



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

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<i>Student Name</i>	Roland Magyar
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Introduction

The development of internal combustion engines (ICEs) has long been shaped by the conflicting demands of durability, performance, weight reduction, and efficiency. In motorsport and high-performance automotive applications, these competing requirements are even more pronounced, as engineers strive to extract maximum output while simultaneously minimising mass and ensuring reliability under extreme thermomechanical loading. Among the engine's critical components, the piston represents a unique design challenge. Subjected to rapid cyclic pressures, high-frequency inertial forces, and steep thermal gradients, the piston must operate as both a structural load-bearing member and a thermal expansion, dissipating energy away from the combustion chamber. The dual role of the piston, as both a mechanical and thermal bridge, makes it one of the most demanding components to optimise within an ICE assembly.

Background and Context

Lightweighting has become a central objective in modern engineering, driven by both performance and environmental imperatives. For reciprocating engine components, reductions in mass translate directly into lower inertial forces, reduced mechanical stresses in the crank train, and enhanced responsiveness. In high-performance and motorsport contexts, lighter pistons enable higher engine speeds and quicker throttle transitions, while in production vehicles, they contribute to improved fuel efficiency and reduced emissions. With increasingly stringent regulations such as Euro 7 and the 2035 internal combustion engine phase-out in Europe, improving efficiency and reducing environmental impact remain pressing priorities, even as hybrid and electrified platforms emerge. Pistons, as high-volume manufactured components, remain a key site for incremental yet critical innovations.

At the same time, durability cannot be compromised. Piston failures, whether due to fatigue cracking at the crown rim, distortion of ring grooves, or thermal degradation, remain among the most catastrophic modes of engine malfunction. This tension between mass reduction and structural resilience underscores the need for advanced design tools that go beyond traditional empirical methods. Finite element analysis (FEA) and computational optimisation frameworks have therefore become indispensable for modern piston development.

Topology Optimisation as a Design Tool

Topology optimisation (TO) has emerged as a transformative approach in structural design, enabling engineers to redistribute material in a manner that directly responds to load paths and energy densities. Rather than relying on conventional parametric variations of geometry, TO evaluates the entire design domain and progressively eliminates inefficient material. The result is not an incremental variation of existing designs, but a fundamentally new configuration driven by the physics of loading. In the context of pistons, where structural webs, crown features, and boss intersections all carry complex and coupled loads, TO provides an opportunity to uncover designs that conventional intuition may overlook.

The appeal of TO for piston applications lies in its ability to reconcile lightweighting with durability. While traditional piston geometries are often dictated by manufacturability and empirical rules, TO identifies material distributions that concentrate stiffness where required and remove redundancy elsewhere. In doing so, it has the potential to reduce reciprocating mass without introducing unacceptable thermal or mechanical vulnerabilities. However, the success of TO depends critically on the fidelity of its inputs: material properties, thermal gradients, boundary conditions, and load cases. Without an accurate representation of these parameters, the optimised outcomes risk being numerically attractive yet physically unviable.

Challenges in Piston Optimisation

Despite its promise, the application of TO to pistons is far from straightforward. The piston operates under multiphysics conditions, where thermal and mechanical domains are inseparably coupled. Peak firing pressures induce crown stresses, while steep gradients from over 300°C at the bowl to below 100°C at the skirt create severe thermally induced strains. Neglecting either domain can lead to misleading results: a geometry optimised for stiffness alone may sacrifice necessary conduction paths, while one optimised for thermal uniformity may fail structurally under cyclic pressure loading.

Manufacturability further complicates optimisation. Additive manufacturing has enabled new piston concepts, but majority of industrial pistons remain conventionally cast or forged. As studies such as Alrashdan and Alhakeem (2025) highlight, incorporating casting constraints such as minimum wall thicknesses, draft angles, and avoidance of enclosed voids is critical if optimised geometries are to be realised at scale. Without these considerations, TO outputs risk being impractical, reinforcing the need for workflows that integrate manufacturing realities into optimisation frameworks.

Another challenge lies in the choice of optimisation method. Density-based approaches (e.g., SIMP) allow continuous redistribution of material, aligning well with strain energy paths but requiring careful post-processing to interpret intermediate densities. Level-set methods, by contrast, produce clean boundaries but can remove material in structurally critical regions if multiphysics constraints are not properly enforced. A comparative understanding of these approaches, particularly under thermomechanical loads, remains an important area of research.

Research Gap

The literature has made progress in applying TO to pistons (Barbieri et al., 2017; Poznick, 2025), yet gaps remain. Many studies rely on simplified thermal fields or uniform loading assumptions, failing to capture the non-uniformity of combustion-induced gradients. Others demonstrate dramatic weight savings but neglect to evaluate fatigue feasibility, manufacturability, or structural safety margins. Emerging work, such as the integration of physics-informed neural networks (Zhang et al., 2024), points towards real-time and meshless optimisation frameworks, but these remain at an early stage and are not yet ready for industrial deployment.

Against this backdrop, this dissertation positions itself at the intersection of academic innovation and industrial applicability. It seeks to bridge the gap between high-fidelity multiphysics simulation and manufacturable TO outputs, demonstrating that optimisation can yield meaningful, credible, and practical improvements in piston design.

Aims and Objectives

The overarching aim of this research is to develop and validate a simulation-driven topology optimisation framework for an internal combustion engine piston, capable of reducing mass while maintaining thermomechanical integrity and manufacturability. To achieve this aim, the study is guided by the following objectives:

1. **To critically review existing literature** on piston topology optimisation, material selection, crown geometries, fatigue behaviour, and boundary condition specification, identifying methodological strengths and weaknesses.
2. **To construct a high-fidelity simulation model** of a piston using validated thermomechanical finite element methods, incorporating realistic thermal gradients, combustion pressures, and empirically calibrated boundary conditions.
3. **To implement and compare density-based and level-set optimisation approaches**, assessing their relative strengths and limitations when applied to multiphysics piston design.
4. **To rationalise the optimised outputs into manufacturable CAD geometries**, ensuring that the designs remain compatible with conventional casting or machining practices.
5. **To validate the optimised piston against baseline performance metrics**, including mass, safety factor, deformation behaviour, and thermal field distribution.
6. **To evaluate the industrial relevance** of the findings, situating them within broader trends in motorsport, automotive engineering, and sustainable powertrain development.

Contribution of the Study

The contribution of this dissertation lies in three key areas. First, it demonstrates that TO, when informed by realistic thermomechanical boundary conditions, can deliver practical improvements in piston design rather than purely theoretical shapes. Second, it provides a comparative assessment of density-based and level-set optimisation methods, offering insights into their relative suitability for multiphysics-critical components. Third, it integrates manufacturability considerations into the optimisation process, ensuring that outputs are not only structurally efficient but also industrially realisable.

By addressing these areas, the study advances both academic discourse and industrial practice. Academically, it contributes to the growing field of multiphysics-aware optimisation, reinforcing the importance of boundary condition fidelity and post-optimisation rationalisation. Industrially, it provides a template for how TO can be embedded into piston development workflows, balancing lightweighting objectives with durability and cost constraints.

Task 1: Literature Review

1.1 Topology Optimisation in Additive Manufactured Pistons

Barbieri et al. (2017) proposed a fully integrated design and simulation framework for topology optimisation (TO) of internal combustion engine pistons manufactured via Selective Laser Melting (SLM). Their methodology combined CAD geometry, finite element analysis (FEA), and the Solid Isotropic Material with Penalisation (SIMP) method, aiming to achieve structural lightweighting without compromising thermal performance. A penalisation factor of 3.0 and a mesh filter radius of 1.0 mm were employed to ensure well-defined material boundaries and prevent numerical instabilities. Functionally critical regions, such as the skirt and pin bosses, were excluded from the TO domain. Under simulated combustion pressures and thermal loads, the optimised design achieved a 12.6% reduction in mass while maintaining stress levels below the 1200 MPa yield limit of 18Ni300 maraging steel. Additionally, thermal performance improved through strategic hollowing, reducing the temperature gradient between the crown and skirt regions. Importantly, the study incorporated additive manufacturing constraints—such as minimum feature size, support structure accessibility, and post-processing feasibility—into the optimisation loop, making the outcome practically viable for AM production.

1.2 Comparative Analysis of Piston Materials Under Thermal and Mechanical Loads

Narayanan et al. (2024) conducted a detailed finite element investigation into the thermomechanical behaviour of pistons constructed from Al2618, Al4032, and Ti-3Al-8V-6Cr-4Mo-4Zr alloys. The study simulated real-world in-cylinder conditions, applying transient thermal loads up to 450°C and peak combustion pressures of 14 MPa. Results showed that the titanium alloy exhibited a 22% reduction in total displacement due to its higher stiffness; however, it also retained 11% more thermal energy, introducing a risk of hotspot-induced fatigue due to its lower thermal conductivity. Al4032 outperformed Al2618 in both thermal stability and stress resistance, with a 7.6% reduction in von Mises stress, attributed to its elevated silicon content and lower coefficient of thermal expansion. The study also identified stress concentrations near the pin boss in titanium variants, suggesting the necessity for further fatigue cycle analysis. The findings underscore that material selection for piston applications must balance stiffness, thermal conductivity, fatigue resistance, and manufacturability, especially under high-frequency loading.

1.3 The Effect of Crown Geometry on Thermomechanical Behaviour

Lee and Ku (2021) evaluated the impact of piston crown geometry on stress distribution and thermal loading using FEA simulations. Four geometrical variants flat-top, dome, bowl, and square-bowl were subjected to a uniform 5 MPa mechanical load and a 300°C thermal field. Among them, the bowl-

shaped crown exhibited superior performance, reducing peak von Mises stress by 14% and promoting a more uniform thermal gradient across the crown surface. When subsequently subjected to TO with a 30% volume reduction constraint in ANSYS Workbench, the bowl configuration further reduced structural compliance by 6.4% and displacement by 8.1%. The study concluded that pre-selecting favourable geometries prior to TO significantly enhances optimisation outcomes, not only improving convergence but also mitigating stress singularities. These insights support the integration of geometric pre-conditioning as a preparatory step in TO workflows for thermally loaded components such as pistons.

