation of Trapped Air Mass

The calculation of the trapped air mass in the cylinder was the first unexpected modification to the model. We used several characteristics related to the overall valve design that Realis provided to compute this. This made it possible for us to apply the following formula:

$$\dot{m} = \frac{\int A \cdot V_{intake}}{\rho} \quad (2)$$

Where: $\dot{m}$ is the Trapped Air Mass (m³); A is the Valve Area (m^2); V_{intake} is the velocity at the intake (m/s); ρ is the density (kg/m³).

Due to the inability to receive the exact two primary values A and V_{intake}, further assumptions and simplifications were necessary. The intake velocity is dependent on the pressure differential between the intake manifold and the cylinder, which introduces a requirement for a feedback loop in the model to provide realistic and time-varying pressure values. Additionally, both the valve area and intake velocity break down into further sub-models involving cam profiles, valve dynamics, and sonic flow limitations, all of which significantly affect the mass estimation accuracy. This information is detailed further in section 5.3.

4.3 Engine Cycle Timing Synchronisation

Because each phase of a four-stroke engine—intake, compression, combustion, and exhaust—must take place in an exact sequence throughout 720 degrees of crankshaft rotation, precise timing synchronisation is crucial. In this model, timing circuits are used to divide the engine cycle into its four strokes, ensuring that each subsystem activates only during its appropriate crank angle window.

4.4 Multiphase Pressure Framework

The primary variables that regulate the pressure inside the cylinder during the intake stroke are the temperature of the incoming charge, the amount of air sucked in, and the cylinder capacity at that crank angle. Since no energy has been contributed and combustion has not yet occurred, the Ideal Gas Law provides a straightforward and precise method of measuring in-cylinder pressure now.

The formula for the ideal gas law is as follows

$$\mathrm{P} = \frac{\mathrm{m} \cdot \mathrm{R} \cdot \mathrm{T}}{\mathrm{V}} \tag{3}$$

Where: P is the instantaneous cylinder pressure (Pa); m is the mass of the gas in the cylinder (kg); R is the specific gas constant for the air-fuel mixture ($J \cdot mol^{-1} \cdot K^{-1}$); T is the temperature within the cylinder (K); V is the instantaneous cylinder volume (m^3)

The trapped air-fuel combination is compressed into a smaller volume when the piston rises during the compression stroke, which causes the cylinder pressure to rise significantly. Assuming no heat exchange with the environment occurs during this brief, quick process, adiabatic behaviour dominates the compression phase in contrast to the intake phase, where pressure is primarily a function of air mass and temperature.

We can then model the pressure increase solely using the gas mixture's specific heat ratio and volume reduction thanks to this thermodynamic assumption. To maintain the dynamic continuity of the engine cycle, the pressure at each crank angle is calculated by consulting the pressure and volume from the preceding time step.

In this way, the model mimics the natural build-up of pressure in an actual engine as the piston approaches top dead centre (TDC), right before ignition. Here, the specific heat ratio (γ) is crucial since it affects how steep the pressure curve is. Because of this, the compression phase is crucial for confirming the model's sensitivity to thermodynamic parameters and physical accuracy [17]. The exact formula used is as follows:

$$P_1 \, V_1^{\gamma} \; = \; P_2 \, V_2^{\gamma} \tag{4}$$

Where: P_1 and P_2 refer to the old and new compressive pressures respectively (Pa); V is the rate of change of volume (m^3); γ is the specific heat ratio.

This pressure formulation accurately depicts the dynamics of the cylinder in real time by capturing the increasing resistance against the piston as the mixture compresses. Additionally, it gets ready for combustion, which releases the energy that has been stored. It is essential to maintain a perfect pressure profile during compression since any deviation can have a major impact on peak pressure, ignition timing, and engine performance.

This is the most crucial and energy-intensive phase of the engine cycle, when we take into consideration the fuel load that the ECU has added. When the air-fuel mixture ignites, a large amount of thermal energy is released, and the cylinder pressure quickly increases. The base pressure forecast is improved by the energy contribution from the injected fuel mass, even though it still adheres to the adiabatic compression relationship.

This addition modifies the pressure profile to reflect the steep and sharp rise typical of hydrogen combustion. The updated formula enhances the base adiabatic expression by adding the following

$$\frac{m_g \times LHV \times \gamma}{V} \tag{5}$$

Where: m_g is the mass of the gas (kg); LHV is the lower heating value of hydrogen; γ is the specific heat ratio; V is the cylinder volume (m^3).

The rapid increase in pressure seen close to top dead centre is explained by this phrase, which also takes into account the energy contributed to the system during combustion. Accurately simulating this addition is essential to reproducing the strong pressure peak observed in actual H2ICE behaviour because hydrogen has a high energy density and flame speed. In addition to driving engine power, this pressure surge is crucial in determining performance metrics including torque, efficiency, and heat transfer.

To accurately replicate the controlled burn profile observed in the Realis WAVE model, the Simulink implementation incorporates a deliberate delay of 20 simulation steps at the combustion stage. With this modification, the peak pressure will closer align with the timing seen in Realis, which utilises a comparable 16-step delay. The difference in step count reflects the difference in resolution between the two platforms—our Simulink model operates at a finer crank angle increment of 0.36 degrees per step, compared to 0.45 degrees per step in Realis. By calibrating this delay accordingly, the model achieves a more realistic pressure rise timing, preserving the sharp combustion characteristics typical of hydrogen and improving overall simulation fidelity.

4.5 In-Cylinder Temperature

The temperature within the cylinder is calculated using the same information provided in intake stroke for the pressure. Slight alterations are made through the inclusion of temperature coefficients that better reflect the influence of varying engine speeds. These values are extracted from the Realis WAVE model and serve to align the Simulink output with validated combustion behaviour observed at different conditions.

Since the temperature at each crank angle is determined using the instantaneous pressure and volume values that were previously determined, the precision of those subsystems is crucial to this stage. The ideal gas law is applied:

$$\mathrm{T} = \frac{\mathrm{P} \cdot \mathrm{V}}{a_{temp} \cdot \mathrm{R} \cdot \mathrm{m} + b_{temp}} \tag{6}$$

Where: T is the cylinder temperature (K); P is the instantaneous cylinder pressure (Pa); V is the instantaneous cylinder volume (m^3); a_{temp} is a proportional heat coefficient adjusting for gas behaviour; R is the specific gas constant for the air-fuel mixture ($J \cdot mol^{-1} \cdot K^{-1}$); m is the mass of the gas in the cylinder (kg); b_{temp} is an offset heat coefficient accounting for thermal delay.

4.6 Woschni's Correlation

A key aspect of internal combustion engine simulation is the Heat Transfer Rate (HTR), especially for hydrogen-fuelled engines where high combustion temperatures can place heavy thermal stresses on engine parts. Predicting thermal losses and assessing engine efficiency, material stress, and long-term durability all depend on accurate heat transfer modelling. In this project, the convective heat transfer rate between the in-cylinder gas and the cylinder walls is calculated using Woschni's empirical correlation—a widely accepted approach in engine thermodynamics [18]. This formula is as follows:

$$\dot{Q} = h \cdot A \cdot (T_g - T_w) \tag{7}$$

Where: h is the heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$); A is the surface area of the combustion chamber (m²); T_g is the instantaneous gas temperature inside the cylinder (K); T_w is the wall temperature of the combustion chamber (K).

