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Review

A Comprehensive Review of the GT-POWER for Modelling Diesel Engines

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Abstract: The increasing demand for efficient and environmentally friendly diesel engines necessitates advanced simulation tools, with Gamma Technologies' GT-POWER emerging as a leading software suite for this purpose. This review paper examines the capabilities of GT-POWER for modelling diesel engines, exploring its fundamental principles, user interface, modelling techniques, and simulation capabilities, alongside comparisons with other formidable simulation tools. Moreover, various case studies from the literature are presented to illustrate its application. While there are some shortfalls within the context of GT-POWER, such as the need for further exploration of underutilized areas, the current focus on primarily 1D and multi-zone modelling requires expansion. Coupling GT-POWER with other simulation software for multiphysics analyses—such as CFD for combustion, structural analysis for component stress, fluid flow, and heat transfer—offers significant potential; however, this integration remains largely unexploited. Despite its limitations, the results consistently reveal the software's versatility in optimizing engine performance across diverse applications, including component design, alternative fuel evaluations, and integration with various technologies such as MATLAB/Simulink, Artificial Neural Networks, and Python. The consistent findings across multiple studies further confirm GT-POWER's effectiveness as a leading simulation tool for advancing diesel engine technology. Ultimately, this study bridges the gap between theoretical understanding and practical application, making it a valuable resource for researchers and engineers in the field of internal combustion engine optimization.

Keywords: diesel engine; simulation; GT-POWER; modelling; MATLAB; Simulink

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1. Introduction

In the evolving landscape of automotive engineering, searching for more efficient, powerful, and environmentally friendly diesel engines is a constant challenge. Diesel engines play a crucial role in various applications ranging from transportation to industrial machinery, necessitating innovative approaches to design and optimization [1,2]. To achieve enhanced performance and reduced emissions, researchers increasingly rely on advanced simulation tools. Among these, Gamma Technologies' GT-POWER stands out as a leading software suite designed specifically for the modelling of internal combustion (IC) engines and their components [3,4]. GT-POWER facilitates comprehensive simulation capabilities that allow users to analyze engine performance, optimize design parameters, and predict the impact of various operating conditions. Its one-dimensional (1D) modelling approach simplifies complex interactions within the engine system, enabling rapid analysis and iterative development cycles [5]. With features such as advanced combustion modelling, thermodynamic analyses, and component characterization, GT-POWER empowers users to explore the complex dynamics that govern diesel engine behavior.

The significance of the present study is that it provides a comprehensive guide to utilizing GT-POWER for research and development purposes. The study contributes to research by outlining the software's features (such as 1D modelling, comprehensive component libraries, advanced combustion modelling, and parameter sensitivity analysis) which enable researchers to design, optimize, and validate IC engine models in a virtual environment. A comparison of GT-POWER with leading alternatives like Converge CFD, ANSYS Fluent, and AVL FIRE reveals distinct advantages, especially for researchers focused on IC engine modelling. GT-POWER's specialized design for 1D simulations provides a streamlined workflow for analyzing engine performance, thermodynamics, and dynamic processes. This reduces the need for extensive and costly physical experimentation. The objectives of this study are to examine the capabilities of GT-POWER and its potential for enhancing understanding of IC engine performance, optimizing designs for improved efficiency and reduced emissions, and exploring various operating conditions through simulation, ultimately leading to advancements in engine technology.

Previous studies that have successfully modelled and simulated diesel engines using GT-POWER are explored in detail. Furthermore, this study examines the integration of other machine learning techniques, including MATLAB/Simulink, Artificial Neural Networks (ANNs), and Python, within the context of GT-POWER. This integration facilitates rapid performance optimization, allowing researchers and engineers to efficiently explore design alternatives without the extensive computational overhead. By combining current knowledge and practical experience with GT-POWER, this review bridges the gap between theory and application, contributing to advancements in diesel engine design and overall performance improvements.

2. Overview of GT-POWER

GT-POWER is a powerful simulation software suite specifically designed for modelling and analyzing the performance of IC engines, including diesel engines. With its advanced 1D modelling capabilities, GT-POWER enables researchers to simulate a wide range of engine components and processes, including combustion, fluid dynamics, thermodynamics, and emissions [3,6]. The software provides a simple interface and a detailed library of predefined models, allowing users to effectively design, optimize, and validate engine systems in a virtual environment. GT-POWER is widely used in both research and industry, facilitating the development of innovative solutions that enhance engine efficiency, reduce emissions, and improve overall performance. Its flexibility and comprehensive features make it a vital tool for automotive engineers and researchers striving to meet the challenges of modern engine design [7]. GT-POWER software has several features and functionalities which make it suitable for modelling diesel engines. Table 1 provides these features and functionalities for better understanding of the software.

Table 1. Basic features and functionalities of GT-POWER [6–9].

Feature	Functionality
1D modelling capabilities	1D modelling techniques simplify complex engine system simulations, allowing for quick evaluation of different configurations and conditions.
Comprehensive component library	An extensive library of predefined engine components, including pistons, valves, turbochargers, and intercoolers, facilitates quick assembly of engine models.
Advanced combustion modelling	Supports various combustion models, such as multi-zone and single-zone approaches, enabling detailed simulation and analysis of combustion processes.

Table 1. *Cont.*

Feature	Functionality
Thermodynamic analysis	In-depth thermodynamic analyses, calculating key parameters like pressure, temperature, and heat transfer throughout the engine cycle.
Fluid dynamics simulation	Effectively simulates fluid flow within engine components, offering insights into aerodynamics, fuel delivery, and scavenging processes.
Emission prediction	Includes tools for predicting emissions based on combustion characteristics, helping engineers optimize designs to meet regulatory standards.
User-friendly interface	The insightful graphical user interface (GUI) simplifies model creation and manipulation, allowing for easy visualization and adjusting the simulation.
Parameter sensitivity analysis	Provides capabilities for conducting sensitivity analyses, enabling users to identify critical parameters that significantly affect engine performance.
Data visualization tools	Offers powerful data visualization options, including graphs, charts, and animations, to help interpret simulation results effectively.
Integration with other software	Can interface with other simulation tools and software, such as MATLAB/Simulink, enhancing its versatility for multi-domain modelling approaches.
Real-time simulation	Supports real-time simulation capabilities, enabling on-the-fly adjustments and interactions during testing and development phases.
Custom model development	Flexibility to create custom components and systems, customizing the software to meet specific modelling needs or unique engine configurations.
Case studies and benchmarks	Provides access to various case studies and benchmarking data, enabling validation of the model against industry standards and historical performance parameters.

3. GT-POWER User Interface

3.1. Navigation Through GT-POWER's Interface

GT-POWER's interface is designed to be user-friendly, facilitating an efficient modelling experience for engineers and researchers [10,11]. Upon launching the software, users are welcomed with a clean and organized workspace featuring a comprehensive menu bar at the top providing direct access to various functions such as file management, simulation settings, and visualization tools. The main workspace is divided into two key sections (Figure 1): the model tree on the left, which allows for viewing and organizing engine components hierarchically, and the central modelling area on the right, where users can design and manipulate their engine models through a drag-and-drop functionality. On the central modelling area, users can display specific parameters for the selected component, enabling detailed customization [12,13]. Context-sensitive help is readily available throughout the interface, guiding specific features and functionalities [14]. Shortcuts and toolbars enhance navigation efficiency, making it easy to switch between different sections of the software.

3.2. Explanation of Menus, Toolbars, and Windows

The menu functionality provides potential and existing users with a comprehensive understanding of how the software is structured and how it can be effectively utilized to enhance modelling workflows in IC engine simulations. By detailing the key features of each menu, users can recognize how these functionalities align with their specific needs whether they are focused on project management, data manipulation, or real-time analysis. The emphasis on customization and user support underscores GT-POWER's commitment to user-orientated design, which is crucial in fostering a positive user experience [15,16]. Understanding the available support resources, such as documentation and tutorials can empower users, particularly those new to the software or the field, by reducing the learning curve and increasing their confidence in using the tool effectively. The interface features a comprehensive menu bar at the top, which includes several primary menus such as a file, home, view, data, tools, utilities, Git, and help shown in Figure 2 and briefly described in the next paragraph.

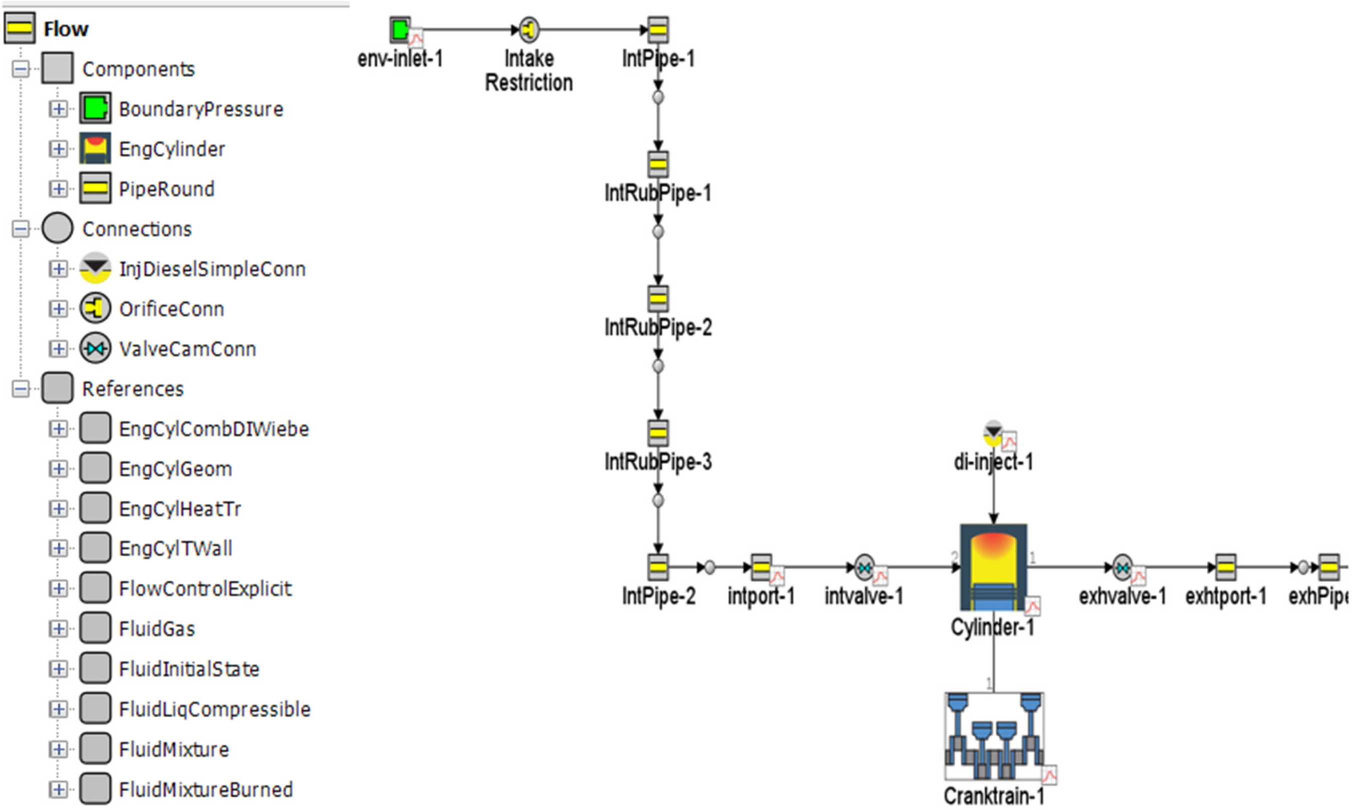

Figure 1. GT-POWER ISE v2024 main workspace.