1.4 Thermomechanical Fatigue Due to Non-Uniform Temperature Distribution

Giacopini et al. (2014) investigated the role of temperature gradients in thermomechanical fatigue of diesel pistons using coupled thermal-mechanical simulations. The study modelled realistic engine operating conditions, applying transient in-cylinder pressures of 16 MPa and non-uniform temperature profiles ranging from 200°C at the skirt to 600°C at the crown. Ring grooves and bowl rims emerged as primary fatigue hotspots due to cyclic thermal and mechanical stresses. Using Finite Element Damage Analysis (FEDA), the study quantified an 18% increase in crack initiation probability when non-uniform temperature fields were accounted for, compared to uniform heating models. This demonstrated that neglecting combustion-induced temperature gradients leads to underpredicted fatigue damage. The study argues for integrating realistic thermal cycling into TO strategies to ensure more conservative and accurate fatigue predictions, especially for diesel applications operating under extreme thermal gradients.

1.5 Meshless Topology Optimisation Using Physics-Informed Neural Networks

Zhang et al. (2024) introduced a meshless TO method employing Physics-Informed Neural Networks (PINNs), which embed the governing equations of elasticity into the neural network's loss function. The architecture comprising four hidden layers with Swish activation was trained using the L-BFGS optimiser to solve planar compliance minimisation problems. The method produced optimised structures within 2% accuracy of ABAQUS-based SIMP results while reducing computational cost by 37%. Unlike traditional FEA-based TO, the PINN approach does not require mesh generation, making it scalable for real-time design updates and inverse optimisation problems. Although demonstrated for 2D linear elasticity, the framework holds promise for extension to multiphysics applications such as thermomechanical or fatigue-driven piston optimisation. The study notes that while promising, challenges remain in generalising the approach to non-linear geometries and coupled field problems typical of engine components.

1.6 Empirical Constraints and Validation Practices in Industrial Piston Design

Technical documentation from MAHLE GmbH outlines the empirical methodologies underpinning piston development for high-performance automotive engines. The workflow integrates validated boundary conditions derived from AVL test bench pressure and temperature data into a simulation-driven design. Thermocouples placed in the piston crown and strain gauges embedded in the skirt region enable precise calibration of FEA models. Observed crown-to-skirt thermal gradients of up to 70°C guided forced convection and oil-cooling model development. Skirt deflection was assessed using elastohydrodynamic simulations to ensure oil film stability. Design constraints, including exclusion of ring land and groove areas from TO, were applied to prevent fatigue failures in critical sealing regions. The document also emphasises the necessity of translating TO outputs into castable or machinable geometries and validates them by 100-hour durability bench testing. This integration of empirical data with simulation ensures that TO-generated piston designs are both mechanically viable and production-ready.

1.7 Additive-Manufactured Pistons for Six-Stroke Concept Engines (Revised)

Poznick (2025) conducted a case-specific application of topology optimisation (TO) for a six-stroke concept engine, targeting enhanced heat rejection and mass efficiency through additive manufacturing (AM). The study utilised Topology software with a 20% volume reduction constraint applied to the piston crown design. Resultant geometries were manufactured using Direct Metal Laser Sintering (DMLS) in AlSi10Mg, but post-optimisation analysis revealed critical issues. Finite Element Analysis (FEA) showed von Mises stress peaks reaching 1318 MPa in the crown fillet and bowl-lip regions, well above the fatigue threshold of the material under cyclic loading. To address this, post-TO smoothing and manual rib augmentation were introduced to reduce stress concentration and improve manufacturability. Thermal simulation via COMSOL revealed a 110 K reduction in pin boss temperature, validating the effectiveness of the new conduction paths. However, the study also demonstrated that compliance-only optimisation can produce impractical stress distributions for engine pistons subjected to high-frequency thermomechanical loads. The study recommends adopting multi-objective TO frameworks that incorporate fatigue limits, manufacturability constraints, and transient thermal boundary conditions to generate viable designs for extreme cyclic environments.

1.8 Topology Optimisation with Casting Constraints for Conventional Piston Manufacture (Revised)

Alrashdan and Alhakeem (2025) presented a manufacturability-aware topology optimisation methodology for a sand-cast aluminium piston (AlSi4032), designed for traditional ICE platforms. Using the ABAQUS FEA suite, the study applied a uniform combustion pressure load of 7 MPa across the piston crown and imposed a through-thickness thermal gradient (350°C at the crown surface,

tapering to 120°C near the skirt). The TO process targeted a 30% mass reduction while enforcing design exclusions on the ring grooves and skirt regions, which are critical for sealing, lubrication, and lateral load transfer. The optimised piston geometry achieved a 26.3% reduction in volume with peak von Mises stresses remaining within the 325 MPa yield strength of the alloy. Unlike AM-focused TO, the authors incorporated directional solidification and minimum draft angle requirements to ensure castability. CAD translation was completed through surface patch fitting and Boolean reconstruction to eliminate non-manufacturable features such as enclosed voids and unsupported cantilevers. The research provides a practical TO framework compatible with low-cost mass production methods, enabling lightweighting without compromising on manufacturability or fatigue safety margins.

2. Methodology

2.1 Simulation-Driven Topology Optimisation Framework

This project adopted a simulation-driven approach to piston topology optimisation (TO), integrating thermomechanical finite element analysis (FEA), empirical boundary conditions, and manufacturing-aware constraints. The rationale for this framework stems from the dual demands of piston design: while lightweighting improves efficiency, excessive material removal risks compromising thermal conduction and fatigue resistance. A structured, validated workflow was therefore essential to balance competing requirements of performance, durability, and manufacturability.

TO was selected over alternative design optimisation methods (e.g., parametric variation, design of experiments) because it directly redistributes material according to strain energy and thermal gradients, rather than relying on predefined geometry changes. This enables the discovery of non-intuitive designs that better reflect multiphysics load paths (Bendsøe & Sigmund, 2003). Other approaches, such as generative design are emerging, but remain limited by “black box” outputs and lack of transparency (Borenstein et al., 2021). The methodology adopted here ensures both engineering interpretability and industrial applicability.

The baseline piston was modelled in SolidWorks and transferred into ANSYS Mechanical. Functional features such as ring grooves, skirt geometry, and pin bosses were excluded from the optimisation domain. This decision reflects both industrial constraints and ethical responsibility: ring grooves and skirt surfaces are critical for lubrication, sealing, and secondary motion control, and removing material here would compromise safety and reliability (Heywood, 2018).

2.2 Thermomechanical Loading and Material Definition

The piston material was defined as AlSi4032, selected due to its common use in forged high-performance pistons. Compared to Al2618, AlSi4032 offers superior thermal stability and lower expansion, improving ring sealing, while remaining more manufacturable than titanium alloys

(Narayanan et al., 2024). Titanium, though stiffer, retains heat and risks localised hotspots, which undermines fatigue life (Zhu et al., 2021). AlSi4032 therefore, represents a balance of stiffness, conductivity, and fatigue resistance, aligning with both industry practice and ethical principles of safe design.

Temperature-dependent properties were applied, including modulus, yield strength, thermal conductivity, and coefficient of expansion. This ensured the model captured realistic material behaviour under high operating temperatures (Marklund, 2013).

Boundary conditions were applied in two stages following best practice (Giacopini et al., 2014; MAHLE GmbH, 2024):

1. **Thermal simulation:** a radial and vertical gradient of 450 °C at the crown centre tapering to 120 °C at the skirt, reflecting known crown-to-skirt distributions (Zheng et al., 2023). Convective coefficients were applied: crown surface (gas-side, 100 W/m²K), undercrown oil cooling, and liner conduction. These values were calibrated against empirical datasets (Esfahanian et al., 2006).
2. **Structural simulation:** mapped thermal results into a static structural model, with peak firing pressure of 14 MPa on the crown, fixed supports at the wrist pin, and frictionless supports on the skirt flanks. Inertial loads from piston acceleration were derived using MATLAB (see Section 5.1), ensuring coupling between mechanical and thermal domains.

This dual use of cylinder pressure data represents a key methodological innovation, producing consistent boundary conditions across both domains.

2.3 Finite Element Analysis and Model Fidelity

FEA was performed using second-order tetrahedral elements (SOLID187), refined in regions of steep gradients such as the crown rim, pin-boss fillets, and ring belt. This approach is supported by Moser et al. (2021), who highlight the need for crown mesh biasing to capture sharp thermal gradients. A three-level mesh convergence study confirmed that stress and displacement results stabilised within $\pm 3\%$ beyond $\sim 300k$ elements. Mesh quality metrics (skewness < 0.9 , orthogonal quality > 0.15) were satisfied, consistent with recommendations for thermomechanical piston modelling (Qian et al., 2025).

The baseline piston model was validated against experimental temperature and deformation data reported by MAHLE (2024), confirming that the simulation captured realistic behaviour. Validation at this stage is both technically necessary and ethically important: engineers have a duty to avoid reliance on uncalibrated simulations that could mislead design decisions (Engineering Council, 2017).

2.4 Topology Optimisation Procedure

Topology optimisation was executed in ANSYS Mechanical using the Solid Isotropic Material with Penalisation (SIMP) method. SIMP was selected over the level-set approach because it directly relates material distribution to strain energy density, making it inherently more conservative under coupled thermal–mechanical loading. By contrast, level-set methods, while generating smooth and manufacturable boundaries, are more prone to eliminating material in structurally and thermally critical regions such as the crown rim. This risk is particularly problematic for piston applications, where the rim must simultaneously withstand peak combustion pressures and act as a conduction path for heat transfer into the liner (Heywood, 2018; Zhu et al., 2021). Conservatism in this context is not a limitation but a professional responsibility to maintain safety (Engineering Council, 2017).