Woschni's formula for the heat transfer coefficient, h, is given by:

$$h = C_1 \cdot p^{0.8} \cdot T_g^{-0.4} \cdot w^{0.8} \tag{8}$$

Where: C_1 is an empirical constant, typically around 3.26 for most combustion applications; p is the cylinder pressure (Pa); T_g is the gas temperature (K); w is the mean gas velocity (m/s).

In this model, the heat transfer subsystem acts as a final thermodynamic validation. It synthesizes inputs from pressure and temperature calculations and responds dynamically to crank angle changes, ensuring that the simulated heat loss pattern aligns with real-world expectations

Transforming these ideas into a useful, functional simulation is the next stage now that the theoretical foundation has been developed, and the essential thermodynamic behaviours have been identified. In the section that follows, the Simulink engine model is broken down into subsystem blocks that demonstrate how each formula and idea—from temperature and pressure dynamics to combustion energy input and heat transfer—is integrated. In a modular, crank-angle-resolved configuration, these parts cooperate to replicate the entire engine cycle, providing the framework for control integration and performance assessment.

4.7 Additional Key Performance Indicators

For control models like the one developed in this project, KPIs serve several purposes. They verify that important engine characteristics, such as pressure rise and thermal performance, are accurately depicted under various circumstances. KPIs also allow for real-time control modifications for stable H2ICE operation and guide calibration of key parameters like fuel injection and ignition timing. Additionally, KPIs enable direct comparisons between simulation outputs and real-world test results, building greater confidence in the model's accuracy.

First the work done (J) is calculated through the following formula shown.

$$W = \int P \, dV \tag{10}$$

Where: P is the instantaneous cylinder pressure (Pa); V is the cylinder volume (m³)

The next calculation is for indicated power (W) which is a simple formula using the following:

$$P = \frac{W \cdot N}{60} \tag{11}$$

Where: W is the indicated work done (J); N is the engine speed (rpm).

A significant parameter in indicated torque (N.m) can then be derived using this power and is shown in the following calculation:

$$T = P \cdot \omega \tag{12}$$

Where: P is the indicated power (W); ω is the angular velocity (rad/s).

Finally, the thermal efficiency (η) can be calculated using the added energy from figure 5.6. The complete formula for this is as follows:

$$\eta = \frac{W}{m_f \cdot LHV} \times 100 \tag{13}$$

Where: W is the indicated work done (J); m_f is the mass of fuel (kg); LHV is the lower heating value.

5. Engine Model

While the model encompasses a broad range of components, this section will focus on key functional elements. Subsystems not discussed in detail will be referenced.

5.1 Engine Subsystems Overview

The model serves as the backbone for this project and is to be introduced in this section. Figure 5.1 showcases the intricate details into a more accessible visual representation. The reasoning this approach was taken was to provide a straightforward view of how these subsystems interact with each other whilst avoiding the dense network lines provided in the Simulink model.

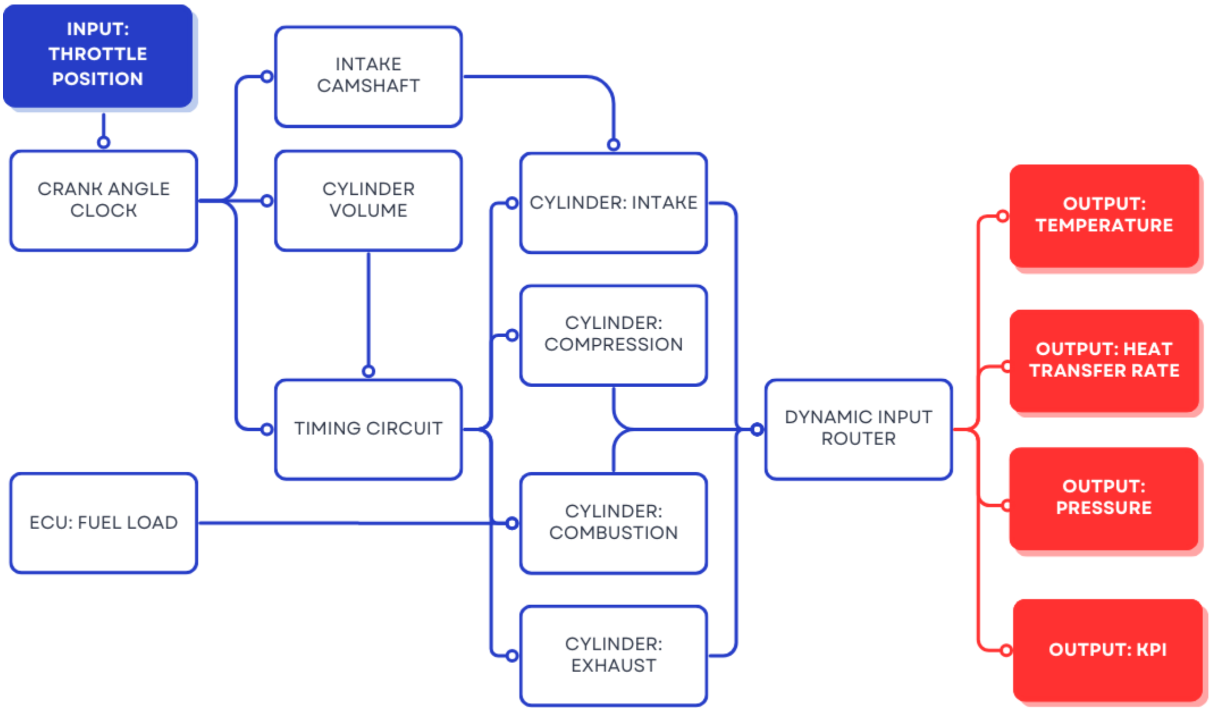

Figure 5.1: H2ICE Subsystems Overview

Figure 5.1 illustrates the process flow where a single input progresses through the system to generate various outputs. Beginning with the crank angle clock, which supplies both the crank angle range and the duration of an engine cycle, the system culminates at a series of elements termed 'switches' in Simulink. These switches gather various cylinder pressures, influenced by the model's timing circuit.

As previously noted, not all subsystems will be depicted in this report due to their inherent simplicity and the considerable space their detailed illustrations would require. Below is a list of these subsystems accompanied by concise explanations:

- **Crank Angle Clock**: Converts engine RPM into radians, then multiplies by the simulation time to determine the crank angle, providing a precise measurement of the engine's rotational position.
- **Timing Circuit**: Splits the simulation time into four sections corresponding to each stroke of the engine cycle, ensuring that the timing of events is synchronized with the engine's operational phases
- **Exhaust System**: Captures the last value from the combustion stroke and maintains this value throughout the exhaust phase.
- **ECU**: Calculates the fuel mass by dividing the air mass by the air-fuel ratio

5.2 Cylinder Volume Subsystem (1)

Using the cylinder geometry parameters supplied by the Realis WAVE model, the Cylinder Volume subsystem (Figure 5.2) is made to replicate the setup found in that model. Using the formula generated from the engine's bore, stroke, and connecting rod length as stated in the Realis model configuration, this subsystem determines the instantaneous cylinder volume at every given crank angle