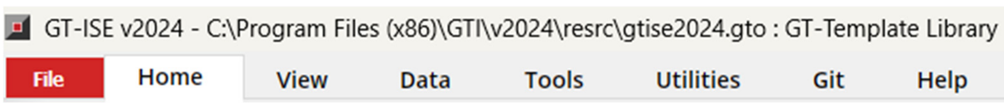

Figure 2. GT-POWER ISE v2024 menu bar.

GT-POWER provides a comprehensive framework for IC engine simulations underscored by its thoughtfully designed menu functionalities that enhance user engagement and efficiency [17]. The file menu facilitates efficient project management by allowing users to create, open, and save simulation files, while the home menu ensures rapid access to common tasks and tools, thereby improving overall workflow efficiency. In addition, the view menu permits customization of the user interface, fostering a personalized environment conducive to effective data visualization [18,19]. The data menu serves as a central hub for managing input parameters and outputs, ensuring stringent control over simulation datasets. Additionally, the tools menu offers a range of utilities for model editing, simulation management, and optimization, which further amplifies GT-POWER's analytical capabilities. Support resources embedded within the utilities menu—including documentation and tutorials—aid users in navigating the software with confidence, and the Git menu streamlines version control and collaboration among multiple users [20]. Collectively, these menu designs not only enhance user experience through intuitive navigation and robust data management but also position GT-POWER as a formidable tool for engine modelling [21].

3.3. Customisation Options for User Preferences

GT-POWER recognizes the diverse needs of its users and provides various customization options to customize the interface to individual preferences. Users can modify the layout of toolbars by adding or removing icons based on their frequently used functions. Additionally, the appearance of the interface can be adjusted with themes and colors to improve visibility and comfort during long modelling sessions [22]. Furthermore, the software enables the creation of custom templates and saves specific settings for components, allowing for quicker model creation in future projects [23,24]. This level of customization ensures that the GT-POWER interface is adaptable, promoting an efficient and personalized modelling environment that caters to an individual's workflow and preferences.

4. Building a Diesel Engine Model in GT-POWER

Creating a diesel engine model in GT-POWER involves several steps in the process of defining the engine geometry, components, and essential parameters. This process is vital as it offers a structured framework that guides users through the complexities of engine modelling, ensuring systematic integration of essential components into the simulation [25]. The process is crucial for both novice and experienced users, enhancing their understanding of the interactions among various engine elements and leading to more accurate simulation outcomes. Careful attention must be paid to specific tasks such as defining engine geometry, inputting operating parameters, and setting up combustion models because this directly impacts the fidelity of results [26,27]. By following a logical sequence of steps, users can minimize errors and streamline their workflow, improving efficiency and productivity, especially in research and development settings where timely insights are critical. Furthermore, familiarization with these processes builds user confidence and expertise, empowering individuals to explore more complex analyses and innovate within the field of IC engine research. Ultimately, this process equips users with the necessary skills to conduct meaningful analyses and significantly advances their understanding and capabilities in engine simulations. The basic guide is presented and discussed below:

- Launching GT-POWER: Upon opening the software, one begins by selecting a new project from the file menu, which sets the stage for constructing a blank workspace dedicated to the engine model. This workspace acts as the foundation from which users can build their simulation structure, thus facilitating a well-organized approach to engine modelling [28,29].
- Model tree: Once the workspace is established, users can access the model tree on the interface. This hierarchical display outlines the components within the engine model and provides a clear organization of the various elements involved. In this way, users can explore options for adding new components, thereby streamlining the process of expanding the model as required [26,28,30].
- Add engine components: The next task involves adding engine components to the model. This can be accomplished on the model tree by selecting "Add Component". By choosing the "Engine Cylinder" option, users can accurately define the primary structure of their diesel engine. Following this, additional components such as pistons, crankshafts, valves, calorimeters, and auxiliary systems can be incorporated. These components are readily accessible from the parts library or through the component's menu, allowing for a comprehensive assembly of the engine model [27,28,31].
- Define engine geometry: Users should begin by setting the dimensions of each component using the properties window on the interface. Key specifications, such as bore, stroke, and cylinder head configurations, must be carefully inputted to ensure accuracy. Furthermore, it is important to define the arrangement of the cylinders—whether they

are inline or configured in a V-type layout—reflecting the design intentions of the engine [32,33].

- Inputting engine parameters: This task includes defining the type of fuel (such as diesel) and any relevant fuel blends by selecting appropriate options within the properties window [28]. Additionally, crucial data such as engine speed (in RPM), load conditions, and specific temperature settings must be inputted, laying the groundwork for realistic operational conditions. Users should also specify key performance characteristics, including compression ratio, boost pressure for turbocharged engines, and injection timing to optimize the model's performance outcomes [29,34,35].
- Combustion models setup: GT-POWER offers various options, including single-zone and multi-zone combustion models, allowing users to select the model that best fits their analysis needs [27,28,33]. Adjustments to settings related to ignition timing, air-fuel ratio, and combustion efficiency can then be made to fine-tune the model's predictive capabilities.

Ultimately, building the diesel engine model also requires ensuring that all components are properly connected. This involves utilizing the drag-and-drop functionality to create flow paths between different elements, such as linking the fuel supply system to the combustion chamber and exhaust components. This connectivity is vital for accurately simulating the interactions within the engine.

5. Simulation Setup and Execution

Simulation setup and execution in GT-POWER involves creating a detailed engine model by selecting and assembling various components from the predefined library [36]. Users can define simulation parameters including operating conditions and combustion models, to accurately represent the engine's behavior. Once the model is configured, simulations are run to analyze performance parameters such as brake specific fuel consumption (BSFC), output power, and torque and efficiency. The results can then be visualized through graphs and charts, allowing for the interpretation and optimization of the engine design based on the obtained data [37]. This process enables efficient evaluation of different engine configurations and operating scenarios.

5.1. Setting Simulation Parameters and Conditions

Preparing for simulation in GT-POWER necessitates careful consideration of various parameters that are integral to achieving accurate and relevant results in the context of diesel engine analysis. The first step involves determining the simulation type where the user must decide between a steady-state or transient analysis based on the specific objectives of their investigation. This choice significantly influences the simulation dynamics and the insights generated [31,37]. Concurrently, the selection of an appropriate combustion model—whether opting for a multi-zone or single-zone approach—plays a crucial role in accurately representing the combustion processes, as each model offers different levels of detail and precision reflective of the complexity of the engine operation. Furthermore, defining the operating conditions is of paramount importance, necessitating inputs such as engine speed, compression ratio, load conditions, intake air temperature, and fuel injection timing, all of which must closely align with realistic scenarios to ensure the validity of the simulation [38]. Finally, specifying thermodynamic parameters is essential for conducting powerful thermodynamic calculations, requiring careful attention to pressure and temperature profiles that authentically represent the engine's operating environment. Consequently, precise preparation of these simulation parameters not only lays the groundwork for a successful simulation but also enhances the overall reliability and applicability of the results obtained from GT-POWER [39,40].

5.2. Running Simulations and Interpreting Results

Running simulations in GT-POWER involves a methodical approach that concludes with the interpretation of results, thus enabling meaningful insights into engine performance. After configuring all relevant parameters the simulation can be initiated, with users being able to monitor the process through the GT-POWER interface, allowing for real-time assessment of the run [38,41]. Concurrently, setting up data logging is critical for gathering key output parameters throughout the simulation, including pressure, temperature, and emissions data, which form the foundation of the subsequent analysis. Upon completion of the simulation, users can utilize the advanced data visualization tools provided by GT-POWER to interpret and analyze the results. This involves examining various graphs and charts that clarify key performance indicators such as BSFC, power output, torque, and exhaust emissions [42,43]. The insights gained from this analysis can inform decisions on engine performance and efficiency. Moreover, if the initial results indicate areas for improvement, users have the opportunity to refine their simulation by adjusting relevant parameters and rerunning simulations. This iterative process of optimization enhances the fidelity of the model and also facilitates a deeper understanding of the engine dynamics, ultimately contributing to more informed engineering decisions and advancements in engine design.

6. Challenges and Troubleshooting Methods

Modelling diesel engines in GT-POWER presents various challenges that can impact the accuracy and reliability of simulation results. One may encounter issues such as model complexity, data input errors, and convergence problems during simulations [44]. Understanding these challenges is crucial for effective troubleshooting and ensuring a smooth modelling process. By implementing targeted strategies for resolving issues and optimizing models, the user can enhance the workflow and achieve more accurate performance assessments of diesel engines. The common challenges faced in GT-POWER modelling are presented below, providing troubleshooting tips, and outlining strategies for effective optimization.

- Model complexity: One notable challenge is model complexity; designing a comprehensive and detailed model that accurately represents all engine components and operational conditions can be both overwhelming and time-consuming [44,45]. The complex nature of engine systems demands an iterative approach, in which users begin with a simplified representation that captures key components and functionalities. Once a basic model is established, additional details and complexities can be incorporated gradually, allowing for more manageable development and refinement [46].
- Data input errors: Another common issue is the occurrence of data input errors which can significantly undermine the validity of simulation results. When incorrect or incomplete data is entered into the model, the subsequent outputs may reflect inaccuracies that mislead analysis and decision-making. To mitigate this risk, thorough validation of all input parameters is essential [47]. Users should establish a concise review process to ensure that the data entered is both accurate and complete, thereby preventing potential data-related discrepancies that could compromise simulation integrity.
- Simulation convergence issues: Users may encounter simulation convergence issues which manifest as difficulties in achieving stable solutions during runs. These issues may stem from overly complex models or inappropriate parameter settings that hinder the user's ability to find a solution. In such instances, users should consider modifying the solver settings—potentially by adjusting the time step size or modifying iteration limits—to enhance stability and promote convergence within the simulations [46,48].