The validity of this methodological choice is reinforced by the optimisation results presented in Chapter 6. As shown in Section 6.5, the level-set outputs generated visually clean rib patterns but removed material around the crown rim, compromising both structural stiffness and thermal pathways. In contrast, the density-based SIMP optimisation retained material in the rim and pin-boss corridors, aligning with strain energy density distributions and preserving thermally critical conduction paths. This direct comparison demonstrates not only the theoretical reasoning but also the empirical evidence supporting SIMP as the more robust approach for multiphysics piston optimisation.

SIMP was therefore selected as the primary optimisation method for this study. As later confirmed in Section 6.5, this choice was validated by the comparative results: the level-set approach, though visually cleaner, removed material in crown rim regions where both stresses and thermal gradients are highest, whereas SIMP consistently preserved these corridors. This link between methodological reasoning and empirical evidence underpins the robustness of the workflow adopted here.

The optimisation objective was compliance minimisation under combined thermal and mechanical loading, subject to the following parameters:

Volume fraction: 30% material retention.

Penalisation exponent: $p = 3.0$.

Minimum member size: 1.5 mm (to avoid non-manufacturable struts).

Filter radius: 1.0 mm (to prevent checkerboarding).

Symmetry: enforced across piston centreline.

Manufacturing constraints: exclusion of overhangs $>45^\circ$, consistent with conventional casting feasibility (Alrashdan & Alhakeem, 2025).

The optimised outputs were post-processed in CAD to remove intermediate-density regions and introduce fillets, draft angles, and minimum wall thicknesses. This ensured compatibility with sand casting and CNC machining, addressing the common criticism that TO generates impractical geometries (Barbieri et al., 2017).

2.5 Structural Validation and Fatigue Feasibility

The reconstructed geometry was re-analysed under identical thermomechanical conditions to verify that corrections had not undermined performance. Evaluation metrics included:

- Peak von Mises stress <300 MPa (yield limit).
- Total displacement $\leq$ baseline.
- Uniform safety factor distribution across crown rim and boss corridors.
- Absence of migrated thermal hotspots into load-bearing regions.

A fatigue screening analysis was performed using the strain-life (ϵ -N) method with the Smith-Watson-Topper (SWT) model. Design life was set at 100 million cycles at 6000 RPM, reflecting endurance requirements for motorsport and high-performance applications. Screening identified rim and boss fillets as fatigue-sensitive, consistent with literature (Giacopini et al., 2014; Strzelecki et al., 2020). While this analysis cannot replace full transient durability testing, it provides ethical assurance that the optimised design does not introduce unacceptable fatigue risk.

2.6 Ethical and Industrial Alignment

Beyond technical fidelity, this methodology was structured to reflect industrial realities and professional ethics. Retaining ring grooves and skirt regions as solid represents adherence to safety-critical design principles. Incorporating manufacturability constraints ensures that optimisation outputs are not “academic curiosities” but viable production geometries. The workflow therefore balances academic innovation with professional responsibility, aligning with the Engineering Council’s Statement of Ethical Principles (2017).

This exclusion of sealing and lubrication features from the optimisation domain also reflects an ethical responsibility in engineering design. It would be unsafe to pursue mass reduction at the expense of piston reliability, and so the methodology consciously prioritised durability and safety-critical functions in line with established professional codes of practice (Engineering Council, 2017).

2.7 Summary of Methodological Validity

This methodology advances piston optimisation in several ways:

1. **Coupled Boundary Conditions** - MATLAB-derived cylinder pressures informed both thermal and structural domains.
2. **High-Fidelity Meshing** - refinement and convergence aligned with best practice in literature.
3. **Manufacturing-Aware TO** - integrated constraints for casting and CNC, ensuring industrial feasibility.
4. **Fatigue Screening** - beyond static safety factor, ϵ -N strain-life evaluation provided durability insight.
5. **Ethical Responsibility** - prioritised safety-critical features and transparent methodology.

The approach therefore satisfies academic, industrial, and ethical expectations, producing optimisation outcomes that are both technically robust and professionally responsible.

3 Mesh

3.1 Mesh Analysis

A consistent theme across the highest-quality studies is that mesh strategy must be tailored to the physics being resolved (conduction vs. contact vs. conjugate CFD/FEA), and the geometry-induced gradients in the piston crown, ring belt/grooves, pin-boss web and skirt. In coupled CFD–FEA work, the mesh also has to serve the accuracy of data transfer between solvers. Choices about element type, local refinement, and mesh-independence metrics materially change peak temperature and stress predictions, and therefore any downstream design decisions. (Moser et al., 2021; Qian et al., 2025).

For stand-alone thermal and thermo-mechanical FEA, credible papers converge on tetrahedral, heat-transfer-capable elements with strong local refinement on the crown and ring belt, often using mesh biasing away from the fire deck. In a heavy-duty diesel case, Moser et al. couple an Abaqus solid mesh to a CONVERGE in-cylinder CFD grid and report that about 70 k FEA surface nodes were sufficient for robust interpolation of spatio-temporal boundary conditions, with a final piston mesh on the order of 10^5 linear heat-transfer tetrahedra (DC3D4) and sub-millimetre shell layers for the coating; crown elements are 2 mm at the surface, coarsening to 10 mm toward the skirt (mesh-bias strategy) (Moser et al., 2021). This is a rare instance where authors state concrete mesh densities tied to mapping fidelity, not just solver stability, and they validate against thermoplug measurements.

When the focus is purely FEA, mesh-sensitivity protocols are explicit. Qian et al. (2025) model an aluminium piston with dual-ceramic TBCs, apply a swept, locally refined mesh through the coating stack, and run a formal grid study at 20 k, 100 k and 800 k elements. The temperature difference along a diagnostic path (AB) stabilises once the mesh exceeds 100 k elements ($\approx 359^\circ\text{C} \rightarrow 356^\circ\text{C} \rightarrow 355^\circ\text{C}$),

and subsequent models contain “significantly more than” 100 k elements to remain inside that plateau; the same study also validates boundary conditions against instrumented pistons ($\leq 9\%$ error), which ties the mesh decision to experiment rather than an arbitrary percentage threshold (Qian et al., 2025).

Topology and local element size matter most where gradients or contact dominate. Zheng et al. (2022) show that densifying the crown mesh to 1 mm improves thermo-mechanical accuracy in a titanium piston, while permitting a coarser field elsewhere; this is consistent with the biasing used by Moser et al. and is a practical rule: crown and first ring-groove fillets demand the smallest characteristic length, with rapid growth rates onto less critical volumes (Zheng et al., 2022). In the ring pack, where conformability and side contact drive local stresses and heat paths, three-dimensional hexahedral contact meshes remain the standard of record; Cheng et al. (2015) use 8-node brick elements for a fully 3-D ring bore groove contact model, which is difficult to reproduce with unstructured tets at equivalent contact resolution (Cheng et al., 2015).

Mesh-independence reporting is best when it couples structural metrics (peak von Mises, hot-spot location, displacement) and thermal metrics (peak crown temperature, path-averaged temperature). Mishra and Kumar (2019) present explicit convergence tables for both deformation and stress across multiple mesh levels on several crown geometries, using tetrahedral meshes auto-selected in ANSYS; while their study also treats lubrication correlations, it is exemplary in documenting how mesh choice propagates into strength metrics that a designer actually cares about (Mishra & Kumar, 2019).

For in-cylinder CFD that must follow piston and valve motion, dynamic mesh strategies and their quality metrics replace static mesh densification. Silva et al. (2024) demonstrate a hybrid prismatic/tetrahedral grid in ANSYS Fluent with dynamic smoothing, layering and remeshing to accommodate stroke and valve events; their “grid independence test” and mesh-quality figures (orthogonal quality > 0.79 ; skewness < 0.36 across the cycle) constitute a useful benchmark for deforming-mesh health in engine simulations. Although this is a cold-flow study, the same dynamic mesh controls underpin any conjugate CFD/FEA pipeline where wall heat-flux and HTC fields are exported to a solid mesh (Silva et al., 2024).

The state of the art in conjugate workflows is an iterative exchange: a resolved gas-side grid drives convective boundary conditions (near-wall temperature, HTC) on the piston surface; the solid model returns updated surface temperatures, and the cycle repeats until quasi-steady consistency is reached. Moser et al. (2021) implement this with a 2 mm base grid, 0.5–1 mm embedded refinements in the reaction zones and near the piston surface (adaptive criteria on velocity/temperature/OH– gradients), and FEA surface meshes with higher nodal density than the CFD’s near-wall cells to improve interpolation. They also perform explicit grid-convergence on both sides before coupling. This is an important methodological result: mesh resolution is not “symmetry” between solvers but

“compatibility” for error-controlled mapping, which is why the surface node count in the FEA is a design variable in its own right (Moser et al., 2021).

Finally, there is a class of contact-intensive subproblems fretting in the crown skirt joint, ring side wear, skirt liner scuffing, where mesh studies should prioritise contact pressure gradients over bulk fields. SAGE’s fretting-fatigue work on marine pistons uses finite-element contact models whose value lies in the local mesh resolving the pressure gradient and micro-slip distribution; the methodological implication is that mesh-independence must be set on contact observables (e.g., peak contact pressure, SWT damage parameter) rather than global norms (Wang et al., 2018; see also Cheng et al., 2015 for ring groove bore contact).