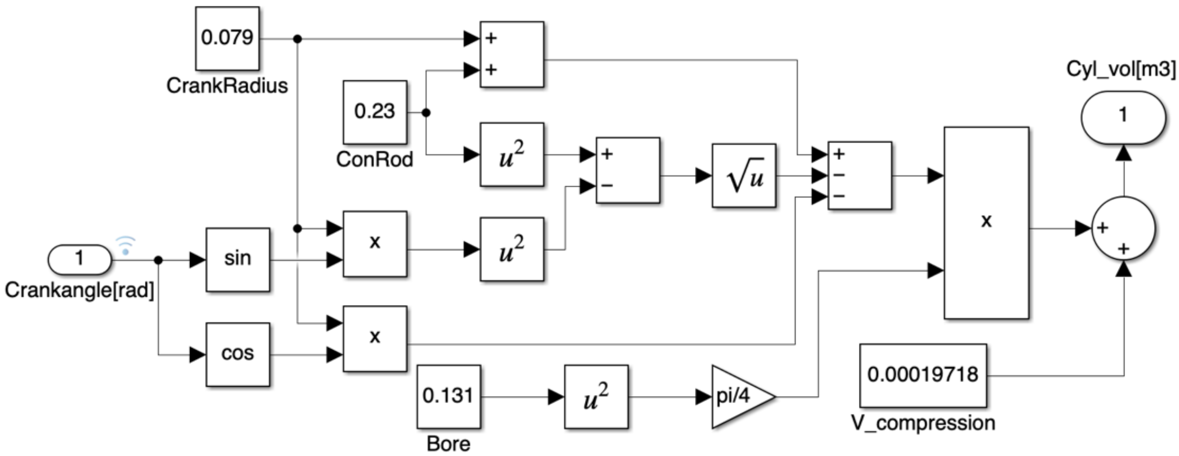

Figure 5.2: Cylinder Volume Subsystem

5.3 Air Mass Subsystem (2)

In Figure 5.3, air mass calculation employs a 1D lookup table derived from the cam profile in Realis to estimate the valve area. This valve area regulation crucially influences the engine's volumetric efficiency by controlling the airflow during the intake stroke. By accurately modelling this, the simulation ensures that the air dynamics entering and exiting the engine closely mirror real engine behaviour, thereby enhancing the precision of performance predictions.

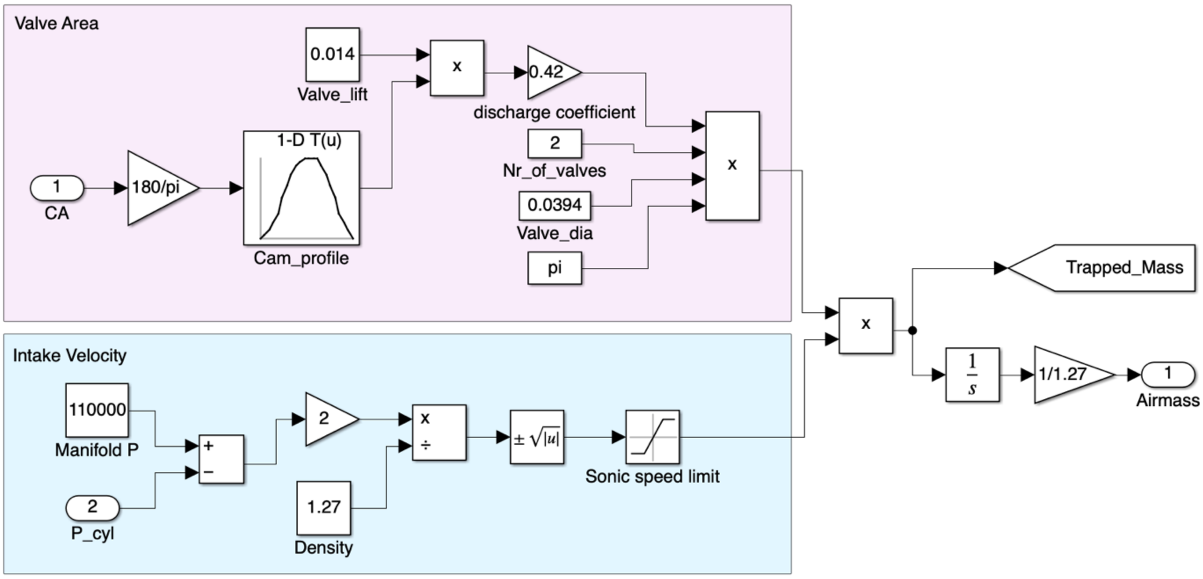

Figure 5.3: Air Mass Subsystem

Velocity within the Air Mass subsystem is modelled to ensure that air moves through the engine at speeds that do not exceed the sonic threshold, thus preventing the formation of shockwaves. The flow velocity formula is used to calculate this, and this approach ensures that the airflow dynamics are realistic, and that the engine operates within safe and efficient operational parameters. Combining these two allows for the calculation of the trapped air mass which is integrated into the ECU to calculate the fuel mass and the air mass, which is used in various subsystems,

5.4 Intake Subsystem (3)

The intake is the first major cylinder subsystem. Figure 5.4 illustrates how we can determine the pre-combustion cylinder pressure before injecting our fuel or adding our spark by using simply the initial mass of air—provided by Realis—and the recently computed air mass. This system makes use of the ideal gas law, which is the most straightforward approach to pressure calculation in our model.

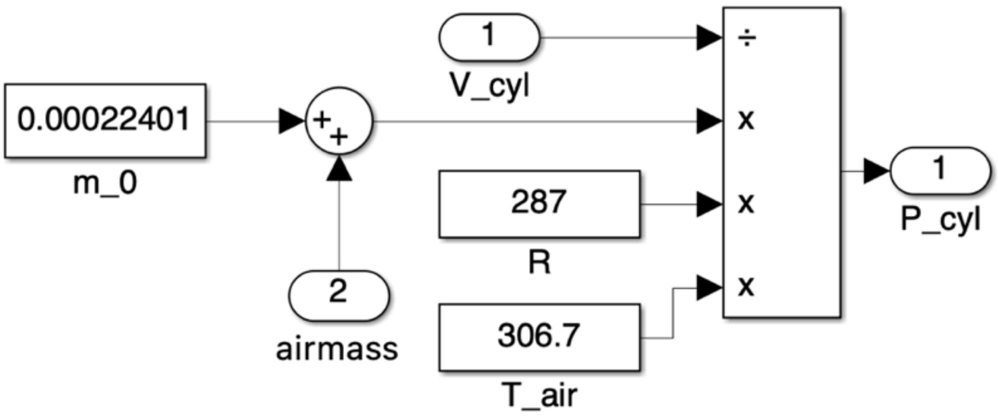

Figure 5.4: Intake Subsystem

5.5 Compression Subsystem (4)

The following subsystem models the compression stroke of the engine, capturing both pressure and temperature changes during the cycle.