Ensuring that the simulation settings are appropriately aligned with the model's complexity is a critical aspect of effective troubleshooting in GT-POWER.

- Combustion models: The selection and configuration of combustion models present another layer of complexity for users, particularly for those who may lack extensive knowledge of combustion processes. Understanding the distinction of the various combustion models available in GT-POWER is crucial for achieving accurate representations of combustion phenomena. To assist users in navigating this challenge, GT-POWER provides built-in help resources and user manuals, which are invaluable for clarifying specific error messages and offering recommended solutions [34,49]. By employing these resources, users can enhance their understanding and better configure the appropriate combustion model suited to their simulation objectives. Overall, addressing these challenges with a systematic and informed approach can significantly enhance the effectiveness of simulations in GT-POWER and contribute to more reliable outcomes in IC engine modelling.

7. Comparisons with Alternative Modelling Tools

The comparison of GT-POWER with alternative modelling tools is crucial in this work as such comparison highlights the relative strengths and limitations of GT-POWER in the context of other leading simulation tools. Understanding these aspects enables potential users or researchers to ascertain if GT-POWER aligns with their specific modelling needs, particularly in internal combustion engines. For example, while GT-POWER excels in one-dimensional performance modelling, a user considering complex three-dimensional simulations may need to evaluate alternatives such as ANSYS Fluent or AVL FIRE. Additionally, insights into computational costs allow organizations to weigh their budgetary constraints against the need for high-fidelity results and advanced modelling features. Understanding real-time capabilities also influences how effectively a tool can support rapid design iterations and testing environments [50]. Overall, this comparative analysis assists in strategizing and optimizing the simulation processes, ensuring that researchers select the software that aligns most closely with their operational goals, technical needs, and resource availability, ultimately leading to more effective and efficient engine design and performance outcomes. Table 2 summarizes the comparisons between GT-POWER and alternative simulation tools.

When evaluating GT-POWER against formidable alternatives like Converge CFD, ANSYS Fluent, and AVL FIRE, it becomes evident that GT-POWER holds distinct advantages, particularly for users/researchers focused on IC engine modelling. Its design specifically caters for 1D simulations, offering a streamlined approach to analyzing engine performance, thermodynamics, and dynamic processes [55,56]. This focus allows for lower computational costs and rapid simulation capabilities, making it an excellent choice for preliminary design phases and parametric studies. While GT-POWER does have limitations in terms of model fidelity due to its 1D nature, its strengths in efficiency and ease of use are significant considerations for engineers seeking quick insights into engine behavior without the heavy computational demands of 3D tools.

While tools like Converge CFD and ANSYS Fluent provide high-fidelity modelling and advanced real-time capabilities through complex simulations, they come with increased costs and computational resource requirements that may not make them accessible or necessary for every project. AVL FIRE specializes in combustion modelling, but also presents cost concerns and has limited capability in certain applications [57]. Thus, GT-POWER emerges as a valuable solution for users who prioritize efficiency, cost-effectiveness, and practical application in engine analysis, particularly when the primary need is for rapid modelling and iterative assessments throughout the design process. Ultimately, the choice of simulation software hinges on aligning capabilities with specific needs and for many users, GT-POWER represents a pragmatic and effective option within the area of engine simulations.

Table 2. Comparison of GT-POWER with alternative modelling tools [51–54].

Feature/Aspect	GT-POWER	Converge CFD	ANSYS Fluent	AVL FIRE
Application	Designed for 1D engine modelling, allowing for analyses of engine performance, thermodynamics, and dynamic processes.	Optimized for detailed transient simulations of complex fluid flows, specifically tailored to IC engines.	A 3D CFD tool capable of handling detailed fluid dynamics and heat transfer simulations.	Focused on CFD simulations for IC engines and powertrains, excels in detailed combustion modelling.
Computational cost	Has lower computational costs due to its 1D modelling focus, which generally requires less computational power and time compared to 3D simulations.	Has high licensing costs and necessitates substantial computational resources due to its focus on detailed transient simulations.	High licensing costs that may disadvantage some potential users, and computational resource requirements can be significant for larger models.	Has high licensing fees. However, computational costs are moderate but can elevate due to demanding simulation requirements.
Model fidelity	Limited to 1D simulations; it focuses on thermodynamic processes but may lack the detail in fluid dynamics and multiphase interactions present in more advanced 3D tools.	Exceptionally high fidelity in turbulent flow and combustion modelling due to its adaptive meshing capabilities.	High modelling fidelity due to the capability of 3D modelling, especially with complex geometries and turbulent flows.	Excels in high-fidelity combustion modelling, providing detailed insights into thermal behavior and emissions.
Real-time capabilities	Its strong point lies in its rapid simulation capabilities for parametric studies and real-time performance evaluations, making it ideal for preliminary insights in the design phase.	Designed for real-time simulations, leveraging automatic meshing and efficient handling of complex flows to allow near-real-time evaluations.	Provides real-time simulation through live data streaming and integration with other ANSYS products, but complex scenarios may challenge real-time responsiveness.	Supports real-time analysis to some extent, particularly for engine performance during testing.
Limitations	Limited to 1D, lacks 3D capabilities.	High cost, resource-intensive for large models.	High licensing cost, complex setup.	Significant costs, limited beyond certain applications.

8. Practical Application of GT-POWER for Modelling Diesel Engines

Recent literature highlights the effectiveness of GT-POWER in employing 1D and multi-zone modelling techniques to optimize engine efficiency and reduce emissions [58]. These studies also emphasize the importance of validating simulation results against other similar previous studies or experimental data to ensure accuracy, as well as the integration of GT-POWER with other simulation tools to enhance predictive capabilities. This section reflects GT-POWER's role in driving advances in diesel engine technology and continuous improvement of engine designs. This is achieved by reviewing studies that have successfully used GT-POWER to model and simulate diesel engines, analyzing how their objectives were met. This analysis builds upon the capabilities of GT-POWER detailed in Sections 1–6.

8.1. Optimisation of Engine Performance

Kulkarni et al. [59] developed a comprehensive 1D model of a single-cylinder four-stroke direct injection (DI) diesel engine aimed at enhancing experimental analysis for students during laboratory sessions. This model, illustrated in Figure 3, enables students to simulate the actual engine located at the laboratory in order to conduct various performance assessments, including valve lift profile optimization, thermal analysis of the cylinder, and evaluation of engine noise during the intake and exhaust phases. Furthermore, the design encompasses the entire engine cycle, comprising intake, compression, power, and exhaust strokes. In a separate investigation, Johansson and Wagnborg [60] performed a detailed analysis of engine cold start simulations using GT-POWER. Their study emphasized the importance of considering the behavior of the engine and its associated components when creating a simulation model. Test-rig data were used to validate the results. Simplifications for different systems were, however, needed to create the start-up models. Interval analysis was employed for uncertainties quantification. The findings from the GT-POWER model indicated that the start-up process is significantly influenced by the cranking torque provided by the starter motor, which varies based on temperature and engine speed.

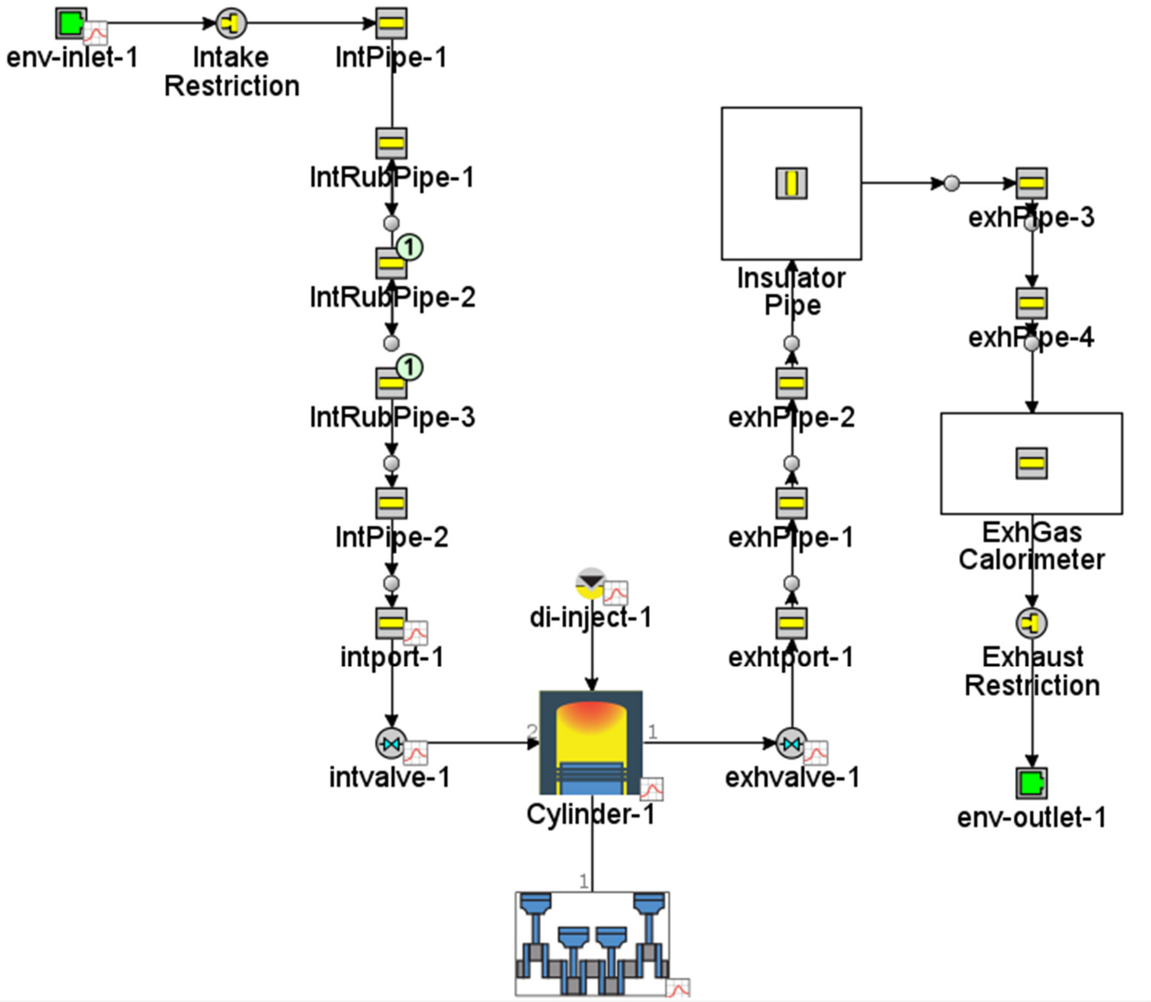

Figure 3. Engine flow-path model (GT-POWER, Integrated Simulation Technology, Pune) [59].