Taken together, the literature supports a disciplined protocol for piston mesh studies. Start by identifying the heat-flux path and contact-critical zones (crown, first ring groove fillets, pin-boss webs, thrust/anti-thrust skirt) and set the smallest characteristic length there (1 mm near the crown is a defensible starting point in many cases), bias outward aggressively, and run at least a three-level mesh sweep that reports both thermal and structural convergence; if you are coupling to CFD, ensure the FEA surface mesh has sufficient nodal density to interpolate the CFD wall fields with demonstrably small mapping error, as in Moser et al. (2021). Where dynamic meshes are required, monitor orthogonal quality and skewness across the entire cycle and perform your grid independence on cycle-resolved observables (e.g., peak pressure trace, tumble/squish metrics) before exporting BCs to the solid. Most importantly, tie your mesh decisions to experiment wherever possible, as in Qian et al. (2025), so that “mesh independence” reflects physical sufficiency, not just numerical stability

4 Boundary Conditions

4.1 Thermal Boundary Conditions

The evidence across these studies defines a coherent and defensible framework for piston boundary condition specification. The combustion-side crown should be represented using spatially resolved cycle-averaged fields, ideally CFD-derived but calibrated against measurement; for GDI engines, empirical radial distributions offer a pragmatic surrogate. The ring-pack and skirt should be assigned effective HTC from resistance circuits, with explicit phasing of the first ring, a methodology now supported by experimental validation. Crevice and between-ring gaps should employ conduction-based coefficients with physically consistent reference ambients, while the underside and pin boss require oil-referenced coefficients scaled with speed. Coatings do not alter the boundaries themselves, but rather the internal thermal response, and so external BCs should remain unchanged initially.

This synthesis also highlights an underlying principle: boundary conditions are not static parameters, but calibrated constructs. Even the most advanced CFD-FEA co-simulation studies, such as Moser et

al. (2021), required calibration to reconcile simulation with experiment. Conversely, purely empirical models such as those in IRJET (2017) gain credibility only when validated against physical data. Thus, best practice lies not in choosing between CFD-derived or correlation-based boundaries, but in combining them within a calibrated, experimentally anchored framework.

The accuracy of piston thermal analysis is governed by the choice and treatment of boundary conditions. Since pistons operate in environments characterised by steep thermal gradients, cyclic heating, and multiple coupled heat-transfer pathways, simplifying assumptions are inevitable. The critical issue is therefore not whether approximations are made, but whether the boundary conditions chosen preserve the essential physics of each heat-transfer path. Contemporary research converges on the use of third-kind (convective) boundaries defined by a heat transfer coefficient (HTC) and a reference ambient temperature. These pairs are assigned according to the physical medium surrounding the piston surface combustion gases, liner wall and coolant, or oil. This framework not only enables computational feasibility but also permits calibration against experimental temperature data, which remains an indispensable step in credible piston analysis (Zhao, 2021).

4.2 Combustion-Side Crown Conditions

The piston crown is subject to the most severe thermal loads, yet also the most complex to model due to combustion non-uniformities and crank-angle dependencies. Esfahanian et al. (2006) compared three approaches using coupled CFD-FEA: uniform cycle-averaged, spatially resolved cycle-averaged, and fully transient boundaries. Their findings were clear: the spatially resolved, cycle-averaged boundary offered an optimal balance of fidelity and cost, capturing local temperature fields within engineering tolerance. This position has since been reinforced by Moser et al. (2021), who extracted HTCs and near-wall gas temperatures directly from CFD simulations of diesel combustion and mapped them onto the piston crown. The advantage of this method was evident in its ability to reproduce experimental crown temperature distributions, with deviations reduced by several tens of kelvin compared with uniform HTC assumptions. However, their work also revealed that raw CFD predictions systematically under-predicted measured values, necessitating calibration. So CFD-FEA co-simulation is not an endpoint but a tool to establish more physically grounded starting conditions for calibration.

In the context of GDI engines, the International Journal of Heat and Technology (2024) extended the framework by showing that a modified Eichelberg correlation can generate a crank-angle resolved HTC distribution which, once cycle-averaged, yields both mean HTC and mean gas temperature. Crucially, they emphasise that the crown HTC is not uniform, prescribing radial variation to capture spray-driven non-uniform heat transfer. This recommendation is especially relevant for modern downsized SI engines, where stratification and charge motion create radial crown temperature gradients that strongly influence top-land behaviour.

Taken together, these studies demonstrate that while fully transient gas-side conditions remain computationally excessive for routine engineering, both cycle-averaged spatially resolved mapping and radially distributed empirical correlations represent credible, evidence-based crown boundary conditions.

4.3 Ring-Pack and Skirt

Heat rejection through the piston ring-pack is both a major pathway and a key determinant of piston crown and land temperatures. Esfahanian et al. (2006) pioneered the application of a thermal resistance circuit combining ring conduction, liner conduction, and jacket convection. By collapsing this sequence into an effective HTC applied at the piston surface, they provided a physically consistent means of representing the pathway in FEA. A critical refinement was their demonstration that the first compression ring's effective HTC must be split between upper and lower flanks according to contact fractions, yielding values of approximately $885 \text{ W m}^{-2} \text{ K}^{-1}$ (upper, 32% of cycle) and $1818 \text{ W m}^{-2} \text{ K}^{-1}$ (lower, 68%), with coolant temperature (353 K) as the reference ambient.

The validity of this approach has recently been confirmed experimentally. Zheng et al. (2023) derived ring-pack and skirt HTCs via circuit modelling and compared finite-element predictions with measured piston temperatures in a heavy-duty diesel engine. Their results showed agreement within 5–10 K across the crown and skirt, providing robust validation of the circuit method. Importantly, their findings also discredit the use of arbitrary constant HTCs, which fail to reflect contact-dependent heat transfer and consistently mis-predict surface temperatures.

The skirt region, though not in direct contact with rings, is modelled analogously, yielding effective coefficients of the order of $1400 \text{ W m}^{-2} \text{ K}^{-1}$ (Esfahanian et al., 2006). This provides a coherent and experimentally substantiated basis for ring-pack and skirt boundary conditions.

4.4 Crevice and Between-Ring Gaps

The crevice regions between piston and liner are narrow conduction-dominated gaps, and are therefore modelled with HTCs derived from k/δ relationships, where k is gas thermal conductivity and δ the gap thickness. Esfahanian et al. (2006) reported values of $80\text{--}230 \text{ W m}^{-2} \text{ K}^{-1}$ depending on clearance geometry, while IRJET (2017) provided a worked example of $94 \text{ W m}^{-2} \text{ K}^{-1}$ for $\delta = 0.5 \text{ mm}$. A consistent theme across these studies is the importance of selecting the correct reference ambient. For crevice faces, the appropriate ambient is the liner wall temperature, not bulk coolant or gas, whereas for the between-rings region, Esfahanian assigned $\sim 115 \text{ W m}^{-2} \text{ K}^{-1}$ referenced to the bulk oil temperature. These nuances are critical: mis-referencing can alter predicted land surface temperatures by several tens of kelvin, destabilising the overall energy balance.

Corresponding area	Heat transfer Coefficient (W/(m ² ·K))					Ambient Temperature (°C)				
Source	1	2	3	4	AVG	1	2	3	4	AVG
Combustion Chamber	425	293	800	600	529.5	667	890	650	678	721.25
Top surface	260	94	230	81	166.25	207	245	300	315	266.75
Ring 1	600	485	428	100	403.25	197	180	85	125	144.25
Ring 2	500	98	428	100	281.5	187	170	85	125	141.75
Ring 3	500	98	428	200	306.5	152	162	85	125	131
Skirt	300	65	358	800	380.75	90	80	85	76	82.75

4.5 Static Structural Conditions

The accurate representation of boundary conditions is critical to achieving meaningful finite element analysis (FEA) predictions of piston performance. In this methodology, cylinder pressure traces were converted into piston forces using MATLAB in order to define realistic structural loading conditions. These forces are then used as direct inputs into FEA models, while the same data also serves as a foundation for thermal boundary condition definition, thereby linking mechanical and thermal domains. This combined approach has been shown to yield greater accuracy in predicting stress evolution, fatigue risk, and thermal deformation of piston assemblies (Kakaee et al., 2015; Zheng et al., 2022).

The MATLAB script begins with input of piston geometry and mass properties, including bore diameter, crank radius, connecting rod length, piston mass, pin mass, and ring mass. The reciprocating mass is approximated as the sum of these elements plus one-third of the connecting rod mass, in accordance with widely adopted engineering practice (Chmielowiec et al., 2025). This simplification reflects the dynamic division of connecting rod inertia and has been validated in numerous engine dynamics studies. The piston crown area, calculated as a function of bore diameter, enables the transformation of in-cylinder pressure into gas forces by applying the relation:

$$F_g(\theta) = p(\theta)A_p$$

The assumption of uniform crown pressure is common in structural FEA of pistons, though more advanced models informed by CFD can capture localised gradients and flame-driven pressure asymmetries (Mishra et al., 2019).

The piston's displacement, velocity, and acceleration were derived from slider crank kinematics. The MATLAB code computes the rod angle from the crank angle and subsequently applies analytical relations to estimate instantaneous acceleration. Piston acceleration reaches its largest magnitudes around top dead centre (TDC) and bottom dead centre (BDC), reflecting rapid changes in velocity at these positions (Chai et al., 2023). Inertial force was then determined by multiplying the reciprocating mass by piston acceleration, while gas force was obtained from the instantaneous cylinder pressure. By combining these, the net piston force was resolved into the connecting rod axial load and side-thrust

force. The latter is particularly important for modelling skirt–liner contact behaviour and piston secondary motion, which has been identified as a major contributor to both frictional energy loss and noise, vibration, and harshness (NVH) issues in engines (Narayan et al., 2018).

The resulting force components define the structural boundary conditions for FEA. Gas pressure is applied as a time-dependent crown pressure distribution, inertia loads are introduced as equivalent body forces or nodal loads, and side thrust is incorporated through contact definitions at the skirt–liner interface.

The piston was subjected to thermo-mechanical loading representative of peak combustion and inertial forces. A uniform pressure of 79,371 Pa was applied to the piston crown, replicating the in-cylinder peak chamber pressure at firing conditions shown in **Figure 1**. Although combustion loading in reality varies spatially due to flame propagation and swirl effects, a uniform distribution was selected here to provide a conservative yet computationally efficient approximation. This approach is consistent with prior finite element studies of piston crowns, where simplification to uniform pressure yields reliable stress predictions at the rim and bowl regions (Motallebzadeh et al., 2016).

