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Research Proposal

Research Methods (ACHA7027)

***Analysis and optimisation of drag racing fuels: a simulation
study***

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Date (04/2026)

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Introduction

Drag racing engines operate under extreme conditions, requiring rapid energy release, and high combustion efficiency. Fuel selection is therefore critical, as different fuels exhibit distinct combustion characteristics such as ignition delay, burn rate, and energy release (Glassman, I. et al. (2014)). Motorsport regulations define the range of fuels and oxidisers permitted within drag racing classes, including gasoline, ethanol, methanol, hydrogen, nitromethane, and the use of nitrous oxide as an oxygen-enriching agent (UK&ITA (2021)). Combustion behaviour varies significantly between these fuels; for example, methanol demonstrates reduced ignition delay and higher peak in-cylinder pressures compared to gasoline (Boggavarapu, P. et al. (2025)). In addition, fuels with high latent heat of vaporisation can cool the intake charge, increasing air density and improving combustion potential (Kasseris, E. and Heywood, J.B. (2012)). Oxygen availability can be further increased through nitrous oxide, which provides additional oxygen for combustion (Nemés, A., a et al. (2026)).

This research will compare gasoline, ethanol, methanol, hydrogen, and nitromethane, both with and without nitrous oxide (except for nitromethane which will only be simulated without), to determine how performance can be optimised through variation of air–fuel ratio (AFR) and ignition timing. The study will be based on a representative 1990 GSXR 1100 engine model and will use a dual simulation approach, combining ANSYS FORTE combustion modelling with Realis WAVE engine simulation to provide a consistent and validated framework for fuel optimisation.

Literature Review

This literature review examines the key factors influencing combustion performance in high-performance internal combustion engines, with a focus on fuel behaviour and oxygen availability. It begins by outlining fundamental combustion principles, before comparing gasoline, ethanol, methanol, hydrogen, and nitromethane relative to a gasoline baseline. The role of oxygen enrichment and nitrous oxide is then explored. Due to the limited availability of studies directly comparing multiple fuels under consistent conditions, it is necessary to critically analyse and synthesise findings from a range of sources. This approach establishes a coherent foundation for the comparative and optimisation-based methodology adopted in this study.

Combustion Fundamentals

Combustion behaviour in spark-ignition engines is governed by multiple parameters, most importantly including flame speed, ignition delay, and equivalence ratio, all of which directly influence engine performance and efficiency. Flame speed is particularly important, as it determines how rapidly the air–fuel mixture is consumed within the cylinder. A higher flame speed results in faster energy release and more effective pressure development, improving power output. Flame speed is strongly dependent on the equivalence ratio, with maximum values typically occurring near stoichiometric conditions. As mixtures become either lean or rich, flame speed decreases, leading to slower combustion and reduced efficiency (Glassman, I. et al. (2014)). This relationship is also observed across different fuels, including ethanol, where variations in equivalence ratio significantly alter combustion characteristics (Heywood, J.B. (2018)).

Ignition delay, defined as the time between spark initiation and the onset of combustion, also plays a critical role. Shorter ignition delay allows combustion to begin earlier within the engine cycle, improving combustion phasing and increasing the work extracted from the expanding gases. In contrast, longer ignition delays can lead to incomplete combustion and reduced efficiency. (Glassman, I. et al. (2014))

The thermodynamic processes occurring within the cylinder further influence combustion performance. Engine compression and expansion processes are often approximated as adiabatic, meaning that no heat is exchanged with the surroundings during these rapid events (Mayhew, K.W. (2020)). Under these conditions, pressure and temperature rise significantly during compression, promoting efficient ignition and combustion. Deviations from ideal adiabatic behaviour, such as heat losses to cylinder walls is common which results in, reduce thermal efficiency and limit performance.

Together, these factors highlight the importance of controlling combustion conditions to maximise efficiency and power output. Optimising parameters such as equivalence ratio and ignition timing is therefore essential to achieving improved engine performance across different fuels.

Fuel Behaviour Comparison

Gasoline/petrol, commonly represented by iso-octane, provides a suitable baseline for comparing the combustion characteristics of drag racing fuels. Its combustion behaviour is well established and offers a reference point against which differences in burn rate, ignition behaviour, cooling effects, and efficiency can be assessed. Relative to this baseline, ethanol and methanol show advantages linked to oxygen content and evaporative cooling, while hydrogen differs more fundamentally through its very high burning velocity.