Semin et al. [61] focused on the simulation and visualization of engine valve lift, particularly for the intake and exhaust valves in a single-cylinder four-stroke DI diesel engine, utilizing GT-POWER as demonstrated in Figure 4. Their research established a valuable benchmark for other researchers interested in diesel engine valve profiles and timing. This capacity significantly streamlines both the time and cost associated with manufacturing camshafts for various valve profiles and subsequently testing the engine on a dynamometer. To validate this research, it is essential to compare the results with experimental findings in future studies. Building on this foundation, Verma and Bhosale [62] investigated the impact of valve lift and timing events on engine performance using the GT-POWER model developed by Semin et al. [61]. They found that increased valve lifts can enhance engine performance at higher RPMs, while lower valve lifts proved advantageous at reduced operating speeds. Notably, the intake valve lift exhibited a far more pronounced effect on volumetric efficiency compared to the exhaust valve lift. Although this study could not validate the simulation using experimental analysis, it did provide a theoretical basis for engine tests with variable cams.

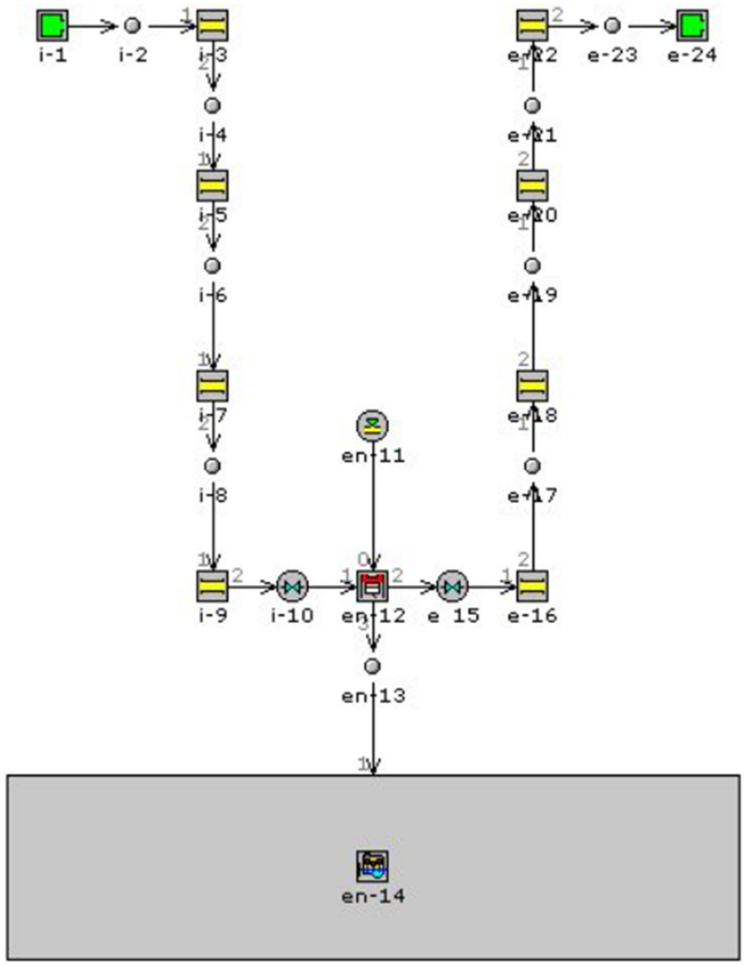

Figure 4. Single-cylinder diesel engine modelling using GT-POWER [61].

Done et al. [63] employed a similar model to simulate a single-cylinder CI engine, focusing on the analysis of combustion characteristics, performance, and emissions. A distinctive aspect of their study was the assumption that the input values for pressure and temperature at the inlet conditions were derived as output values from a turbocharger, despite the engine model being designed without a turbocharger. After conducting simulations over 10 cycles, the results indicated that as the engine RPM increased, there was a corresponding rise in several parameters, including cylinder pressure, cumulative heat release rate, engine torque, brake power, and brake mean effective pressure (BMEP). Furthermore, the concentrations of nitrogen oxides (NOxs) in parts per million (ppms) increased, while the concentrations of hydrocarbons (HCs) and carbon monoxide (CO) in ppms decreased. The accuracy of the GT-POWER model was validated through comparisons with experimental results, demonstrating a strong correspondence between the two sets of data. Moreover, a standard deviation was employed to measure the uncertainties. This alignment serves to justify the reliability and accuracy of the GT-POWER software in simulating engine performance.

8.2. Designing Engine Components

Mohiuddin et al. [64] used GT-POWER software to design an exhaust system, specifically focusing on the exhaust manifold, and subsequently compared and validated its performance to an existing system. As illustrated in Figure 5, the comparative analysis revealed that the newly designed exhaust manifold resulted in lower back pressure, which ultimately enhanced the engine's performance. This effectively showcased the versatility of GT-POWER, demonstrating its ability to design engine components for optimization purposes. Wang et al. [65] designed a muffler for a racing car to comply with formula SAE's strict rules for noise. The study employed GT-POWER software to optimize the internal structure of the muffler, subsequently validating the model through a coupling analysis that examined both dynamic performance and noise levels. This approach showed that the optimized design could effectively enhance performance while minimizing acoustic disturbances. Consequently, the noise was significantly reduced by 20%, and, finally, the design scheme meeting the target was obtained.

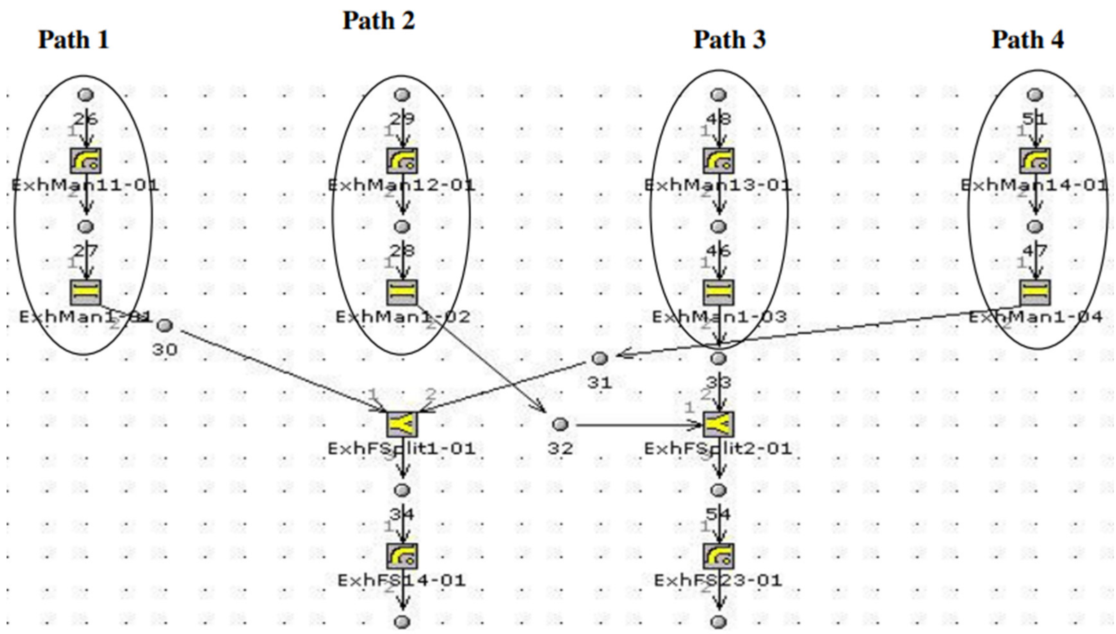

Figure 5. Newly designed exhaust manifold [64].

To improve the performance of an aviation piston engine, Chen et al. [66] developed a simulation analysis model using GT-POWER software aimed at enhancing the engine's exhaust system. The new exhaust system was designed with resonant exhaust pipes, as illustrated in Figure 6. This design was integrated into a GT-POWER model, depicted in Figure 7, for simulation purposes. The D-optimal Latin hypercube sampling method was used to obtain sample data for the experimental design of the structural parameters of the designed exhaust system. The implementation of the resonant exhaust system contributed to a notable increase in engine power, achieving an enhancement of 2.88% at cruising speed.

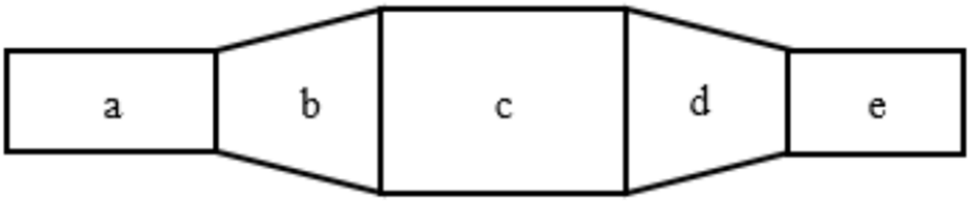

Figure 6. Resonant exhaust system structure inlet, section (a), a gradually expanding section (b), an expansion section (c), a gradually contracting section (d), and a tailpipe section (e) [66].