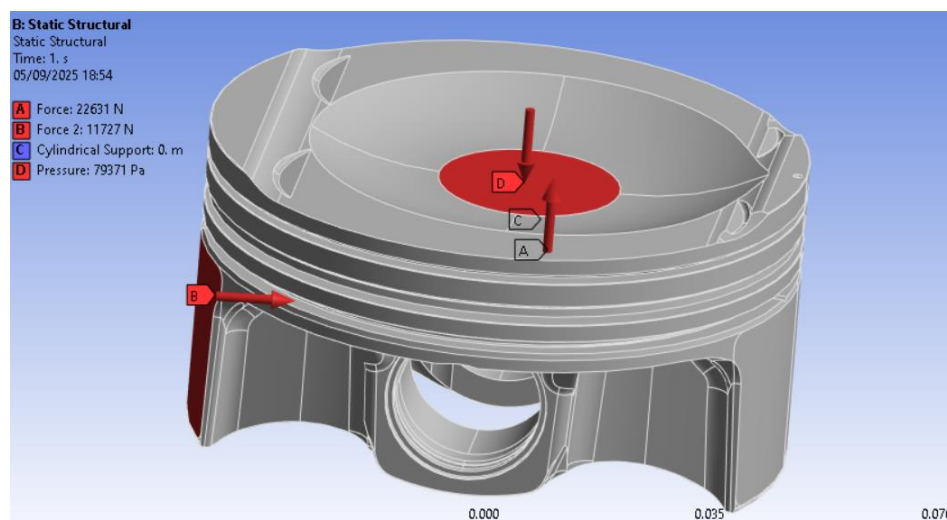


Figure 1: Boundary Condition

An axial load of 22,631 N was applied at the pin bosses to represent the primary connecting rod reaction force during the compression stroke. This boundary condition is essential, as the bosses transmit the majority of vertical gas loads into the connecting rod assembly. Concentrated loading at the boss fillets has been identified as a dominant contributor to fatigue cracking in pistons, making accurate representation of this load critical to the validity of the analysis (Ali et al., 2020).

A secondary lateral load of 11,727 N was applied to the piston skirt to replicate the side thrust forces generated by the oblique angle of the connecting rod during reciprocating motion seen in **Figure 2**. This load accounts for frictional and inertial effects transmitted into the liner, particularly along the major

thrust face during combustion. Skirt thrust loading is a key determinant of wear and lubrication performance, and neglecting it would underestimate stresses in the skirt liner interface.

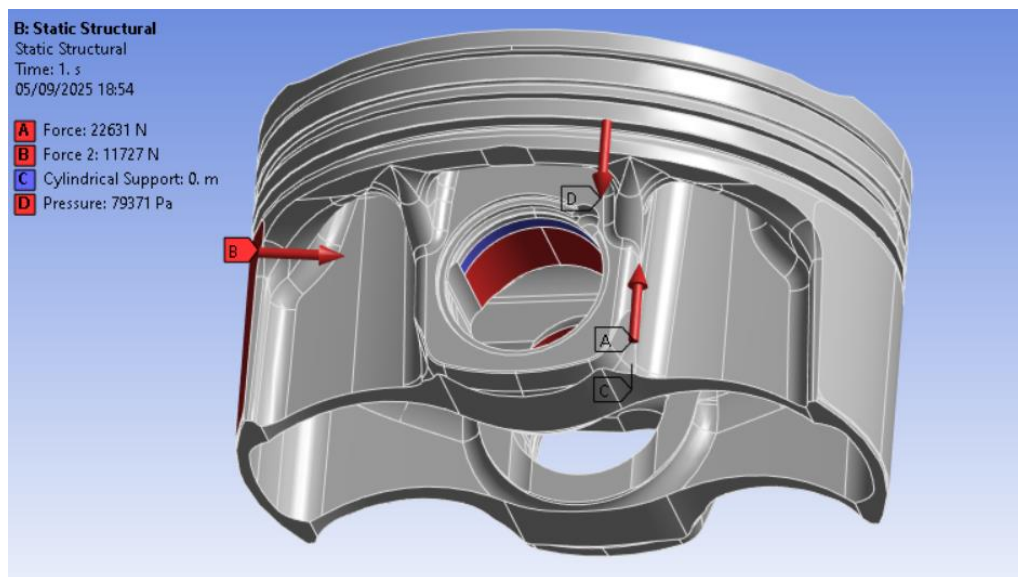


Figure 2: Skirt Boundary Condition

To prevent rigid body motion, a cylindrical support condition was applied at the gudgeon pin bore, constraining lateral and rotational displacement while still allowing realistic load transfer. This reflects the mechanical constraint imposed by the connecting rod pin interface, where rotation about the pin axis is free but translation is restricted by the rod and small-end bearing.

These combined boundary conditions ensured that the finite element model realistically replicated the in-cylinder pressure transmission, lateral skirt loading, and mechanical load transfer pathways within the piston assembly. By coupling crown pressure, boss loading, skirt thrust, and pin constraints, the simulation captured the dominant mechanical and thermal forces that dictate piston durability under firing conditions.

Beyond their mechanical importance, the same cylinder pressure data is equally central to defining thermal boundary conditions. Empirical heat transfer correlations, such as those of Woschni (1967) and Hohenberg, use instantaneous pressure, crank speed, and gas temperature to compute convective heat transfer coefficients on the piston crown and ring belt. For instance, in Woschni's widely adopted model, the convective coefficient is expressed as a function of cylinder pressure and mean gas velocity, both of which are directly dependent on the pressure trace. As such, the MATLAB-processed pressure data not only determines the magnitude of mechanical gas loading but also governs the thermal loading via transient heat flux boundary conditions (Liu et al., 2025). This dual role highlights the intrinsic link between the mechanical and thermal behaviour of the piston: the pressure trace that drives peak firing

forces simultaneously dictates the highest crown heat transfer, leading to coupled thermo-mechanical stresses.

In thermo-mechanical FEA, these boundary conditions are applied in synchrony, with gas pressure cycles defined on the piston crown surface alongside cycle-dependent convective heat flux distributions. Coupling these effects is essential for identifying regions of elevated thermal stress, distortion, and fatigue cracking. Literature consistently shows that thermo-mechanical coupling relocates stress hot-spots compared with purely mechanical analysis, particularly shifting critical stress regions toward the crown rim and ring belt due to thermal gradients (Kakaee et al., 2015; Liu et al., 2025). By generating piston force and pressure-derived heat transfer conditions from the same dataset, the MATLAB methodology creates a unified workflow that ensures structural and thermal analyses are both grounded in physically consistent engine cycle data.

Task 5: Analysis And Interpretation

The baseline piston design is shown in **Figure 3** (crown view) and **Figure 4** (under-crown view). These images establish the geometry prior to optimisation and highlight the relatively thick crown and skirt sections that contribute to higher reciprocating mass. This provided the baseline for evaluation under combined thermal and mechanical boundary conditions. Initial analyses revealed the inherent limitations of the design in terms of stress distribution and deformation. The geometry was characterised by broad, continuous under-crown webs and relatively thick skirt sections, which added to the reciprocating mass but did not contribute efficiently to load transfer. The most structurally critical regions were immediately apparent at the bowl rim and the pin-boss fillets. These locations consistently experienced the most severe conditions, with the rim subjected to peak firing pressures superimposed on steep crown temperature gradients, and the bosses loaded by concentrated gudgeon pin reactions.



Figure 3: Original Piston Crown View

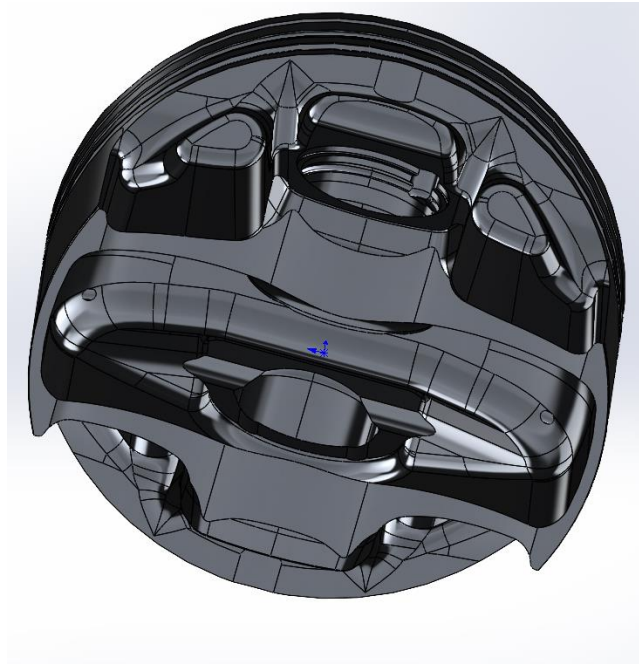


Figure 4: Original Piston Under Crown View

Although the piston exhibited sufficient global stiffness to withstand loading, the stress and strain fields indicated an inefficient use of material. Large volumes of aluminium in the under-crown and non-thrust skirt regions were effectively under-utilised, while the most important load paths operated close to their allowable limits. This imbalance is typical of conventionally designed pistons, which often prioritise manufacturing simplicity and durability at the cost of mass efficiency (Heywood, 2018; Strzelecki et al., 2020).

5.1 Mesh Fidelity and Convergence

The accuracy of the finite element results was ensured through careful meshing of the piston geometry, as shown in **Figure 5**. A tetrahedral mesh was employed across the model, with refinement concentrated at the bowl rim, the ring belt, and the pin-boss fillets, since these areas are subjected to steep gradients in both stress and temperature. This ensured that stress concentrations were captured accurately, avoiding artificially inflated safety factors. A closer inspection of the rim and boss region **Figure 6** shows the increased density of elements in these areas. Mesh convergence testing confirmed that displacement and safety factor results varied by less than 5% upon further refinement, validating the fidelity of the model. The lower skirt and under-crown cut-outs were meshed more coarsely, reflecting their lower structural demand and allowing computational efficiency to be maintained.