Compared with gasoline, ethanol has been shown to improve brake power, torque, volumetric efficiency, and brake thermal efficiency in spark-ignition operation (Al-Hasan, et al. (2002)). One important reason for this is its higher latent heat of vaporisation, which increases charge cooling and therefore improves intake density and combustion potential relative to gasoline (Kasseris, E. and Heywood, J.B. (2012)). Methanol follows a similar direction of behaviour and has been associated with reduced ignition delay, reduced combustion duration, and higher peak in-cylinder pressure than gasoline, indicating faster and more effective combustion under suitable conditions.

Hydrogen differs more significantly from gasoline because of its exceptionally high laminar burning velocity (Verhelst, S. and Wallner, T. (2009)). Its combustion properties also include a much higher adiabatic flame speed than gasoline, which improves combustion stability and supports rapid flame development (Shadidi, B. et al. (2021)). Relative to gasoline, this suggests greater potential for fast and efficient combustion, although its distinct fuel properties require different optimisation strategies.

Overall, compared with the gasoline baseline, ethanol, methanol, and hydrogen each offer potential combustion advantages, but through different mechanisms. Ethanol and methanol are favoured by charge-cooling and combustion-efficiency benefits, whereas hydrogen is favoured by very rapid flame propagation. These differences justify a comparative study in which each fuel is optimised individually rather than assessed using a single operating condition.

Nitromethane Characteristics

Nitromethane exhibits fundamentally different combustion behaviour compared to conventional fuels due to its high intrinsic oxygen content, which allows greater energy release for a given amount of intake air (Özker, H. and Çelebi, S. (2025)). This property enables significantly increased fuel mass flow and is a key reason why nitromethane is used in the highest-performance drag racing applications, particularly within Top Fuel classes. The additional oxygen reduces reliance on atmospheric oxygen, supporting high power output even under rich operating conditions.

In terms of combustion behaviour, nitromethane is associated with high burning velocities, which contribute to improved thermal efficiency and engine performance (Tanoue, K. et al. (2020)). However, its ignition characteristics are complex. Ignition delay is highly sensitive to pressure and equivalence ratio, and nitromethane has been shown to exhibit a weak two-stage ignition behaviour (Gao, Z. et al. (2019)). Additionally,

nitromethane can significantly reduce ignition delay when introduced into a fuel system, highlighting its strong ignition sensitivity (Shang, Y.-L. *et al.* (2021)).

At high pressures, nitromethane combustion involves both deflagration and detonation processes, with burn rates and reaction products playing a critical role in overall combustion behaviour (Perreault, C. *et al.* (2025)). Due to its inherent oxygen content, the addition of nitrous oxide is unnecessary, and its inclusion would not represent typical operating conditions, justifying the decision to analyse nitromethane independently.

Oxygen Enrichment and Nitrous Oxide

Oxygen-enriched combustion involves increasing the oxygen concentration within the intake charge, directly influencing the fuel–oxidiser ratio and combustion process. Even small increases in oxygen concentration can significantly alter combustion behaviour, with a 1% rise in oxygen volume fraction producing measurable changes in combustion parameters (Nemés, A., *a et al.* (2026)). In spark-ignition engines, oxygen enrichment has been shown to increase peak cylinder pressure, heat release, and overall efficiency. For example, substantial increases in brake thermal efficiency and combustion intensity have been observed with elevated oxygen levels (Nidhi and Subramanian, K.A. (2018)). Similarly, oxygen-enriched intake air reduces combustion duration and cycle variation while improving engine output and efficiency (Kajitani, S. *et al.* (1992)). These effects demonstrate that increasing oxygen availability enhances combustion completeness and energy release.

Nitrous oxide (N_2O) provides a practical method of achieving oxygen enrichment in high-performance engines. It is significantly denser than air and contains a higher proportion of oxygen by mass, enabling a greater amount of oxygen to be introduced into the cylinder (Nemés, A., *a et al.* (2026)). Upon decomposition at elevated temperatures, nitrous oxide releases oxygen that actively participates in combustion, while nitrogen remains largely inert. This process can be described as an exothermic decomposition

that supplies additional oxidiser for fuel combustion (Clark, J.D., (1972)). In addition, nitrous oxide provides a cooling effect during intake as it vaporises, absorbing heat from the surrounding charge and increasing intake charge density (Nemés, A., a *et al.* (2026)). Its thermophysical properties and phase behaviour further support its suitability as a combustion-enhancing agent (Ferreira, A.G.M. and Lobo, L.Q. (2009)). These characteristics justify its use in this study as a controlled method of increasing oxygen availability and enhancing combustion performance.