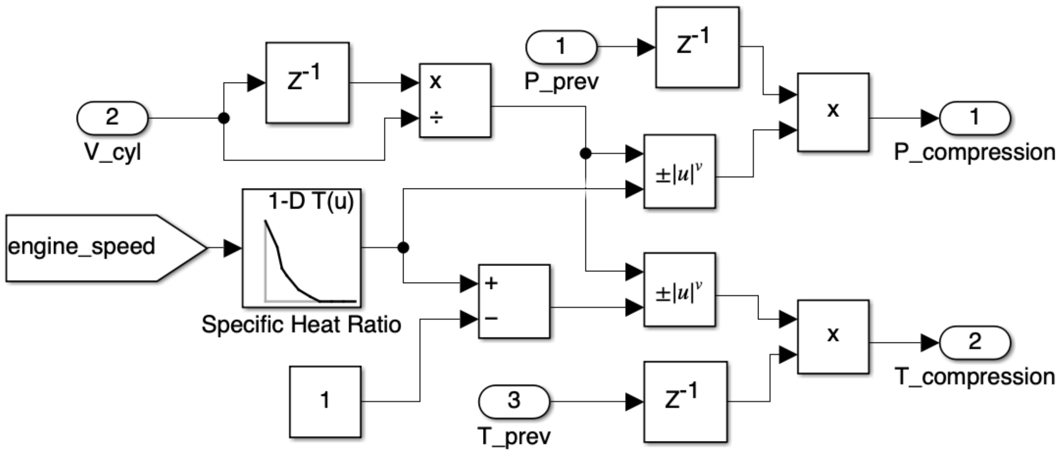

Figure 5.5: Compression Subsystem

The delay blocks in Figure 5.5 store the previous values of pressure, temperature, and volume, allowing the model to calculate how these parameters change over time. By comparing current values with delayed ones, the system determines the rate of change. This enables accurate modelling of the compression process by comparing current and past data, with added precision from lookup tables adjusting the specific heat ratio.

Although the temperature calculation in this model has no effect on the system itself, it's useful in confirming the precision of the final temperature curve calculation thus far. The adiabatic temperature change is computed using the formula previously introduced in Equation (4).

5.6 Combustion Subsystem (5)

The fuel load is injected into out combustion subsystem shown in figure 5.6 making it the most important subsystem in the model. This system uses a combination of the adiabatic compression of the air-fuel mixture and the addition of the energy provided due to the combustion itself. This adiabatic compression process follows the same principles outlined in Section 5.5, where similar thermodynamic behaviour and assumptions were discussed in detail.

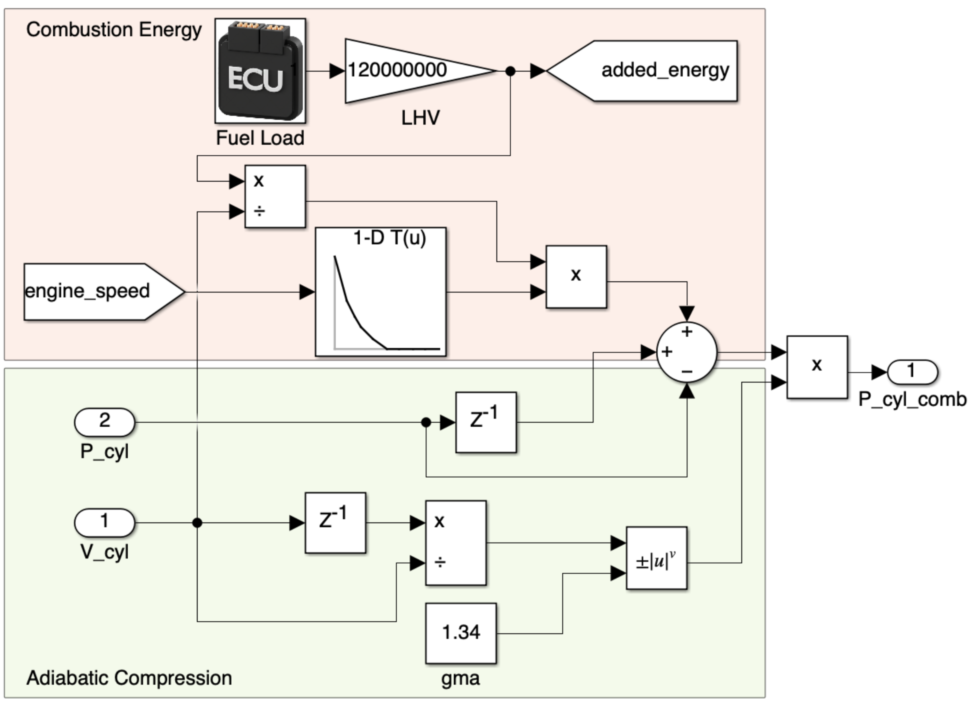

Figure 5.6: Combustion Subsystem

The amount of fuel that is fed into the cylinder directly affects the energy added during combustion, and the ECU plays a key role in this process. The ECU guarantees ideal combustion conditions, which results in effective engine performance and reduced emissions, by modifying the fuel load in accordance with engine needs and operating conditions.

5.7 Dynamic Input Router *Subsystem (6)*

Similarly to the other stroke subsystems, each calculated pressure output—whether from intake, compression, combustion, or exhaust—is routed through a network of switch blocks governed by timing circuits as shown in figure 5.7.

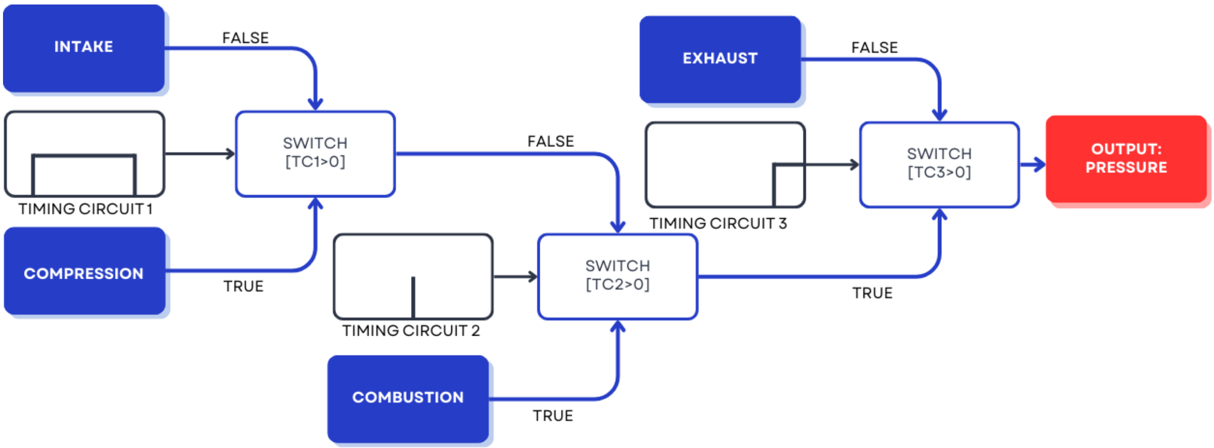

Figure 5.7: Dynamic Input Router Subsystem

Here, the routing logic has been condensed into a flowchart that is easier to understand while maintaining the same logic to increase readability and avoid the visual complexity of Simulink's network lines. It can frequently be challenging to follow the data flow in the Simulink environment due to overlapping connections and nested blocks, particularly when several subsystems are interacting at once.

5.8 Temperature Subsystem (7)

For the Simulink model to effectively simulate the thermal behaviour of an internal combustion engine powered by hydrogen, the Temperature Subsystem is essential. This subsystem determines the engine's cylinder temperature using the Ideal Gas Law, a key idea in thermodynamics. By using variable coefficients, a and b, which are obtained from the Realis for each engine speed, the system is intended to adapt dynamically to the engine's operating conditions.