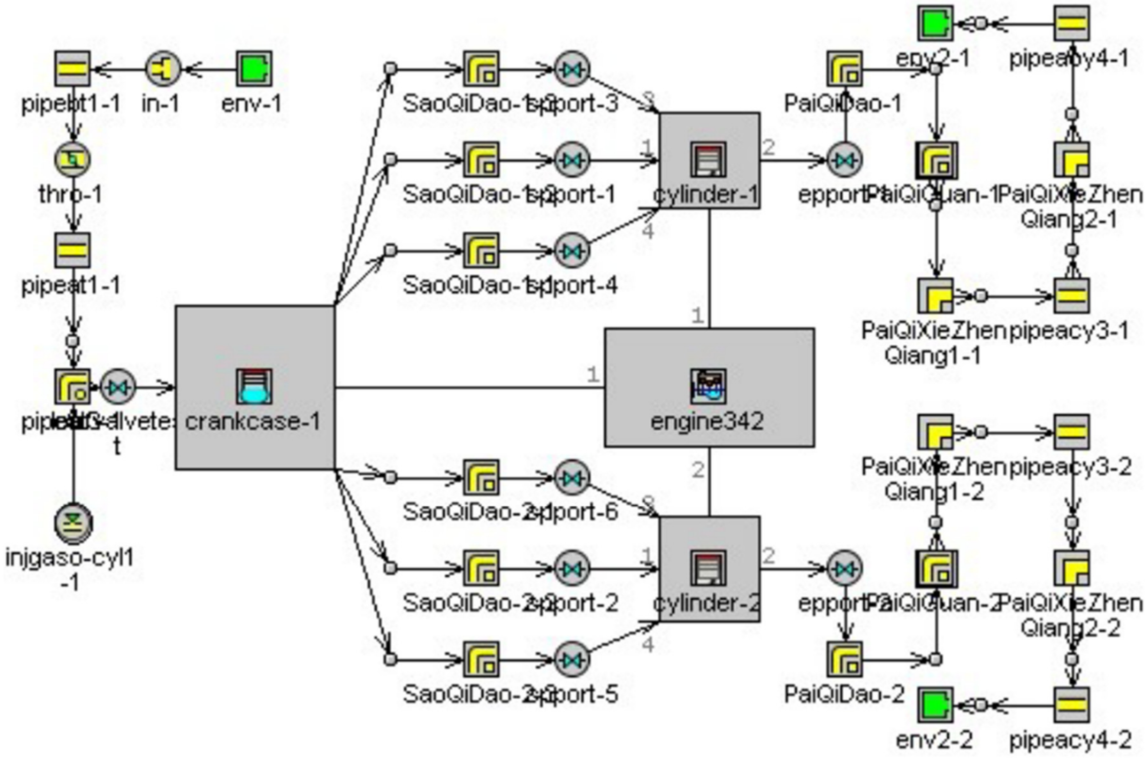

Figure 7. Engine performance simulation model [66].

8.3. Incorporation of Biodiesel Blends

Biodiesels have garnered increasing interest in optimizing diesel engine performance, primarily due to their renewable nature and potential for lower emissions compared to traditional fossil fuels [67]. Many researchers have demonstrated that GT-POWER can play a valuable role in this optimization by enabling simulations of various operating conditions and fuel characteristics [68,69]. For instance, Jiang et al. [69] investigated diesel engine power, BSFC, and emissions as optimization objectives across different load conditions when burning biodiesel in varying ratios. An optimizer model coupled with Simulink was incorporated to justify the reliability of GT-POWER model. Their findings indicated that under 75% load conditions, the model utilizing B10 biodiesel exhibited the lowest NOx emissions, BSFC, and achieved maximum power. Similarly, Semin et al. [70] explored the use of compressed natural gas (CNG) as an alternative fuel in diesel engines through GT-POWER computational simulations. They developed a GT-POWER model for a single-cylinder DI diesel engine, as illustrated in Figure 8. The results of their study demonstrated that CNG could effectively serve as an alternative fuel for diesel engines. Notably, the GT-POWER simulations revealed reductions of 44% in brake power and 49% in brake torque, alongside an increase of 49% in BSFC.

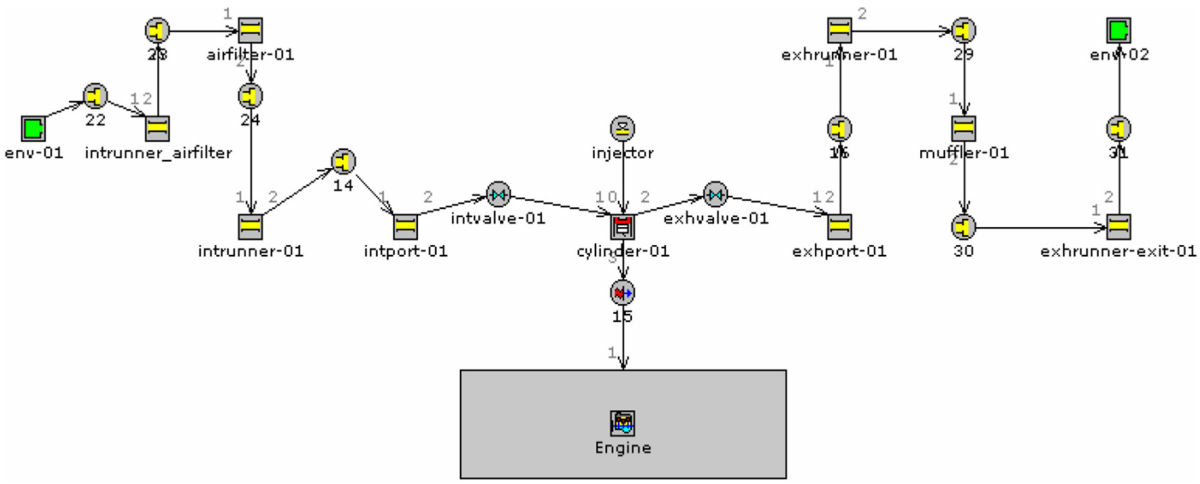

Figure 8. Single cylinder, DI diesel engine model using CNG as an alternative fuel [70].

Shah et al. [71] utilized GT-POWER simulations to identify the optimal biodiesel-diesel blended fuel that could serve as an alternative for unmodified compression ignition (CI) engine, ensuring minimal disruption to engine performance and combustion while keeping NOx emissions as low as possible. The model initially operated on pure diesel before systematically adjusting to various blend ratios by assigning the relevant attributes to the specified components. Experiments were performed to validate the simulated results by fueling the engine with B20 fuel and operating it on an alternative current (AC) electrical dynamometer. The study measured uncertainties to verify the accuracy of the experiments based on the root-mean-square method as seen in Equation (1). Both the experimental and simulated results were in good agreement revealing maximum deviations of only 3%, 3.4%, 4.2%, and 5.1% for NOx, maximum combustion pressure (MCP), engine brake power, and BSFC, respectively.

Furthermore, the combination of biodiesel, ethanol, and diesel in biodiesel–ethanol–diesel (BED) blends is believed to enhance combustion characteristics due to the differing properties of these fuels. Yahuza et al. [72] modelled and simulated combustion parameters (Intport-1 and Intvalve-1) using GT-POWER engine simulation software with BED blends as fuel, as shown in Figure 9. The engine model was calibrated for both standard diesel and biodiesel–ethanol–diesel fuels. The model was validated by comparing its results with those from previous similar studies, thereby reinforcing its credibility and demonstrating its alignment with established findings in the field. The results demonstrated a consistent increase in mass flow rate with engine speed, recording the lowest values of 0.18 kg/s for BED and 0.17 kg/s for diesel at 1760 RPM. This finding supports Peters et al.'s [73] hypothesis that the mass flow rate for proper combustion in a CI engine should range from 0.17 kg/s to 0.222 kg/s.

$$\Delta U = \sqrt{\left(\left(\frac{\sigma U}{\sigma x_1}\sigma x_1\right)^2 + \left(\frac{\sigma U}{\sigma x_2}\sigma x_2\right)^2 + \ldots + \left(\frac{\sigma U}{\sigma x_n}\sigma x_n\right)^2\right) \times \Delta x_n} \tag{1}$$

where ΔU is the total uncertainty and $x_1, x_2 \ldots .\ x_n$ are independent variables having individual errors $\Delta x_1, \Delta x_2 \ldots . \Delta$.

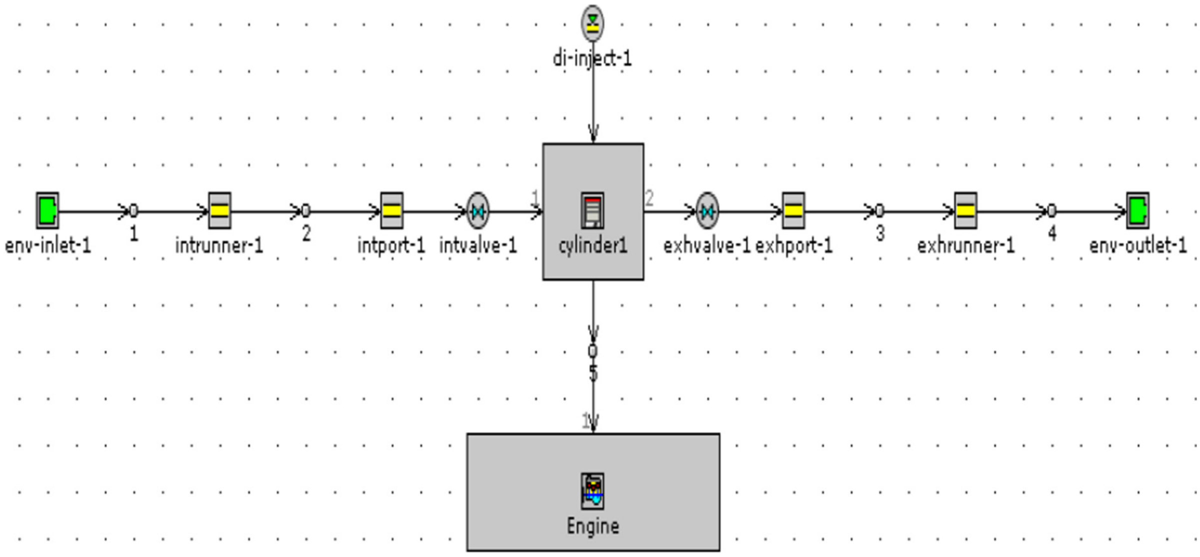

Figure 9. Engine model from GT-POWER software using BED blend as a fuel [72].

8.4. Integration with Dynamic Machine Learning

Incorporating GT-POWER with machine learning for modelling diesel engines combines advanced simulation and machine learning techniques to enhance engine performance analysis. GT-POWER is utilized to create extensive datasets through detailed simulations of various engine parameters, such as thermodynamics and combustion processes [73,74]. These datasets serve as a training foundation for machine learning techniques, which learn to predict engine performance parameters based on input conditions. This integration allows for rapid performance optimization, enabling researchers and engineers to explore design alternatives more efficiently without the extensive computational overhead. Furthermore, the combined approach enhances predictive capabilities and facilitates informed decision-making in research, performance adjustment, and emissions reduction strategies, ultimately streamlining the development process for diesel engines. A window where this advanced feature can be accessed in GT-POWER is shown in Figure 10.