Methodology

Experimental Methodology

Modelling Approach

A simulation-based approach is adopted in this study due to its ability to provide detailed insight into combustion behaviour and engine performance under controlled and repeatable conditions. Experimental testing of multiple fuels under varying air–fuel ratios and ignition timings would be time-consuming, costly, and difficult to standardise, whereas simulation enables systematic comparison across consistent operating conditions. In spark-ignition engine modelling, pressure-based analysis provides a reliable method of estimating combustion behaviour, with heat release derived from in-cylinder pressure offering a good approximation of the combustion process (Eriksson, L. and Andersson, I. (2002)). The compression process can also be effectively represented using a polytropic model, allowing heat transfer effects to be incorporated without requiring explicit modelling.

To balance accuracy and computational efficiency, simplified combustion models are employed. Control-oriented approaches, like Realis WAVE, commonly use the Wiebe function to represent mass fraction burned and combustion rate, providing an effective approximation of combustion behaviour while maintaining manageable computational cost (Tang, J., Zhu, G.G. and Men, Y. (2022)). However, such models require calibration for different operating conditions, highlighting a key limitation (Tang, J., Zhu, G.G. and Men, Y. (2022)). These empirical approaches are consistent with zero-dimensional combustion modelling strategies, where burn rate must be defined for each operating point (Verhelst, S. and Sheppard, C.G.W. (2009)). To address this, detailed combustion simulation using ANSYS FORTE is incorporated to generate accurate combustion characteristics, improving overall model reliability (Cameretti, M.C., De Robbio, R. and Palomba, M. (2023)). The combustion characteristics obtained from the single-cylinder ANSYS FORTE simulation are subsequently applied within a multi-cylinder engine

model in Ricardo WAVE, enabling full-engine performance to be evaluated with improved accuracy and consistency.

Simulation Strategy

A dual simulation strategy is adopted to achieve accurate combustion representation while maintaining computational efficiency across a wide range of operating conditions. ANSYS FORTE is used exclusively for single-cylinder combustion simulations, allowing detailed prediction of ignition behaviour, burn rate, and mass fraction burned (MFB) for each fuel. Due to the high computational cost of CFD-based combustion modelling, it is not feasible to apply this approach across a full multi-cylinder engine or a large number of operating points.

To address this, the combustion behaviour obtained from FORTE is converted into a Wiebe function, which provides an accurate representation of the MFB profile. This function is then implemented within a Ricardo WAVE model, where full-engine simulations are performed. WAVE is used to simulate multi-cylinder operation and airflow dynamics, enabling engine performance to be evaluated under varying conditions while retaining a combustion profile derived from high-fidelity modelling.

To further improve efficiency, design of experiments (DOE) software is used to predict performance trends and generate response surfaces based on a reduced set of simulation results. This reduces the total number of simulations required while ensuring adequate coverage of the operating space, including variations in air–fuel ratio and ignition timing. Such strategies are widely used to replace computationally expensive simulations with structured exploration of the design space (Simpson T.W., Poplinski J.D., Koch P. N., & Allen J.K. (2001)).

It is acknowledged that simulation models may not perfectly predict absolute values; however, they are effective in capturing performance trends, which is sufficient for comparative and optimisation-based analysis (Richardson, D.J. (2021)). This integrated

strategy therefore enables accurate and efficient evaluation of fuel performance across multiple operating conditions.

Model Setup

The simulation setup consists of both single-cylinder and multi-cylinder simulations, with each software used for a specific purpose. ANSYS FORTE is used to simulate a single-cylinder model, focusing solely on combustion behaviour. The model excludes intake and exhaust system components such as ducts and valves and therefore does not directly account for volumetric efficiency unless explicitly pre-defined in the mixture. This allows detailed analysis of combustion processes without the additional complexity of full engine airflow modelling.