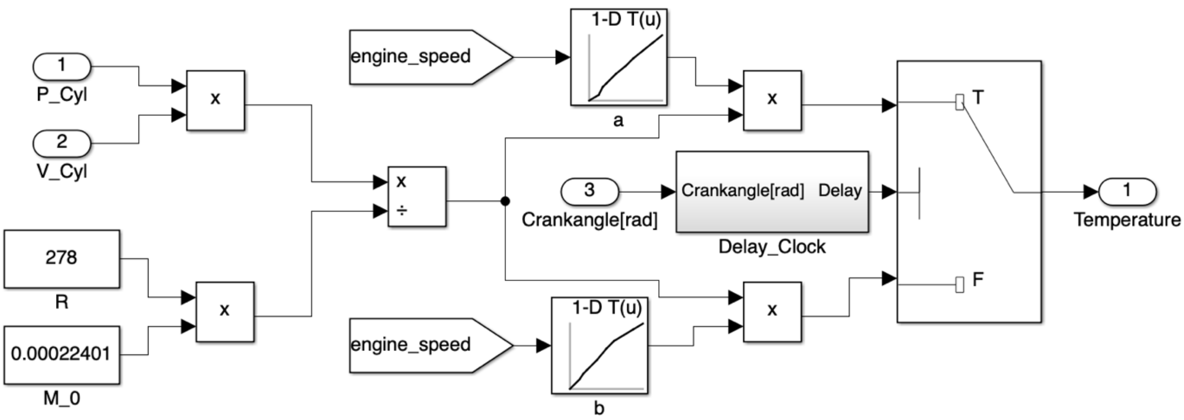

Figure 5.8: Temperature Subsystem

5.9 Heat Transfer Rate Subsystem (8)

The Heat Transfer Rate (HTR) subsystem, shown in Figure 5.9, calculates the thermal energy loss from the in-cylinder gas to the surrounding walls during the engine cycle. It plays a crucial role in verifying the thermal behaviour of the model, particularly in high-temperature hydrogen combustion scenarios

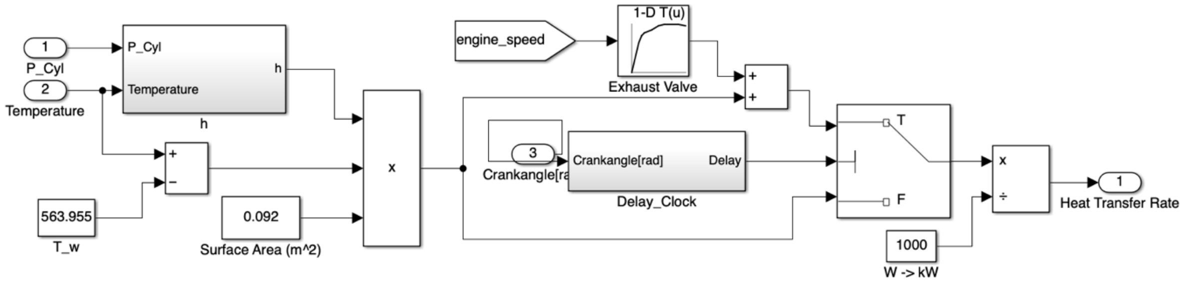

Figure 5.9: Heat Transfer Rate Subsystem

This subsystem relies heavily on accurate pressure and temperature inputs from earlier stages, as these values directly influence the calculation of the convective heat transfer coefficient. Because it depends on the integrity of all prior subsystems, the HTR output effectively acts as a final confirmation of the model's overall accuracy – if the pressure and temperature trends are realistic, the resulting heat transfer curve will also align with expected physical behaviour.

5.10 KPI Calculations Subsystem (9)

The final subsystem (Figure 5.10) in this model is where we find our volume and pressure outputs It is also where more KPIs have been added using these outputs

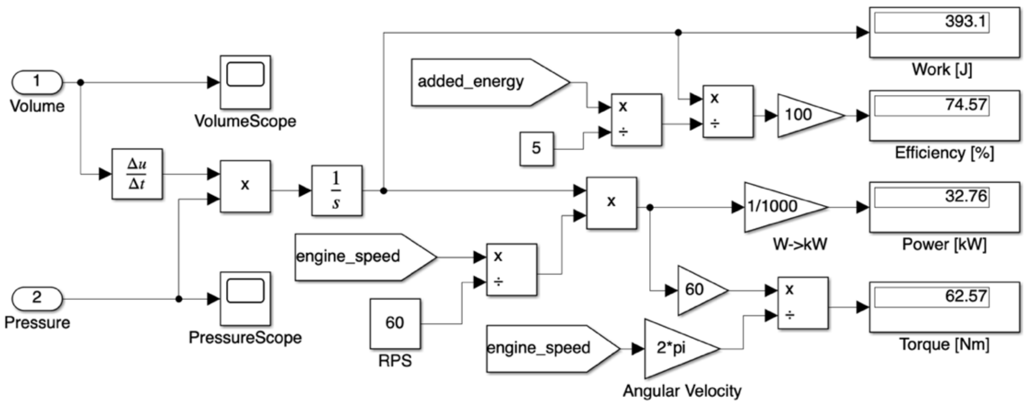

Figure 5.10: KPI Calculations Subsystem

6. Results and Analysis

This section of the report focuses on the three primary outputs – Cylinder Pressure, Temperature and Heat Transfer Rate – as identified in the preparation report. Section 6.4 presents the evaluation of additional key performance indicators that an analyst may find valuable. In their respective parts, each output will be covered in more detail.

6.1 Engine Cycle Performance Indicators

Three main thermodynamic outputs—cylinder pressure, in-cylinder temperature, and heat transfer rate—are crucial markers of system performance in the simulation of internal combustion engines, especially those powered by hydrogen. These variables not only explain the core combustion and expansion processes but also enable the calculation of secondary performance indicators like as efficiency, power output, and work done.

The engine's energy conversion and combustion kinetics are shown by cylinder pressure. It shows how well chemical energy is converted into mechanical work as well as when and how combustion takes place. In hydrogen engines, known for high energy density and rapid flame speeds, pressure rises sharply after top dead centre. Accurately capturing this rise is essential for calculating outputs such as power and work, and for replicating real-world performance.

Closely related to pressure and volume, in-cylinder temperature reveals thermal loading and combustion efficiency. Because of its high flame temperature, hydrogen frequently produces peaks higher than petrol or diesel engines. Assessing thermal stress on engine components, predicting emissions, and evaluating performance all depend on precise temperature prediction.

The heat transfer rate shows the amount of thermal energy that is lost to the cylinder walls. Significant heat transmission occurs, particularly after combustion, because of the intense temperature gradients created by hydrogen combustion. Understanding engine efficiency and creating appropriate heat management systems depend on accurately predicting this loss.

Since our outputs are the most important thermodynamic indicators for evaluating combustion behaviour in an H2ICE, they together serve as the basis for the engine performance analysis in this project. The computation of key performance indicators like indicated work, thermal efficiency, and power is based on these outputs, which are also essential for comprehending how energy is transformed and dissipated during the engine cycle.

Because these variables are interdependent, any error in one of them—for example, an erroneous pressure peak—can spread throughout the simulation and jeopardise the integrity of the model. Therefore, it’s essential to confirm that all indicators show realistic and consistent trends to validate the model's suitability for analysis and future control development.

To help answer our initial aims and objects the Root Mean Square Percentage Error (RMSPE) was calculated at 1500 RPM to quantify cycle-wide error, focusing on a single speed to isolate validation under steady-state conditions. The results produced by the WAVE simulation and Simulink are compared in depth in the following subsection, allowing for a comprehensive assessment of simulation realism and cross-platform consistency at different engine speeds.

6.2 Simulink vs. Realis Model Comparison

Our three essential indicators of performance are illustrated side by side in Figures 6.2a–6.2c at three different engine speeds: 1500, 3000, and 4500 rpm. The Simulink simulation results are displayed on the left, while the Realis WAVE charts are displayed on the right. This arrangement makes it possible to compare the two platforms' behaviour directly.