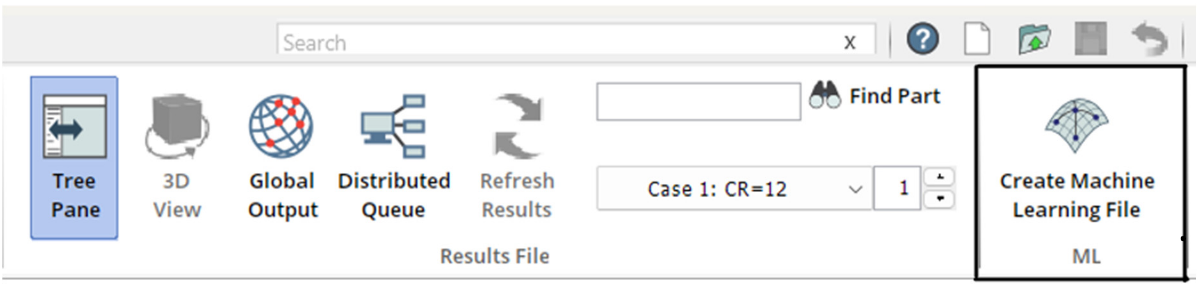

Figure 10. GT-POWER window that enables machine learning incorporation.

8.4.1. MATLAB/Simulink

One of the benefits of using GT-POWER is that it can be integrated with other reputable software such as MATLAB/Simulink. As a result of this, researchers can efficiently explore various design parameters, optimize fuel efficiency, and reduce emissions, significantly accelerating the development cycle. Moreover, the ability to visualize data and performance parameters promotes informed decision-making, ultimately leading to more innovative and effective engine designs. Jiang et al. [75] investigated the performance optimization of the engine intake system. This was achieved by developing an optimized model of the (Figure 11) engine intake system using GT-POWER coupled with MATLAB/Simulink and validated by the experimental results under the different conditions of being at full load. The results suggested that the length of the intake manifold has little influence on the engine power and BSFC but has a great impact on the performance index at high speed.

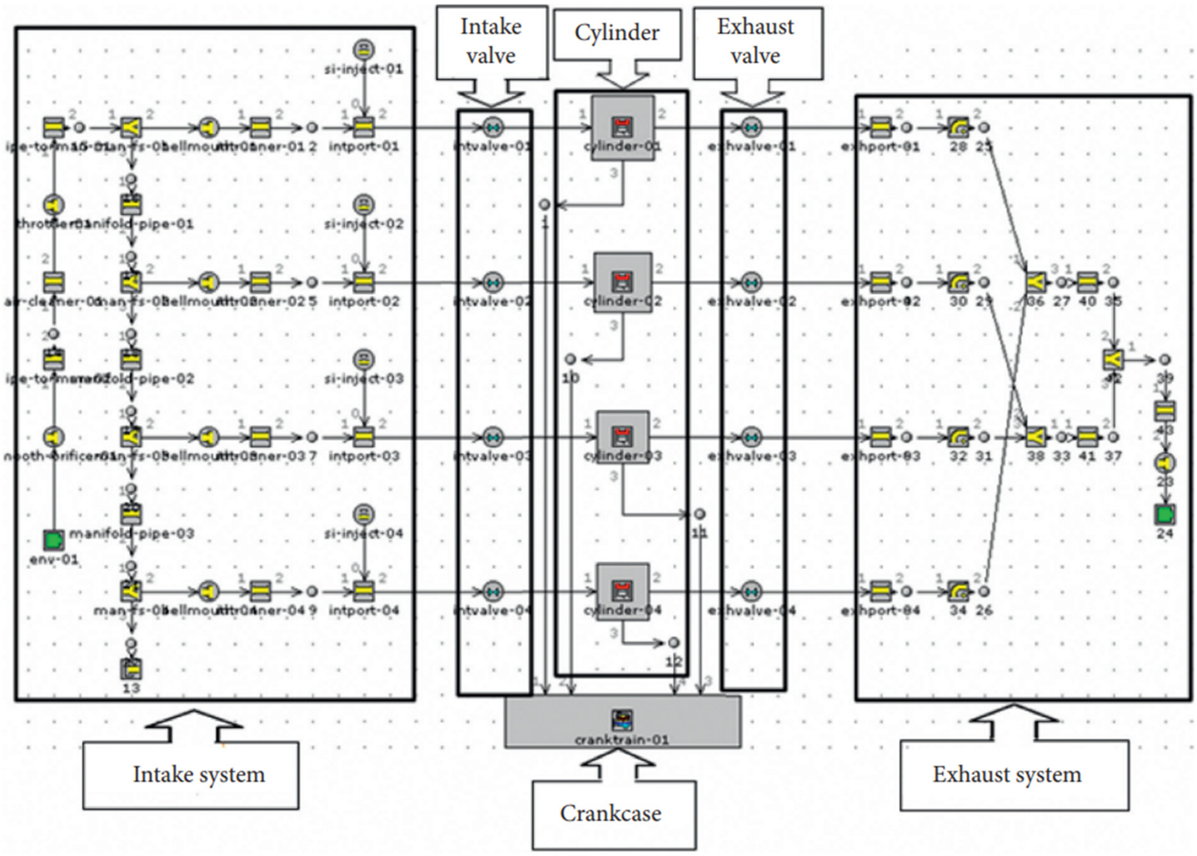

Figure 11. Simulation model [75].

Zhang and Jiang [76] developed a joint simulation environment involving GT-SUITE v7.5 and MATLAB/Simulink. They studied methanol engine speed control by controlling the throttle. They constructed both Proportional-Integral-Derivative (PID) and fuzzy PID control models within MATLAB/Simulink and integrated these control models with the methanol engine model, as illustrated in Figures 12 and 13. The model validation achieved through experimental data demonstrated that the errors in the simulation were less than 5%. This level of accuracy falls well within the acceptable tolerance range for the proposed model, further confirming its reliability. The results demonstrated that while the traditional PID control method effectively met control requirements under single load conditions, the fuzzy PID control showed a reduction of approximately 12% in overshoot of the engine speed step response curve, along with significantly lower speed fluctuations. Similarly, Meng et al. [77] investigated the effects of intake temperature, compression ratio, and pilot fuel injection timing on flue gas waste heat generation in a dual-fuel (DF) engine operating in gas mode. This study was conducted by integrating GT-POWER with the Simulink environment and was validated against the experimental data mode. The errors between the simulation values and experimental values of the main parameters were within 2%, which indicates that the established 1D simulation model can be used for further studies. The findings revealed that as the intake temperature increased, BSFC initially decreased before rising again, while both power output and power generation gradually declined. Conversely, reducing the compression ratio resulted in a progressive increase in BSFC, power, and power generation. Additionally, advancing the pilot fuel injection timing led to reductions in BSFC, power, and power generation.

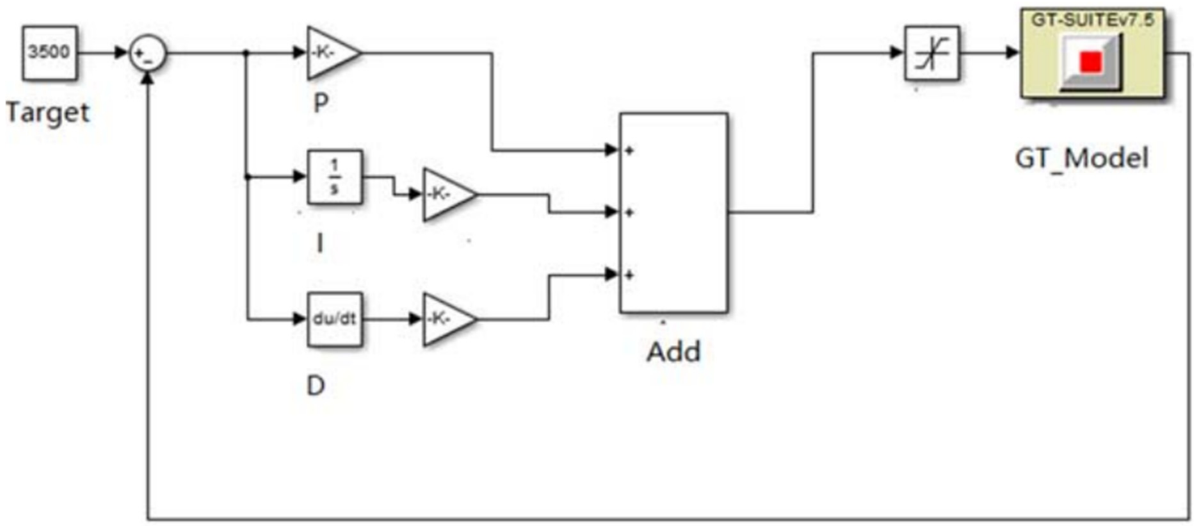

Figure 12. A traditional PID control model [76].

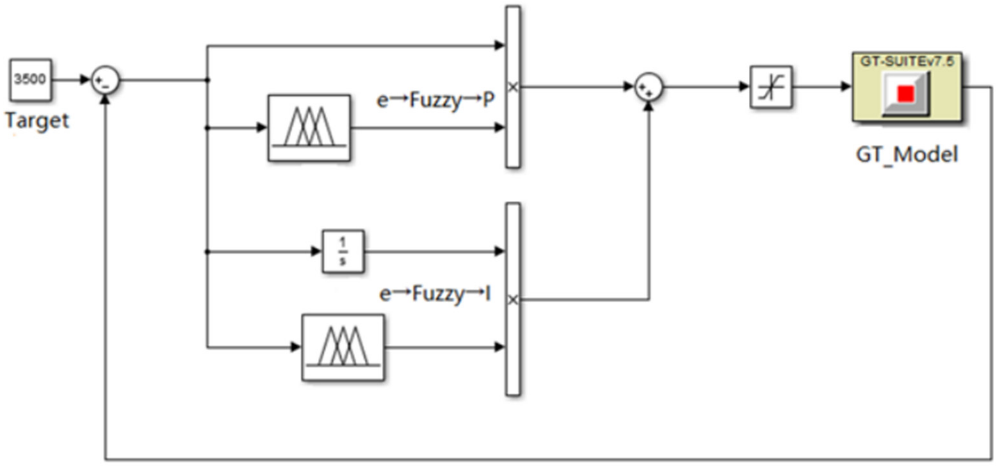

Figure 13. The fuzzy PID control model [76].