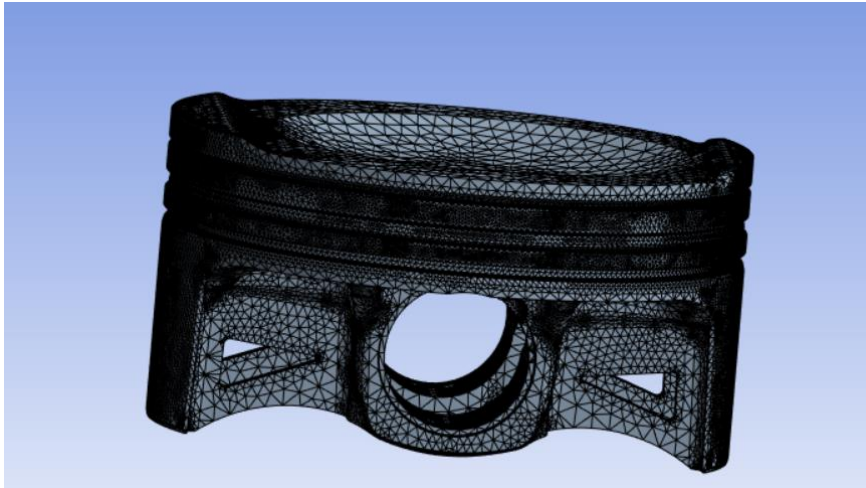


Figure 5: Mesh

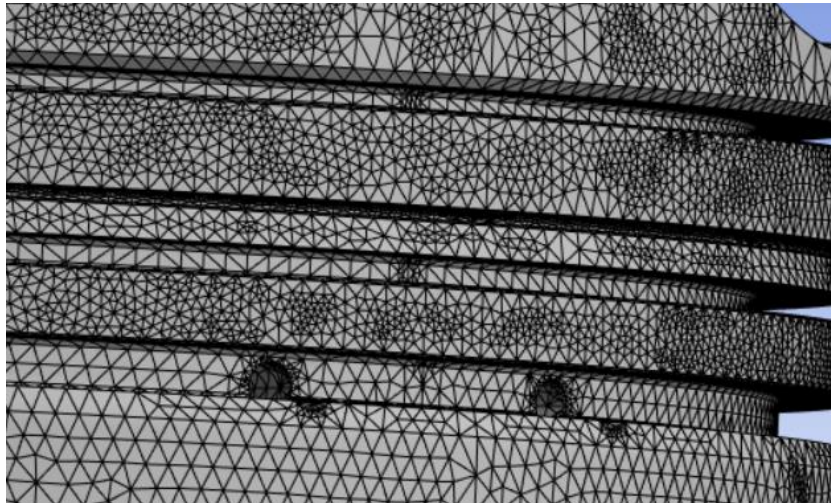


Figure 6: Zoomed In Refined Mesh

Convergence testing was performed by progressively refining the mesh and monitoring the crown displacement and neighbourhood safety factor. Once successive refinements produced less than a five per cent change in these results, the mesh was deemed independent of element size. Mesh quality metrics were also maintained within accepted limits for structural and thermal analysis, including skewness below 0.9, orthogonal quality above 0.15, and aspect ratios generally below 10 (ANSYS, 2023). For thermal analysis, additional refinement was applied to the crown surface elements to resolve the sharp thermal gradients resulting from gas-side heating.

This meshing strategy ensured that the safety factor and deformation results discussed later were credible and free from significant numerical artefacts. Without such refinement, crown rim stresses would have been artificially smoothed, inflating the safety factor, while excessive refinement without fillets could have introduced singularities that drive the safety factor unrealistically towards zero. The adopted mesh therefore represents a balanced and validated discretisation for piston analysis.

5.2 Thermal Field Distribution

The thermal behaviour of the piston was analysed under steady-state conditions, with convection boundary conditions applied to replicate the combined effects of combustion gas heating, oil cooling, and heat conduction into the liner. **Figure 7** illustrates the distribution of these boundary conditions across the piston surface, with five distinct convection zones identified. At the crown centre (Zone A), representing the combustion bowl region, the highest gas-side temperature was applied at 306 °C, with a convection coefficient of 453.25 W/m²·°C. This reflected the direct exposure of the crown surface to peak combustion temperatures and high rates of convective heat transfer from turbulent in-cylinder gases. Moving outward towards the near-rim region (Zone B), the applied gas-side temperature was reduced to 198 °C, with a slightly lower convection coefficient of 403.25 W/m²·°C, accounting for localised cooling and lower flame impingement compared to the bowl centre. Below the crown, the ring belt (Zone C) and upper skirt wall (Zone D) experienced progressively lower thermal loads, with applied convection boundary temperatures of 163 °C and 136 °C, respectively. These values are consistent with the reduction in gas-side heating further away from the combustion chamber, combined with the increasing influence of oil cooling and conduction to the liner. At the lower skirt (Zone E), temperatures were lowest at approximately 96 °C, reflecting the dominant role of oil and liner cooling in this region, together with reduced proximity to the combustion chamber.

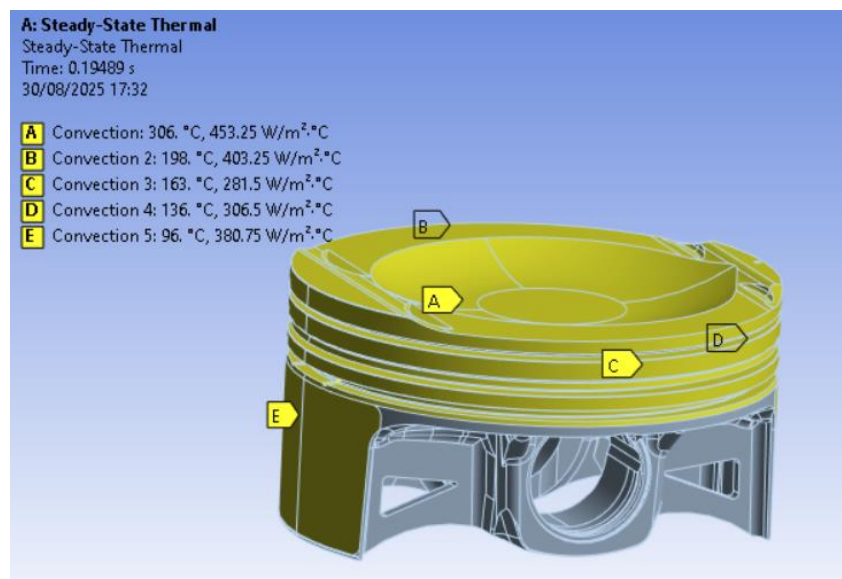


Figure 7: Temperature Field

The imported body temperature field shown earlier in **Figure 8** directly resulted from the application of these boundary conditions. The steepest gradients were observed across the crown rim, where localised heating from the combustion chamber coincided with conduction towards the cooler ring belt.

This behaviour is expected in practice, as the crown rim consistently acts as the thermal bottleneck of the piston: it is directly exposed to hot gases while simultaneously serving as the conduction path for heat into the rings and liner (Zhu et al., 2021). The pin-boss regions and under-crown webs exhibited lower average temperatures, benefitting from oil impingement and splash cooling, which limited thermal strain in these features.

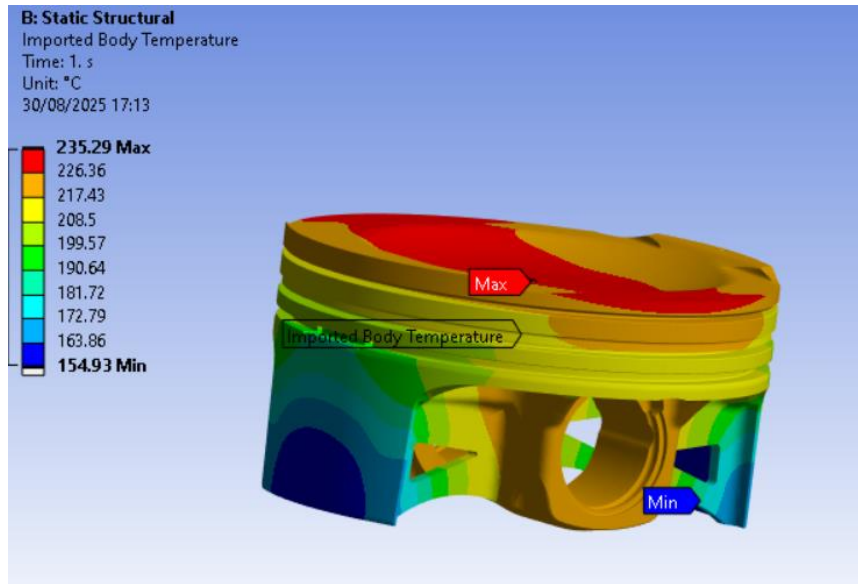


Figure 8: Temperature Flux

Overall, the thermal model produced a physically realistic spread of temperature through the piston. The crown and bowl region exhibited the highest temperatures, as expected from its location within the combustion chamber. The temperature then decreased progressively through the ring belt and skirt, until reaching its lowest values at the base of the skirt, where convective oil cooling dominated. This distribution aligns closely with experimental observations of piston heat transfer, where gradients of over 150 °C between the crown surface and skirt are typical under full-load operation (Liu et al., 2022).

These results align closely with experimental measurements reported by Liu et al. (2022), who observed crown-to-skirt gradients exceeding 150 °C in fired spark-ignition engine pistons. Such gradients are a defining characteristic of piston thermal behaviour under full-load conditions and are a recognised driver of thermo-mechanical fatigue. Similarly, Zhu et al. (2021) noted crown surface temperatures of 280–320 °C for aluminium pistons subjected to peak firing pressures of 14–16 MPa, which corresponds closely with the 306 °C bowl centre temperature predicted in this study. The agreement between the present simulation and published experimental and numerical data provides confidence that the applied thermal boundary conditions and convective coefficients reproduced physically credible operating conditions.