Cylinder pressure profiles produced by the Simulink and WAVE models at three engine speeds are contrasted in Figure 6.2a. With peak values appearing shortly after TDC, both platforms effectively depict the abrupt pressure surge typical of h-combustion. The Simulink model accurately depicts every peak, showing agreement with the Realis reference in terms of overall shape and amplitude.

One noticeable distinction is a subtle pressure increase around 360° crank angle present in the Realis plots but absent in the Simulink outputs. The reason for this discrepancy is that Simulink lacks exhaust phase modelling, but Realis includes exhaust backflow and residual gas effects that cause this secondary rise but makes little reference to it. In addition to explaining the missing pressure bump, Simulink's lack of this feature has a minor impact on downstream factors like late-cycle heat transfer.

The alignment of the crank angle varies across the two sets of charts as well. Although the crank angle ranges seem somewhat off, this variance reflects how each platform divides the engine cycle across time and has no bearing on the underlying performance trends. While the Simulink model is built with a more focused concentration on peak pressure events, the Realis model permits a more comprehensive exhaust phase, giving the gases more room to evacuate. This downstream defect causes a 0.87% error at 1500 rpm, which can be found using a simple RMSPE calculation.

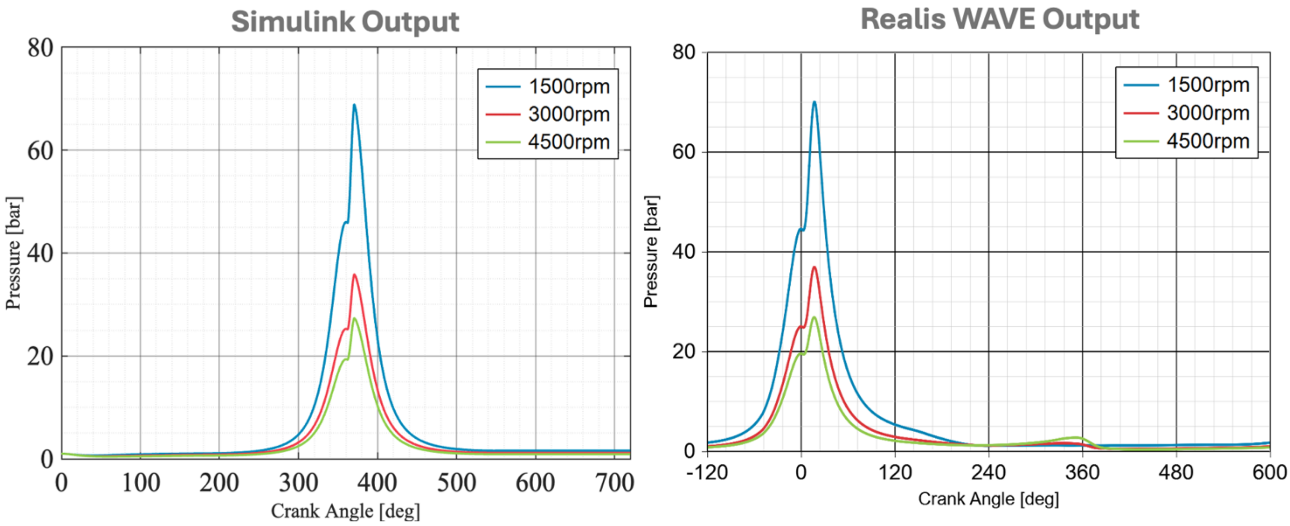

Figure 6.2a: *Pressure vs Crank Angle Outputs*

No significant differences are found between the tested speeds in Figure 6.2b. As anticipated, temperature peaks are sharper and more fleeting at higher engine rpm, and both platforms appropriately capture this tendency. minor, little variations in timing arise from the different definitions of crank angle that each simulation tool uses, but these changes have no bearing on the comparison's validity, and it still shows a RMSPE of 1.21% at 1500rpm.

The Simulink model can accurately reproduce the key combustion thermal features, although Realis' cooling curve appears longer due to its integration of more intricate post-combustion behaviour. This extended tail in the Realis output likely results from its inclusion of exhaust effects and wall heat exchange dynamics, which are simplified or absent in the Simulink implementation.

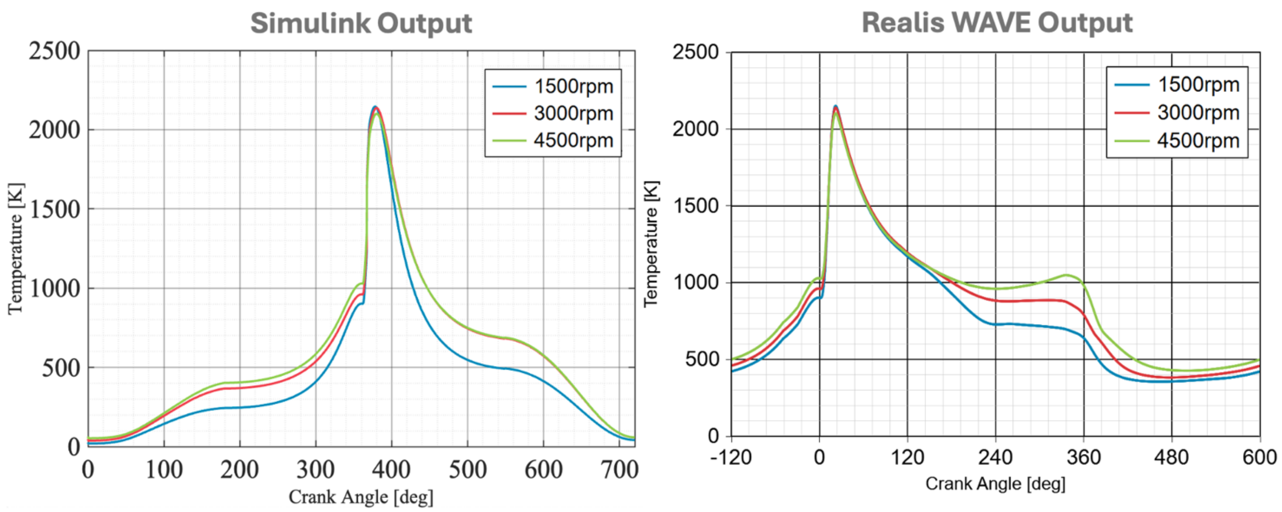

Figure 6.2b: *Temperature vs Crank Angle Outputs*

Both models display comparable heat transfer rate trends and peak timings at all engine speeds, as seen in Figure 6.2c. However, as was already established the Simulink model excludes exhaust phase modelling, it does not include the secondary spike at 360° that is present in Realis. To support the trade-off between combustion stability and thermal efficiency at low speeds, both forecast maximum heat transfer at 1500 rpm, where slower piston movement permits higher thermal dissipation. Overall, with a few end-cycle variations, Simulink successfully reproduces the primary HTR profile at a RMSPE of 2.77% at 1500rpm.