8.4.2. Neutral Network

Recent advances in artificial intelligence (AI) and machine learning (ML) technologies, particularly the application of ANNs, present an innovative approach by providing faster and potentially more accurate predictions of diesel engine performance. Ricci et al. [78] conducted a comparative evaluation of the predictive capabilities of GT-POWER and an ANN model in estimating in-cylinder pressure, with a specific focus on improvements in computational efficiency. For this study, a Back-Propagation Artificial Neural Network (BPANN) was selected, as depicted in Figure 14. The findings demonstrate that the artificial neural network model surpasses GT-POWER in predicting in-cylinder pressure with higher accuracy, achieving a root mean square error (RMSE) consistently below 0.44% across various conditions, which is predicted by Equation (1). In comparison, GT-POWER exhibits an RMSE ranging from 0.92% to 1.57%. In light of circumstances like this, GT-POWER has recently enhanced its ML assistant to support the import of time-series datasets and their training on transient neural networks. These ML models can be exported as C-code, which can then be compiled and run on microcontrollers and other low-power devices. Yap and Karri [79] incorporated the concept of an ANN virtual sensor into GT-POWER software. In this study accurate prediction results were achieved when predicted data was compared with the experimental data during the testing process. The RMSEs for all the predicted parameters were all below 9%. This study introduced the use of ANN virtual sensors for emission prediction and control of a compression ignition engine. Similarly, Jaliliantabar et al. [80] developed a neural network model to predict exhaust emissions and the performance of a CI engine. During the ANN trial, the optimal network architecture for predicting effective power was determined to be 3–8–9 after 150 epochs, as shown in Figure 15. A statistical method was employed to evaluate the results of the ANN model. The coefficient of determination (R^2), which shows the degree of association between predicted and experimental values, was applied as seen in Equation (2). The findings indicated that most emissions decreased when using biodiesel fuel. Parlak et al. [81] demonstrated the application of an ANN model to predict specific fuel consumption and exhaust temperature of a diesel engine, assessing engine performance across various injection timings.

$$RMSE[\%] = 100 \times \sqrt{\frac{1}{N}\sum_{I=1}^{N}\left(\gamma^{i}_{predicted,N} - \gamma^{i}_{target,N}\right)^2} \quad (2)$$

where N = number of observations, i = ith temporal instant, $\gamma^{i}_{predicted,N}$, = normalized predicted value, and $\gamma^{i}_{tareget,N}$ = normalized target value (experimental results).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(\gamma i_{observed} - \gamma i_{estimate})^2}{\sum_{i=1}^{N}(\gamma i_{estimate})^2} \quad (3)$$

where $\gamma i_{observed}$ are the experimental data and $\gamma i_{estimate}$ are the predicted data. These statistical measures provide information about the strength of the linear relationship between the predicted and the experimental data. If the model is "perfect", R^2 is 1. If the model is a total failure, R^2 is zero.

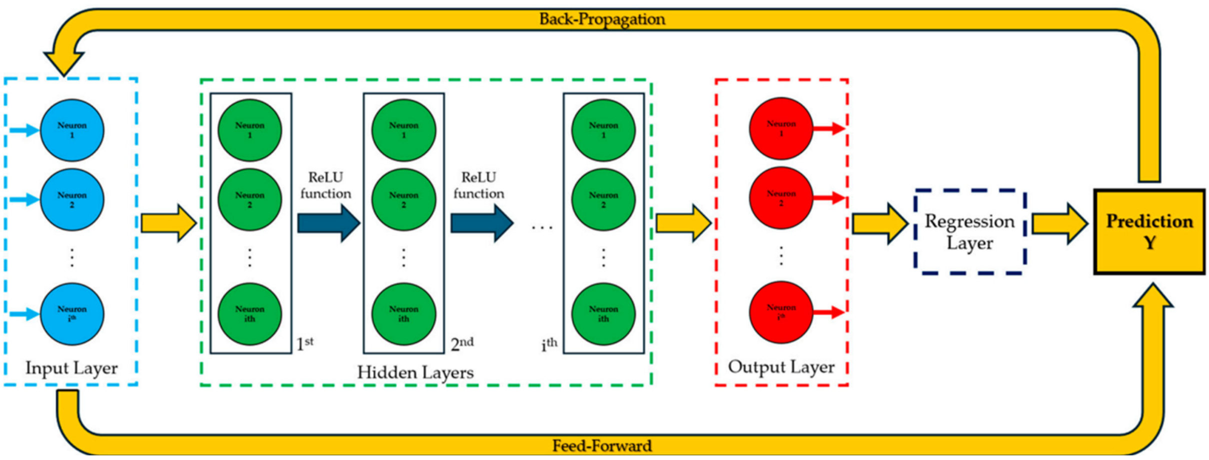

Figure 14. Conceptual layout of the BPANN [78].

Cho and Song [82] used MATLAB and the Neural Network Toolbox for ANN training, and the training results were collected and tested using Simulink. The data for ANN training under an expanded range of conditions were obtained using the GT-POWER engine model. Validation was performed using the experimental data for practical verification. Figure 16a,b illustrate the structure of the artificial neuron and multilayer feedforward network used in the study, respectively. The results of this study demonstrated a high potential for predicting the combustion process. The study is very meaningful as it can serve as a combustion model for engine simulation with high accuracy and utility. Moreover, this work illustrates that training data for the ANN, derived from the GT-POWER engine model, can save both cost and time. Generally, integrating ANNs may increase computational demands and complicate model interpretation due to their closed-system nature, making it challenging to derive clear engineering insights. Several studies have successfully processed large datasets, which allows for a more complex understanding of engine performance under diverse operating conditions [82–84]. However, the reliance on high-quality training data is critical, as poor data can lead to overfitting or inaccurate predictions. Overall, while integrating ANNs with GT-POWER is beneficial, careful consideration of data quality, model validation, and computational requirements is essential for maximizing its effectiveness in diesel engine modelling [85].

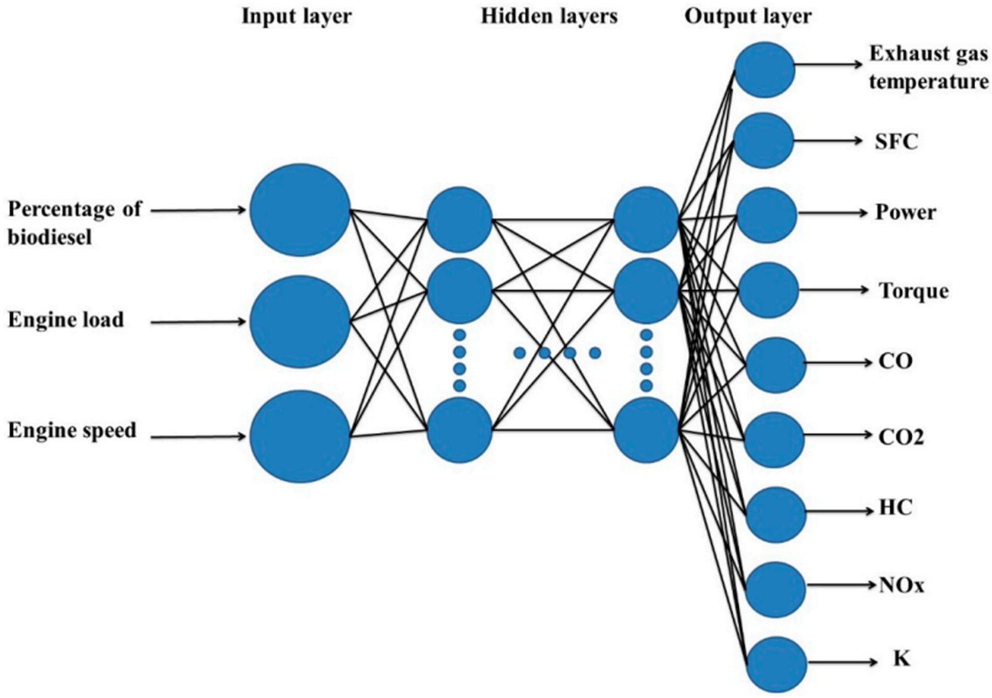

Figure 15. Architecture of the created ANN model [80].

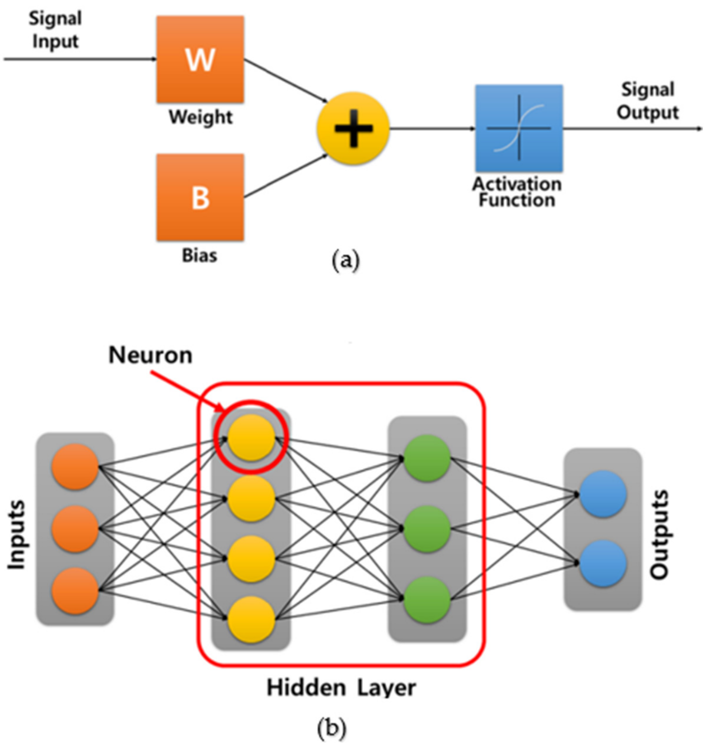

Figure 16. (**a**) Structure of the artificial neuron and (**b**) multilayer feedforward network [82].

8.4.3. Python

Python can be seamlessly integrated with GT-POWER through the GT-Automation package, enabling automation of tasks and saving valuable time [86]. This powerful tool allows the writing of Python code for manipulating GT-POWER models, effectively streamlining processes that would otherwise require manual work within the GT-SUITE interface. This automation of repetitive tasks can assist in reducing the likelihood of errors that often arise from manual operations. Additionally, Python can be employed to create and train metamodels, further enhancing the analytical capabilities within GT-POWER and contributing to more efficient and accurate simulations [87,88].