The combustion behaviour obtained from FORTE is represented through a mass fraction burned (MFB) profile, which is used to derive Wiebe function parameters (a , m , & SoC). These parameters enable the reconstruction of apparent heat release and in-cylinder pressure, forming the basis of the combustion model used in subsequent simulations (Giglio, V. and Di Gaeta, A. (2020)). A double-Wiebe approach may be utilised where necessary, as it has been shown to accurately represent mass fraction burned, heat release rate, in-cylinder pressure, and combustion phasing (Liu, J. and Dumitrescu, C.E. (2019)).

The derived Wiebe parameters are implemented within a Ricardo WAVE model, which represents the full multi-cylinder engine, including valves, ducts, and airflow dynamics. Engine geometry and boundary conditions are based on measurements from a physical engine, introducing potential human measurement error. Within WAVE, the MFB profile must be actively defined and calibrated to ensure accurate combustion representation (Richardson, D.J. (2021)).

Fuel properties are defined using built-in software databases where available. For fuels not included, custom fuel files will be generated using literature-based properties,

acknowledging potential limitations due to incomplete thermophysical data across varying conditions.

Variables

The study considers a set of independent, dependent, and control variables to enable systematic analysis of combustion behaviour and engine performance. The independent variables include fuel type, the use of nitrous oxide (N_2O), air–fuel ratio (AFR), and ignition timing. AFR and ignition timing are selected as primary controllable parameters for optimisation, as they are widely recognised as key factors influencing combustion behaviour in spark-ignition engines (Duan, X., Feng, L. and Xia, Y. (2024)). AFR is particularly significant, as mixture composition, distribution, and temperature directly affect flame propagation speed, combustion stability, and efficiency (Duan, X., Feng, L. and Xia, Y. (2024)). Ignition timing is also critical, as optimal combustion phasing is required to achieve maximum brake torque (MBT). As AFR increases and combustion slows, additional spark advance is required to maintain optimal combustion timing (Ayala, F.A., Gerty, M.D. and Heywood, J.B. (2006)).

The dependent variables represent the outputs used to evaluate performance and include in-cylinder pressure, temperature, polytropic index, power, torque, and efficiency. These variables provide insight into both combustion behaviour and overall engine performance. The polytropic index is included to assess how closely the compression and expansion processes approach ideal adiabatic conditions.

Control variables are maintained constant to ensure consistent comparison between simulations. These include the geometric engine parameters, such as cylinder dimensions and compression ratio, which define the physical characteristics of the engine model. By fixing these parameters, the effects of the independent variables can be isolated, allowing meaningful comparison of fuel behaviour and operating conditions across all simulations.

Design of Experiments

Due to the large number of independent variables, their potential interactions, and the range of dependent variables used to evaluate performance, a full-factorial simulation

approach would require an impractical number of individual runs. This creates a highly complex design space that cannot be efficiently explored through direct simulation alone. Key controllable parameters such as air–fuel ratio and ignition timing are known to significantly influence combustion behaviour, further increasing the complexity of the analysis (Duan, X., Feng, L. and Xia, Y. (2024)).

To address this, design of experiments (DOE) software is employed to reduce the number of required simulations while maintaining effective coverage of the operating space. The software generates predictive models and response surfaces from a limited set of simulation data, allowing relationships between variables and resulting performance trends to be identified without exhaustive testing. Such approaches are widely used in engineering to enable efficient optimisation and exploration of complex design spaces without requiring exhaustive analysis of all possible conditions (Simpson T.W., Poplinski J.D., Koch P. N., & Allen J.K. (2001)).

Data Analysis Methods

Simulation results will be analysed using a combination of thermodynamic and performance-based parameters to evaluate both combustion behaviour and overall engine output. In-cylinder pressure and temperature profiles will be used to assess combustion characteristics, including the rate of pressure rise and peak conditions, which are indicative of combustion efficiency and energy release. These parameters provide direct insight into how effectively each fuel converts chemical energy into useful work.

The polytropic index will be calculated from the logarithm of the pressure–volume data during the compression and expansion processes to assess the thermodynamic behaviour of the system. The relationship between pressure and volume can be used to determine the polytropic coefficient, which indicates the nature of the process (e.g. adiabatic or with heat losses) (Swarts, A. et al. (2004)). Deviations from ideal adiabatic behaviour are identified by comparing the polytropic index to the specific heat ratio (γ),

with differences indicating the influence of heat transfer and fuel evaporation within the cylinder (Swarts, A. et al. (2004)).