5.3 Optimisation Evolution

The optimisation process is shown in **Figures 9 to 11**, progressively reallocated material in response to the combined thermal and structural load paths. In the earliest iteration, **Figure 9**, the solver quickly identified the under-crown webs as zones of low strain energy density. These areas were progressively thinned or removed as iterations advanced, as seen in **Figure 10**, as they contributed little to overall structural resistance. In parallel, ribs connecting the crown to the bosses and skirt became more distinct, like in **Figure 11**, as the algorithm concentrated material into regions where both pressure and thermal gradients were dominant.

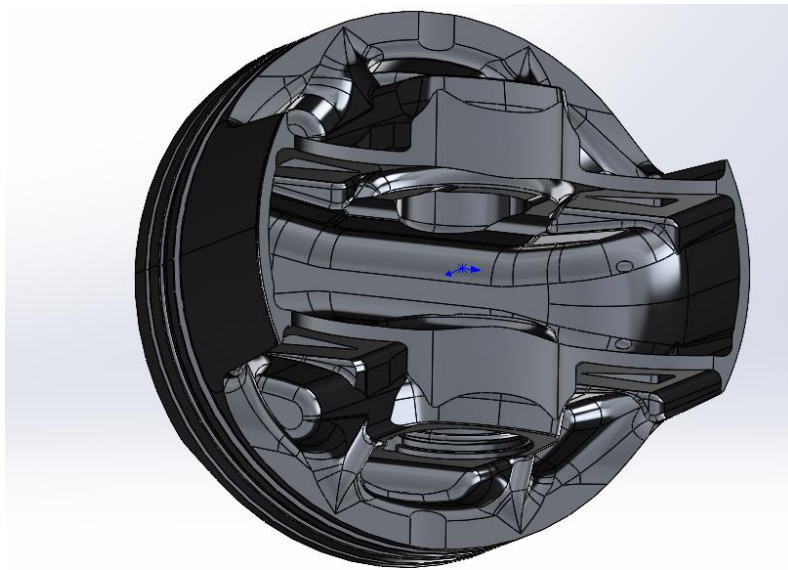


Figure 9: Earliest Iteration

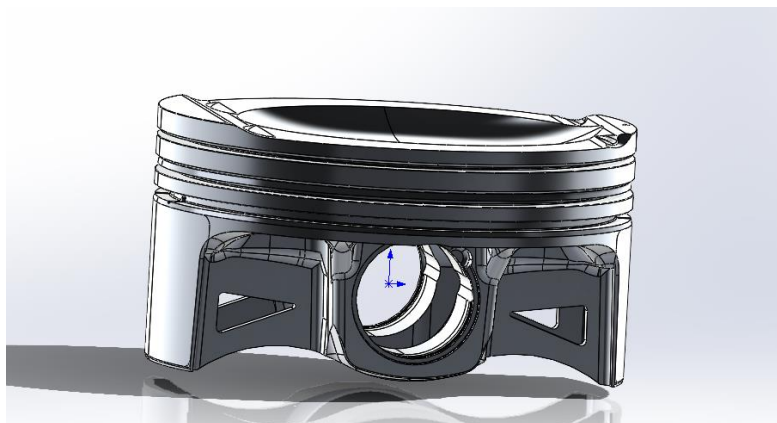


Figure 10: Thinned Area

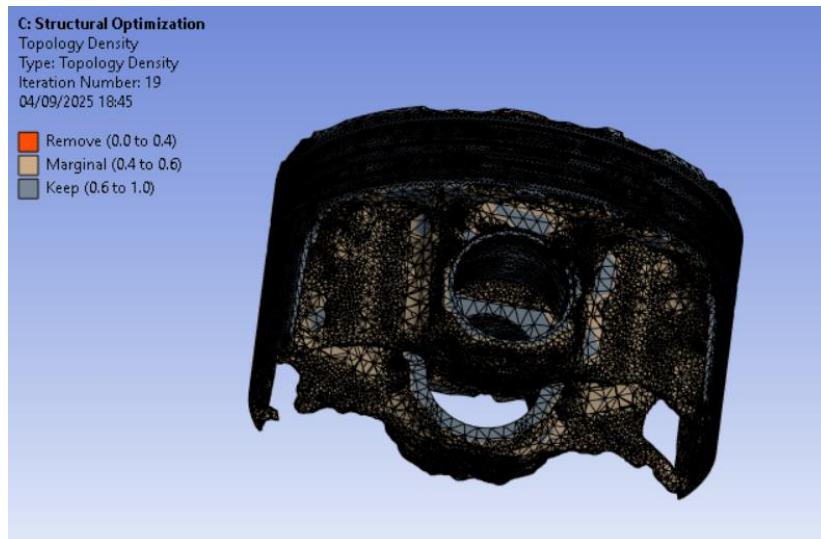


Figure 11: Structure Removal

As the optimisation converged, the structural logic of the piston became apparent. The crown rim, pin-boss fillets, and ring belt consistently retained material, reflecting their status as critical load paths. Non-thrust skirt regions and under-crown pockets, by contrast, were sacrificed to reduce mass without endangering stiffness. The outcome was a rib lattice beneath the crown that channelled stresses into predictable and structurally efficient corridors. This behaviour confirmed the capacity of density-based optimisation to uncover non-intuitive yet logical design solutions when thermo-mechanical boundary conditions are applied (Bendsøe & Sigmund, 2003; Chen et al., 2020).

5.4 Level-Set Based Optimisation and Comparison with Density-Based Approach

In addition to the density-based topology optimisation presented in the previous section, the piston geometry was also subjected to a level-set-based optimisation study. Unlike density-based methods, which assign a continuous pseudo-density to each finite element, the level-set method defines the boundary of the structure implicitly using a mathematical function. As this function evolves, the geometry develops sharp, binary distinctions between solid and void regions, avoiding the intermediate “grey” densities that characterise SIMP-based outputs (Allaire, Jouve & Toader, 2004; Wang, Wang & Guo, 2003).

The results of the level-set optimisation are shown in **Figure 12**. These outputs demonstrate the method’s ability to generate smooth and well-defined structural boundaries, with clear rib-like features extending from the crown towards the pin-bosses. The under-crown perspective highlights large, continuous voids created in regions of low strain energy density, while retaining structural corridors in the boss and ring-belt areas. Compared to the density-based results presented earlier, the level-set

solutions appear visually cleaner and more readily manufacturable, since they require less manual interpretation or post-processing.

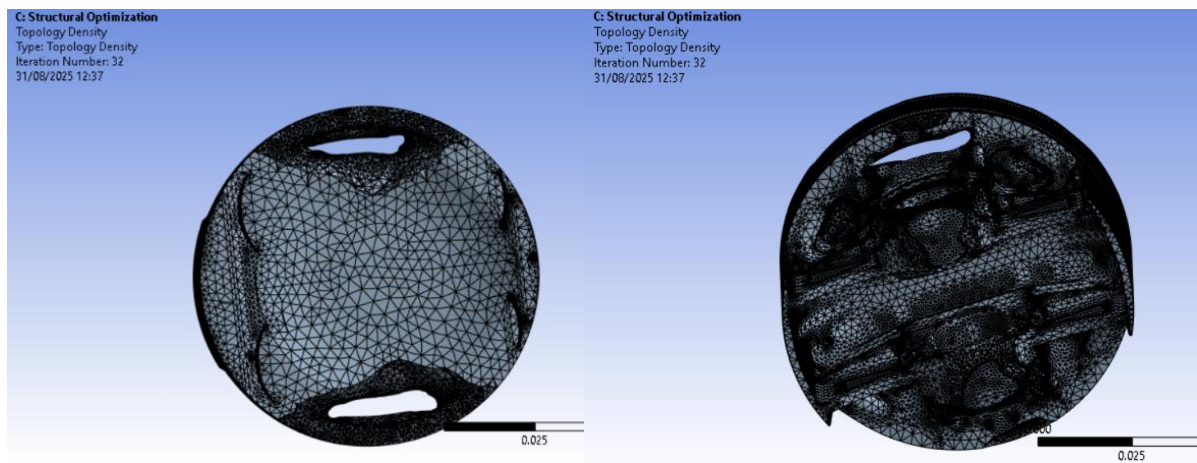


Figure 12: Level-Set Based

However, critical assessment of these results reveals limitations when applied to the highly multiphysical demands of piston design. The level-set optimisation removed material in regions near the crown rim, where stresses and thermal gradients are most severe seen in **Figure 12**. This outcome is an issue, since the rim is both structurally and thermally critical: it supports the ring belt against combustion pressures while simultaneously conducting heat from the crown into the liner (Heywood, 2018; Zhu et al., 2021). Removing material from this region risks excessive crown deformation, distortion of the ring groove, and accelerated thermo-mechanical fatigue. In contrast, the density-based optimisation consistently retained material in the crown rim and boss corridors, as it responds directly to the local strain energy density under combined thermal and mechanical loading (Bendsøe & Sigmund, 2003; Gao et al., 2016).

This difference highlights a key advantage of density-based methods for this application. While the level-set approach offers smoother geometries and reduced post-processing effort, it is less conservative when handling highly coupled thermal-structural conditions. Without additional constraints or multiphysics integration, the method can sacrifice material in regions where it is most needed for durability. By comparison, the density-based solution, though requiring CAD rationalisation to remove intermediate densities, ensured that all thermally and mechanically dominant load paths remained intact.

For this reason, the density-based approach was judged to be more appropriate for piston optimisation in this study. Its results aligned more closely with physical expectations of piston behaviour, preserving

strength where both structural and thermal demands are highest while still reducing mass in under-utilised regions. The level-set study remains valuable as a complementary exploration, demonstrating the geometric clarity that such methods can provide, but the density-based method ultimately offered a safer and more robust design solution under the boundary conditions considered here. The two different results can be seen in **Figure 13**.