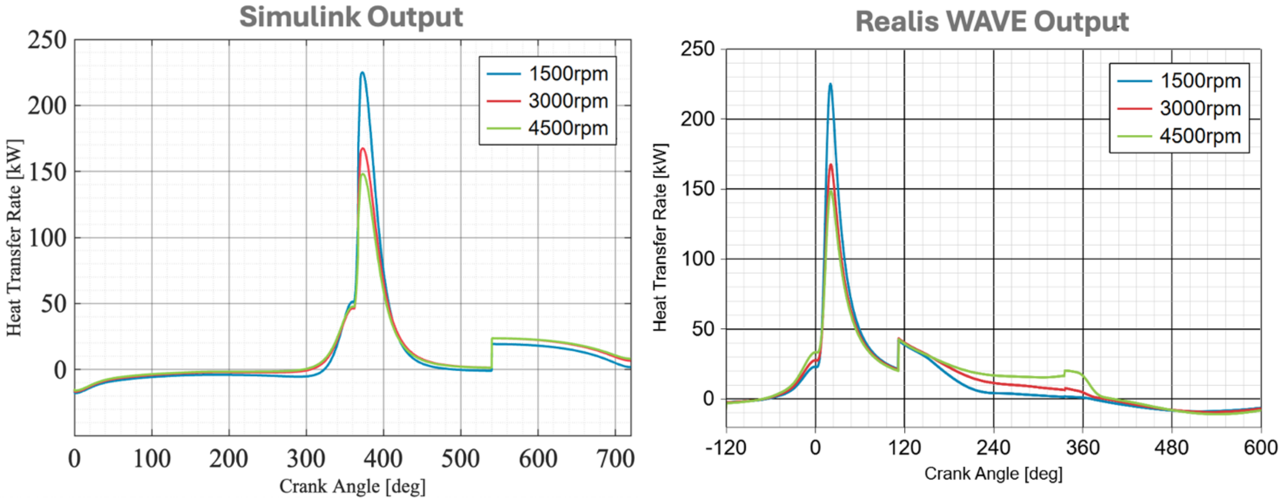

Figure 6.2c: *Heat Transfer Rate vs Crank Angle Outputs*

6.3 Indicated Power-Torque Curve Comparison

The Realis WAVE and Simulink models' power and torque curves are displayed in Figure 6.3. In both situations, torque peaks at about 1000 rpm, and indicated power rises progressively until about 1500–2000 rpm, at which point it starts to fall. This alignment is consistent with the performance of H2ICEs, which produce powerful low-end torque and effective power production at moderate speeds due to their high energy density and rapid flame propagation. Since torque and power are directly produced from in-cylinder pressure throughout the engine cycle, these curves are extremely sensitive to precise pressure and volume estimations. The validity of the thermodynamic models supporting the Simulink implementation is thus confirmed by the close match between Simulink and Realis. This validates its promise as a predictive tool in H2ICE design and optimisation, in addition to reaffirming its feasibility for real-time control applications. [19]

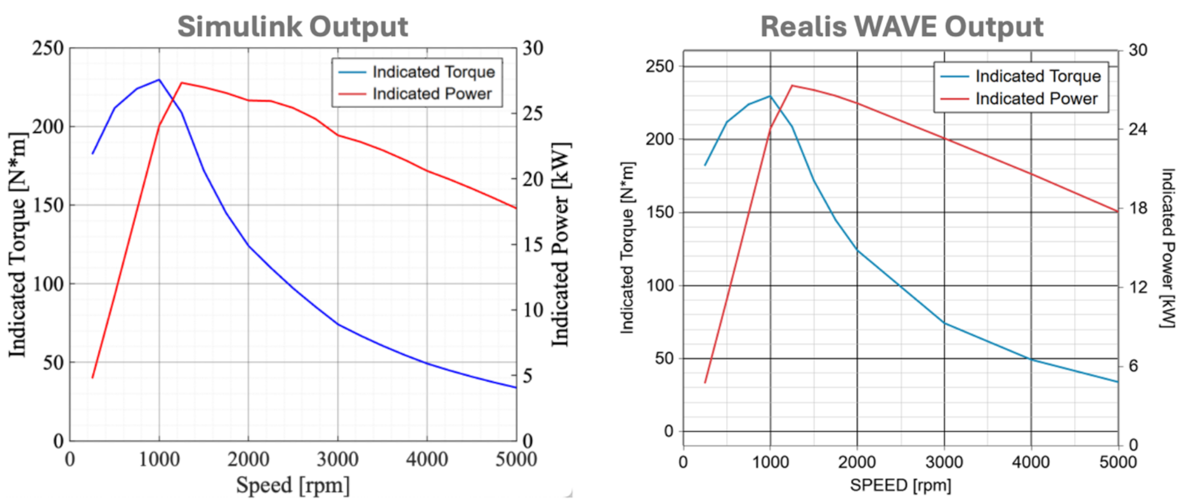

Figure 6.3: *Indicated Power-Torque Curve*

6.4 Additional Key Performance Indicators

In assessing the viability of out modelling system additional key performance indicators have been produced. The values shown in figure 6.4 are the result of a series of calculations that are generated by utilising the cylinder's pressure and the rate of volume change computed in our model. Figure 5.10 has already covered the straightforward set of Simulink blocks that are used to determine these four values.

Parameter	Value	Unit
Indicated Work Done	1079.44	J
Indicated Power	26.99	kW
Indicated Torque	171.8	Nm
Thermal Efficiency	46.43	%

Table 6.4: KPIs for 1500RPM

The chosen KPIs are integral to assessing fundamental aspects of engine performance that are significant from both an engineering and environmental perspective. Here's why each KPI is essential:

Indicated Work Done: Accurately measuring the work done is directly tied to engine performance capabilities of converting fuel into mechanical energy. The engine's design and operational efficiency are positively indicated by the value of 1079.44J, which indicates that the combustion energy is being used successfully. When compared to diesel or petrol engines, hydrogen engines typically exhibit a higher rate of energy conversion efficiency due to the faster burn rate

Indicated Power: The rate of which work is done, or the power are generally higher in H2ICEs due to the expected high power-to-weight ratios. A value of 26.99kW at 1500rpm is robust, illustrating the engine's capacity to handle high-demand scenarios efficiently. This value confirms that the engine is competitive with its petrol and diesel counterparts while being more environmentally friendly

Indicated Torque: Rotational force produced at a standstill indicates the ability to handle loads allowing engineers to improve drivetrain designs and enhance the vehicle's overall handling and performance. Although there is insufficient information to directly compare our value to fuel alternatives, it is reasonable to assume that diesel engines may produce more torque at lower speeds. However, hydrogen engines are rapidly catching up, providing cleaner alternatives with enough torque for most real-world applications.

Thermal Efficiency: Typical values for petrol engines and modern diesel engines, usually range between 30% to 40%. The 46.43% efficiency for a hydrogen engine underscores its capability to effectively convert thermal energy into mechanical work. This high level of efficiency is attributable to hydrogen's properties previously discussed. These findings highlight the strengths of the current model and set the stage for a broader discussion on its implications, limitations, and potential improvements moving forward.

7. Discussion and Conclusion

The primary findings of the study are presented in this chapter, along with suggestions for future research directions to improve the modelling and implementation of hydrogen engines.

7.1 Summary of Findings

Using Simulink and Realis WAVE, this study successfully evaluated the accuracy and viability of simulating a hydrogen-fuelled internal combustion engine. The feasibility of Simulink for simulating H2 combustion was confirmed by the great accuracy with which key outputs including pressure, temperature, and heat transfer rate were reproduced, with errors kept to less than 3%.

The simulation demonstrated how hydrogen, which can generate high peak pressures and temperatures while only releasing water vapour, has the potential to be a sustainable fuel substitute. The integrated electronic control unit (ECU), a crucial component of the vehicle, responded precisely to shifting operating conditions and dynamically changed with engine speed. This confirmed how well the ECU controlled system behaviour and combustion timing.