Engine performance will be evaluated using power, torque, and efficiency outputs obtained from the WAVE simulations. These metrics allow direct comparison of fuel performance under different operating conditions and provide a basis for identifying optimal configurations. Together, these analysis methods enable both detailed combustion assessment and practical evaluation of engine performance.

Expected Results

Based on existing literature, clear differences in combustion behaviour and engine performance are expected between the selected fuels, with gasoline providing a baseline for comparison. Alcohol fuels such as ethanol and methanol are anticipated to produce increased power, torque, and efficiency due to improved combustion characteristics and charge cooling, which enhance intake density and combustion effectiveness (Al-Hasan, et al. (2002); Kasseris, E. and Heywood, J.B. (2012)). Methanol is also expected to exhibit faster combustion and higher peak in-cylinder pressure.

Hydrogen is expected to demonstrate significantly faster combustion due to its high laminar burning velocity, resulting in rapid pressure rise and improved combustion stability (Verhelst, S. and Wallner, T. (2009); Shadidi, B. et al. (2021)). However, this may require careful ignition timing control to maintain optimal combustion phasing.

Nitromethane is expected to produce the highest power output due to its intrinsic oxygen content, allowing greater fuel mass to be burned and supporting high energy release under rich conditions (Özker, H. and Çelebi, S. (2025)). Its combustion is expected to be highly sensitive to operating conditions and ignition behaviour (Gao, Z. et al. (2019)).

The use of nitrous oxide is expected to increase peak cylinder pressure, heat release, and overall efficiency by increasing oxygen availability, combustion completeness, and allowing more fuel mass to be added to the mixture (Nidhi and Subramanian, K.A. (2018)).

Combustion behaviour is also expected to vary with equivalence ratio, with flame speed not necessarily peaking at stoichiometric conditions for all fuels. Variations in equivalence ratio will therefore influence combustion rate, pressure development, and overall performance, reinforcing the need for fuel-specific optimisation (Glassman, I. et al. (2014)).

Evaluation

This study is subject to several limitations relating to modelling assumptions, simulation accuracy, data availability, and time constraints. The use of a Wiebe function in WAVE simplifies combustion behaviour and requires calibration, meaning complex combustion effects may not be fully captured. In addition, FORTE simulations are limited to single-cylinder modelling without intake and exhaust dynamics, so volumetric efficiency effects are not directly represented. This separation between combustion and full-engine simulation may introduce discrepancies between predicted and real engine behaviour.