The built-in Python editor in GT-ISE is a convenient and effective way to develop and execute scripts, automate workflows, and conduct IC engine model analysis. This functionality extends to tasks such as post-processing results and iterating on model designs, enabling a streamlined approach to simulation [89]. Figure 17 shows a typical integration of Python script to a gasoline engine model built through the GT-POWER software [90]. The script demonstrates the ability to programmatically control and modify aspects of a GT-POWER simulation for modelling IC engines using Python.

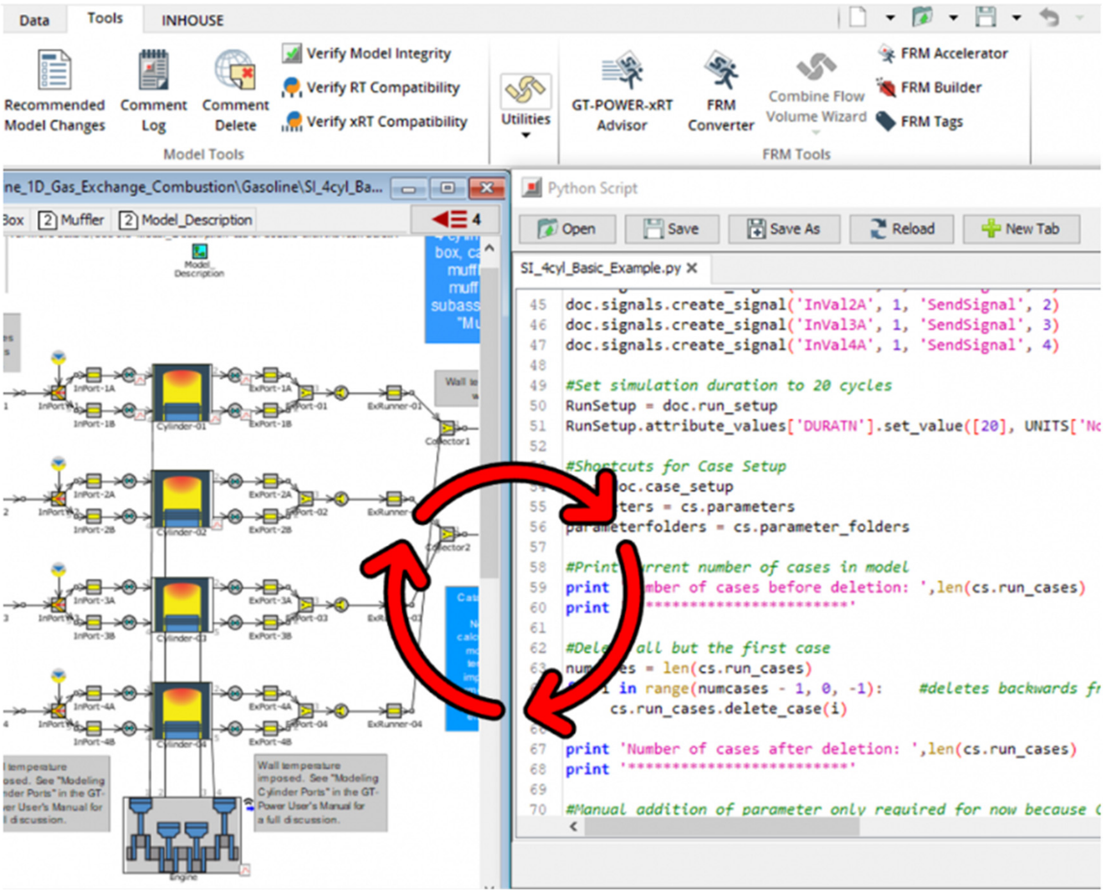

Figure 17. Integrating Python script into GT-POWER for modelling IC engines [90].

While GT-POWER, coupled with Python scripting, offers significant potential for diesel engine modelling, the literature reveals a relative scarcity of studies exploring this specific integration [91,92]. Further research in this area could yield valuable insights and advances in diesel engine simulation and optimization. It is believed that limited documentation and community support for Python integration, coupled with performance considerations and a focus on other integration tools, may restrain exploration in this area [93]. The authors believe that promoting successful case studies or research work could encourage wider interest and usage of Python in conjunction with GT-POWER. Moreover, an effort to provide a wider insight into this phenomenon is sequentially proposed in this study and can be followed in Table 3. It should be noted that Table 3 builds on Section 4. Thus, once the diesel engine model has been created, the Python script can then be integrated.

Table 3. A fundamental guide to integrating a Python script with GT-POWER for modelling diesel engines [92,94,95].

Description	Details
Create input files	Use Python to generate CSV or TXT files to specify engine parameters dynamically based on desired conditions.
Implement automation script	Write a Python script to call GT-POWER simulations using the generated input files (see Figure 17).
Run simulations	Execute the simulations in GT-POWER for the configured operating conditions.
Collect output data	Extract results such as pressure, temperature, torque, and emissions from GT-POWER.
Post-process results	Use Python to analyze and visualize output data (e.g., graphs and statistical summaries).
Validate results	Compare simulation outputs with experimental or previous similar findings data to verify model accuracy.
Repeat and refine	Adjust model parameters and rerun simulations as needed to improve fidelity.

8.5. Novel Insights Gained

The reviewed practical applications demonstrate the extensive capabilities of GT-POWER software in optimizing diesel engine performance and design. It further highlights its application across various aspects of engine development, from 1D modelling for fundamental analysis to multi-zone modelling for complex system simulations. GT-POWER's ability to accurately simulate engine behavior, coupled with its integration potential with other software such as MATLAB/Simulink, ANNs, and Python was explored and found to be a powerful option for researchers [96]. Numerous case studies have been presented to showcase the software's versatility in tackling diverse challenges, including emissions reduction, performance enhancement, and the optimization of engine components and alternative fuel blends. The findings consistently support GT-POWER's effectiveness as a leading simulation tool for advancing diesel engine technology and driving continuous improvements in engine design and efficiency [97].

8.5.1. Emerging Trends

The application of GT-POWER in diesel engine modelling is evolving rapidly, driven by three key trends: first, increasing integration with ML techniques, especially ANNs, is enabling faster and more accurate performance predictions, facilitating optimization of design parameters like valve lift and exhaust systems, and reducing computational burdens for complex simulations; this often involves using MATLAB/Simulink alongside GT-POWER [96,98]. Second, research is heavily focused on optimizing engine performance with biodiesel blends and alternative fuels such as CNG, which GT-POWER can simulate utilizing various fuel ratios and operating conditions to minimize emissions and maximize power output. Third, the use of Python scripting, particularly through GT-Automation, is automating repetitive tasks, streamlining the modelling process and minimizing human error, leading to enhanced efficiency and the ability to handle significantly more complex analyses [99].

8.5.2. Underexplored Areas

Despite advances in GT-POWER applications, several areas remain underexplored. While the reviewed literature mentions uncertainty analysis, its practical application within the presented studies is limited; a more comprehensive approach incorporating uncertainty propagation, sensitivity analysis, and Monte Carlo simulation is needed to fully understand the influence of input parameter variations on model predictions. Furthermore, the current focus is primarily on 1D, therefore multi-zone modelling needs expansion; coupling GT-POWER with other simulation software for multiphysics analyses (e.g., CFD for combustion, structural analysis for component stress, fluid flow, and heat transfer) offers significant potential but remains largely unexploited. Although GT-POWER's model predictive control capabilities are noted, its application in real-time engine control systems for optimization requires further investigation, particularly employing the potential of integrated ML models for real-time adaptive control strategies.

9. Conclusions

This comprehensive review demonstrated the significant capabilities of GT-POWER in diesel engine modelling and analysis. A startup guide is provided to assist researchers to utilize the software effectively. The software's user-friendly interface and extensive component library simplify model creation and analysis, while advanced features such as detailed combustion modelling and thermodynamic analysis provide comprehensive insights into engine behavior. A comparison of GT-POWER with other formidable simulation tools is made and shortcomings and advantages of GT-POWER were highlighted. The review further highlighted numerous previous studies that successfully modelled and simulated diesel engines using GT-POWER. These studies demonstrated the software's versatility in tackling diverse challenges, including performance optimization under various conditions and the design of engine components to meet specific needs. They also evaluated alternative fuels like biodiesels and explored the potential for integrating GT-POWER with MATLAB/Simulink, ANNs, and Python, while assessing the validation methods to ensure accuracy and reliability.

The current study observed that integrating these tools accelerates performance optimization, allowing for more efficient exploration of design alternatives while minimizing computational demands. This integrated approach improves predictive accuracy, informs better decision-making throughout the research and development process (including performance adjustments and emissions reduction strategies), and ultimately streamlines diesel engine development. Consequently, the consistent positive findings across these studies confirm GT-POWER's leading role as a powerful simulation tool, advancing diesel engine technology and driving continuous improvements in design and efficiency. The underexplored areas within the context of GT-POWER were discussed, revealing that the current focus on primarily 1D and multi-zone modelling needs expansion. Coupling GT-POWER with other simulation software for multiphysics analyses—such as CFD for combustion, structural analysis for component stress, fluid flow, and heat transfer—offers significant potential. However, this integration remains largely unexploited. Ultimately, the review successfully bridged the gap between theoretical understanding and practical application, providing a valuable resource for researchers in the field of IC engines.

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editing, N.K. and F.L.I.; supervision, F.L.I. and R.S.; project administration, F.L.I.; funding acquisition, F.L.I. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

GTs	Gamma technologies
IC	Internal combustion
1D	One dimensional
GUI	Graphical user interface
RPMs	Revolutions per minute
CFD	Computational fluid dynamics
3D	Three dimensional
BSFC	Brake thermal fuel consumption
BMEP	Brake mean effective pressure
DI	Direct injection
NOx	Nitrogen oxides
PPMs	Parts per million
HC	Hydrocarbon
CO	Carbon monoxide
CI	Compression ignition
CNG	Compressed natural gas
AC	Alternative current
MCP	Maximum combustion pressure
BED	Biodiesel–ethanol–diesel
PID	Proportional-integral-derivative
DF	Dual fuel
AI	Artificial intelligence
ML	Machine learning
ANN	Artificial neural network
RMSE	Root mean square error
BPANN	Back-propagation artificial neural network
API	Application programming interface
GT-ISE	Gamma technologies integrated simulation environment
CSVs	Comma separated values
TXT	Text

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