Exhaust data was not fully captured in the simulation due to limited information available from the Realis WAVE model, particularly around boundary conditions. As such, exhaust behaviour was not a focus in the current analysis.

7.2 Recommendations for Future Research

To advance H2ICE development and simulation fidelity, the following research directions are proposed:

1. Transient Operation Modelling

To more accurately depict real engine behaviour and confirm the model's resilience in dynamic situations, include non-steady-state variables (such as load variations and cold starts). [20]

2. Start of Injection and Ignition Timing Control

Examine how different SOI and ignition time affect the stability of combustion and the rise in pressure. This is essential for controlling the high flame speed of hydrogen and reducing misfire or knock.

3. Alternative Fuel Blending

Examine how combining hydrogen with different fuels (such as methane or ammonia) can enhance flame control, lower NOx, and increase the engine's operating range. Additionally investigate replacing the hydrogen entirely. [21]

4. Improved Heat Transfer Modelling

Increase accuracy, particularly during the combustion and expansion phases, by permitting varying wall temperatures and more accurate surface area estimates.

5. Material Stress and Durability Analysis

Examine how burning hydrogen affects engine materials over the long run, especially when there is high thermal and cyclic loading.

6. Simulation-Guided Control System Development

Utilise the model to aid in the creation of real-time engine control plans, maybe combining it with AI-based or adaptive systems to optimise combustion.

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Ethics Awareness Form for Taught Student Projects

All students should discuss with their supervisor whether their project might conflict with the University's ethical principles which can be found in the Ethical Policy Framework.

Students should complete the second column in the table below, discussing with their supervisor as appropriate.

Aspect of project	Does the project involve this aspect? (Yes / No)	If Yes, follow the process(es) below
Investigations with human participants and activity falling under the Human Tissue Act	**No**	1. Complete the Ethical Quick Test 2. Follow the process outlined on the HPSC Website
Military Applications, Dual Use Technologies or Security Sensitive Research	**No**	1. Complete the Ethical Quick Test 2. Follow the process outlined in Appendix 4
Accessing potentially security-sensitive material (e.g. online terrorist content or materials)	**No**	1. Complete the Ethical Quick Test 2. Follow the process outlined in Appendix 5
Funding by philanthropic gifts	**No**	Follow the process outlined in Appendix 6
Animal testing	**No**	Contact the Research Governance Officer: researchpolicy@lboro.ac.uk
Possible conflict with ethical principles partially or wholly outside the above.	**No**	1. Complete the Ethical Quick Test

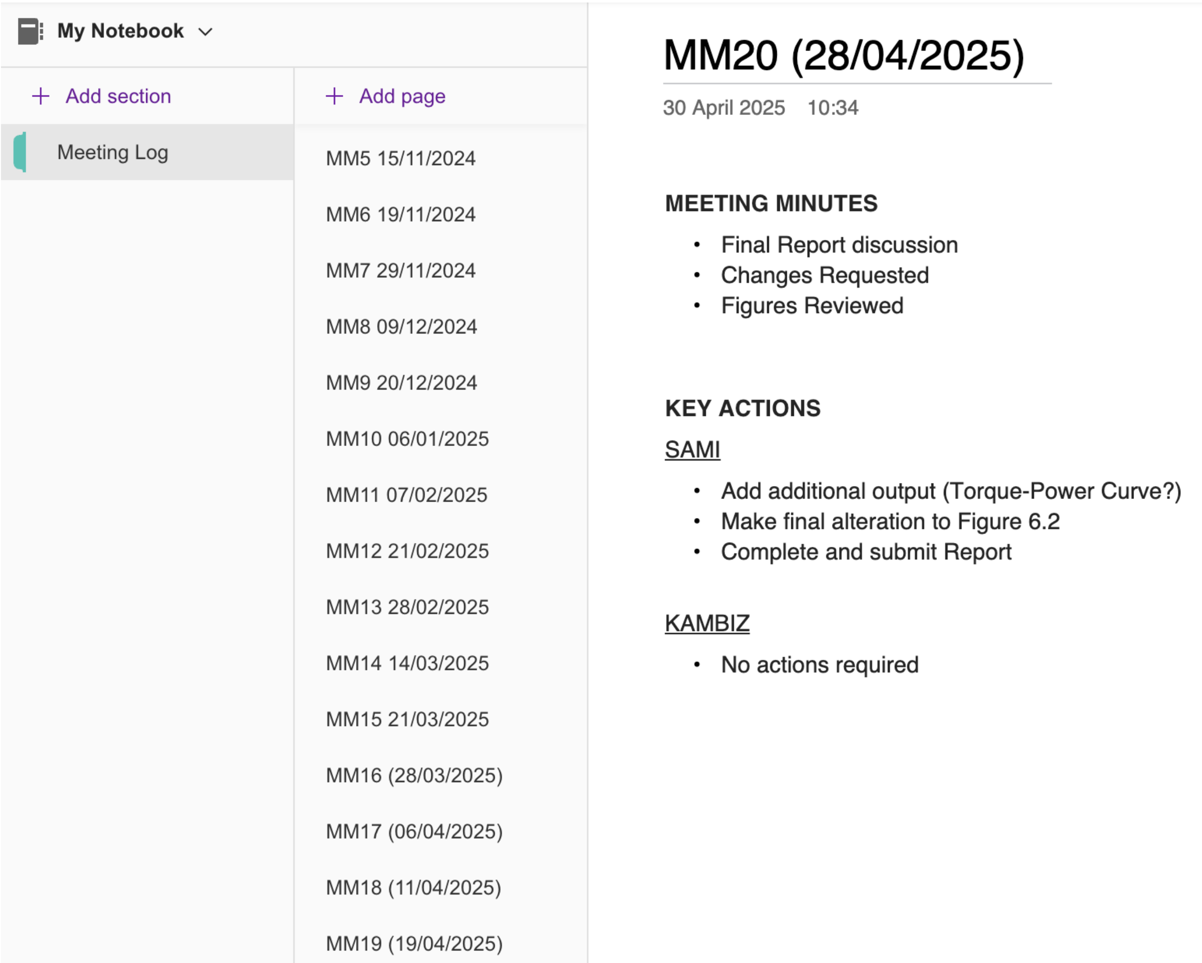
Student Declaration

I confirm that I have discussed the ethics awareness form with my supervisor and, if appropriate, followed the relevant guidance / made the relevant application.
Student name: Sami Khan
Student ID number: F126225
Signature:
Date: 30/04/2025

Supervisor Declaration
I confirm that I have discussed the ethics awareness form with my supervisee and, if appropriate, requested that they follow the relevant guidance / make the relevant application.
Supervisor name: Kambiz Ebrahimi
Signature:
Date: 30/04/2025

Meeting Log

Meeting minutes serve as a record of the meetings for this project. These are documented in a OneNote Notebook and distributed via email following each meeting. An example of one of these meeting minutes is shown below, complete with all the dates.



Student Declaration

I confirm that I have had these meetings with my supervisor and can verify that they took place as scheduled.
Student name: Sami Khan
Student ID number: F126225
Signature:
Date: 30/04/2025

Supervisor Declaration
I confirm that I have had these meetings with my supervisee and can verify that they took place as scheduled.
Supervisor name: Kambiz Ebrahimi
Signature:
Date: 30/04/2025