Project Planner

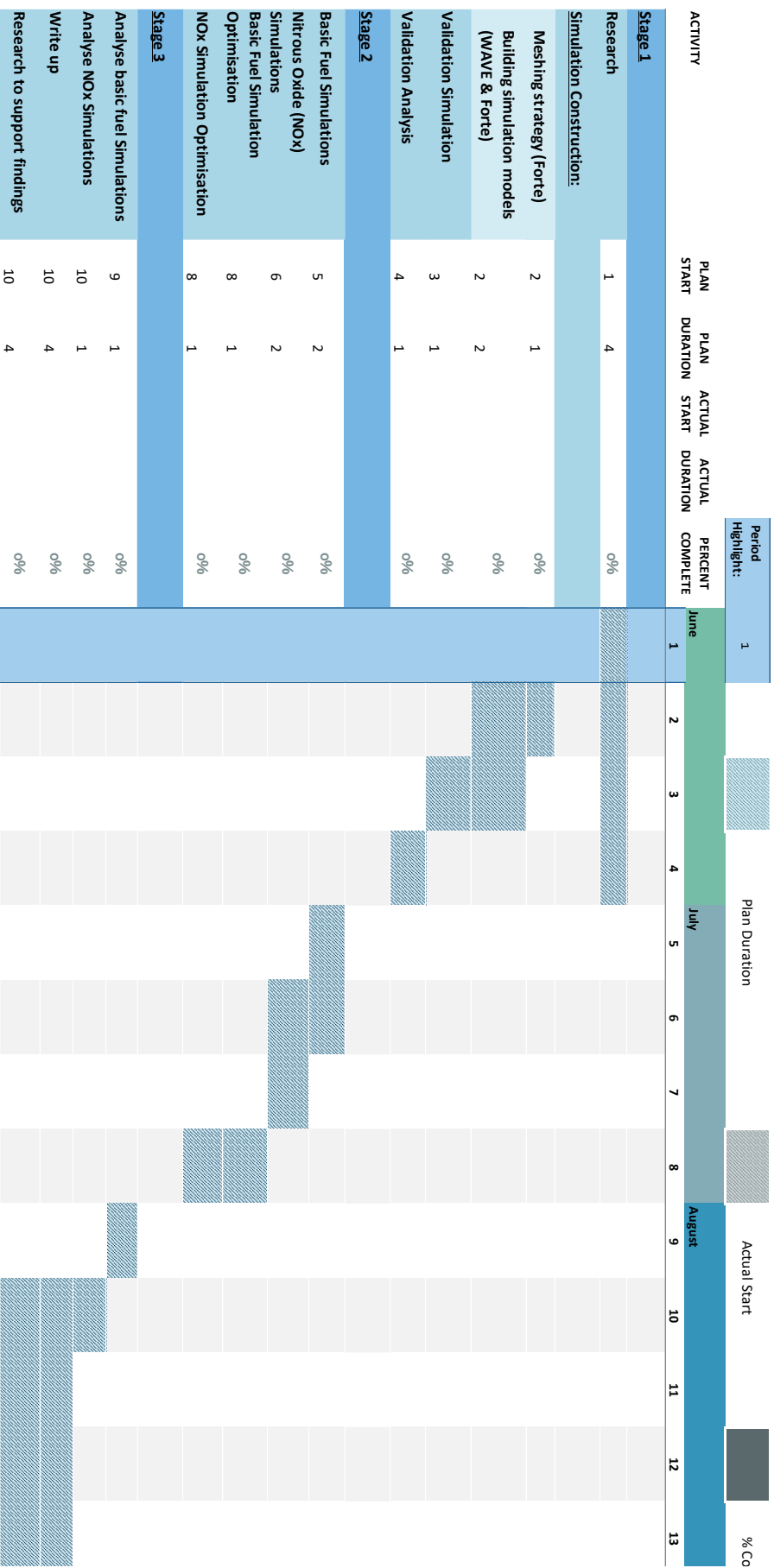


Figure 1: Project proposed timeline (Gantt chart)

Accuracy is further influenced by the use of literature-based or custom fuel files, particularly where complete thermophysical data is not available across all conditions. Measurement-based inputs for the WAVE model introduce potential human error. While DOE software reduces the number of required simulations, time constraints may still limit the extent of optimisation, as shown in Figure 1. These factors may affect absolute accuracy however, comparative performance trends are expected to remain valid.

The research follows a structured sequence, beginning with literature review, followed by model development in FORTE and WAVE. Simulations are then conducted using the planned simulation strategy, with results analysed to identify performance trends and optimal operating conditions.

Ethical considerations are minimal, as the study is entirely simulation-based. No physical testing is undertaken, meaning there are no environmental risks associated with emissions, materials, or engine operation. No hazardous procedures are undertaken, and the project falls within low-risk research activity in line with standard university requirements.

Conclusion

This study proposes a comparative and optimisation-based investigation into the performance of drag racing fuels under extreme operating conditions. By analysing gasoline, ethanol, methanol, hydrogen, and nitromethane, both with and without nitrous oxide, the research aims to determine how air–fuel ratio and ignition timing can be optimised to maximise engine performance. The use of a dual simulation approach, combining ANSYS FORTE for detailed combustion modelling and Ricardo WAVE for full-engine analysis, provides a structured and consistent framework for evaluating fuel behaviour.

The literature highlights that different fuels offer distinct advantages, including improved combustion efficiency, enhanced charge cooling, and increased burn rates, while oxygen enrichment through nitrous oxide further enhances combustion performance as more fuel can be used in the mixture. As a result, it is expected that no single operating condition will be optimal across all fuels, reinforcing the need for fuel-specific optimisation.

Overall, this research is expected to contribute to a better understanding of how combustion characteristics and operating parameters interact, providing insight into fuel selection and optimisation strategies for high-performance spark-ignition engines.

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