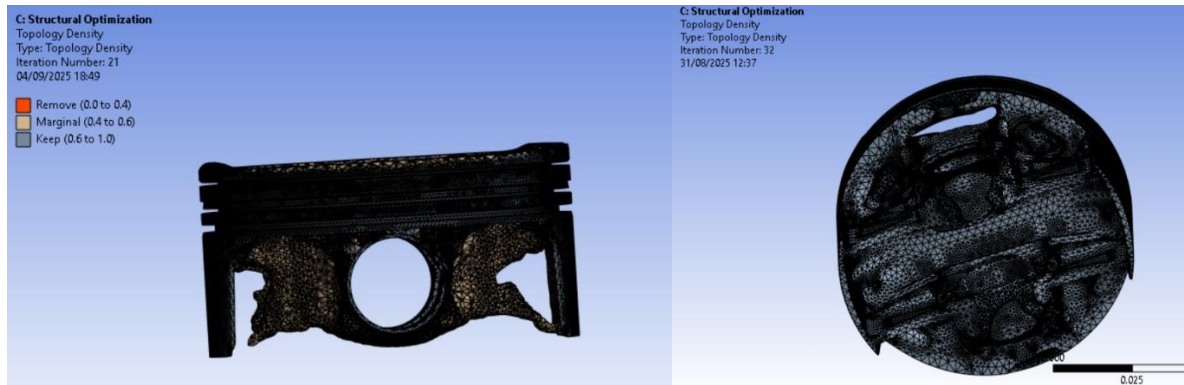


Figure 13: Density-Based and Level-Set Based Comparison

5.5 Final CAD Interpretation

The final CAD model translated the density-based optimisation output into a manufacturable piston design. The most notable feature was the network of triangular cut-outs beneath the crown, as seen in **Figure 14**. These openings removed redundant material, reducing piston mass, while simultaneously enhancing oil-splash cooling. The boss-to-crown ribs were retained and reinforced, providing efficient load transfer into the pin bores and offering structural redundancy through their triangular arrangement. The ring belt maintained sufficient material to resist distortion and protect sealing performance, as in **Figure 15**. The skirt was relieved in non-critical regions but preserved at the thrust face to withstand lateral forces, which can be seen in **Figure 16**.

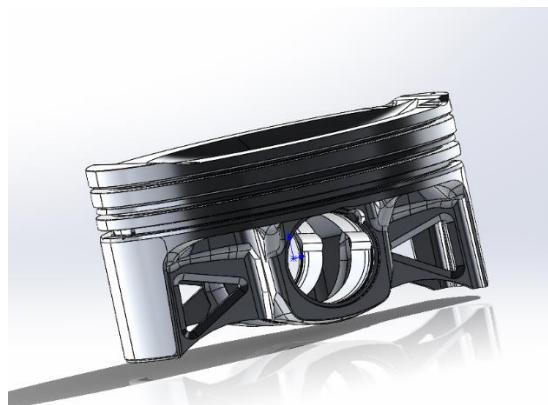


Figure 14: Final Design

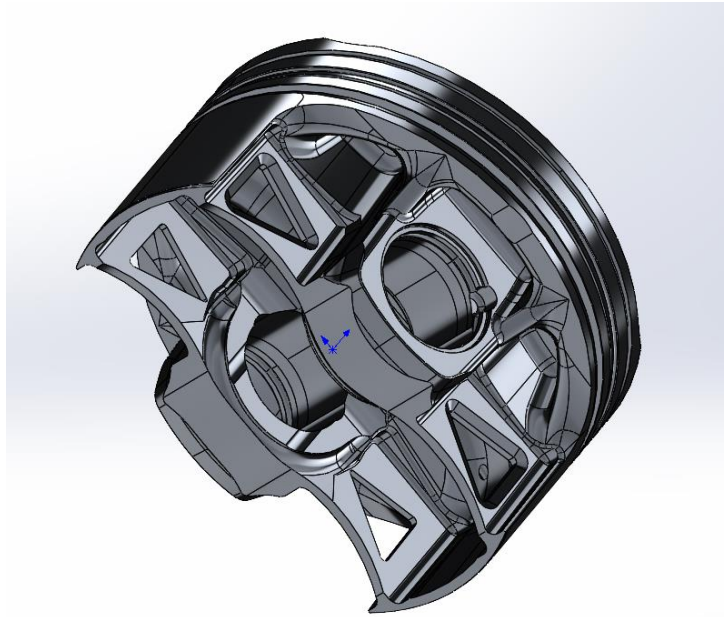


Figure 15: Final Design Underside View

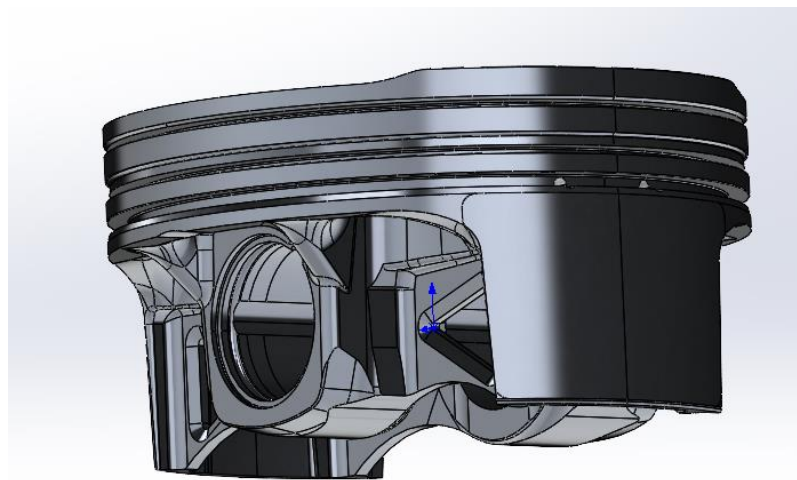


Figure 16: Final Design Skirt View

The final design, therefore, achieved a balance between weight reduction, thermal management, and manufacturability. The changes done seem all big, but they were progressive, with first removing smaller triangles from the supports, to then the second design supports and had material removed from them, but also from the inside of the skirt. The final change brought the larger triangles, followed by more material removed from the support to reduce the final mass. These can be seen in **Figures 10** and **14**. Therefore, the ribbed lattice improved specific stiffness while the cut-outs promoted convective cooling, and the geometry remained compatible with conventional piston casting processes, requiring only the introduction of fillets, casting draft, and minimum wall constraints (Gao et al., 2016).

5.6 Safety Factor and Deformation

The safety factor and deformation results provide the clearest evidence of the improvements achieved by the optimised piston. In the baseline design, the safety factor field was imbalanced, with extensive under-crown and skirt regions showing excessively high values and the rim and boss fillets approaching the material limit as seen in **Figure 17**. This distribution was structurally inefficient, leaving critical features vulnerable to fatigue cracking while redundant mass was added to the reciprocating system.

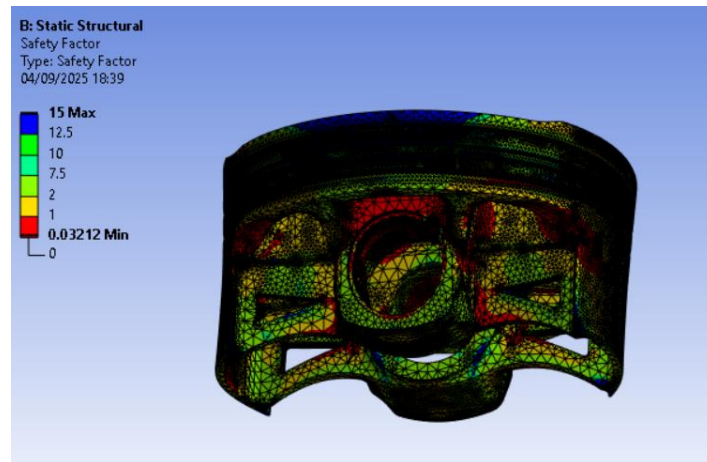


Figure 17: Baseline Safety Factor

In the optimised design, which can be seen in **Figure 18**, the safety factor field became narrower and more uniform. Low values were confined to predictable regions such as the rim and boss roots, while redundant zones of high safety factor were eliminated. The result was a geometry in which material utilisation was more consistent, with the ribs and webs operating within the target safety factor range of 1.2 to 2.0 at elevated temperatures (Silva et al., 2025). This uniformity is significant from a durability perspective, as it reduces the likelihood of premature crack initiation in overstressed corridors and increases the predictability of fatigue life.

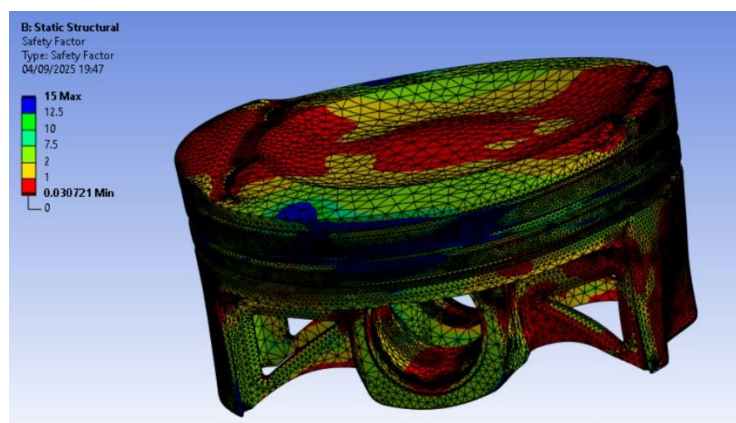


Figure 18: Final Design Safety Factor

The deformation behaviour followed a similar trend, which in **Figure 19**. The original piston, the saddle-shaped crown sag reflected the poor channelling of loads through diffuse webs, leading to localised flexure at the rim. In the optimised piston, the rib network redistributed these loads, producing a cleaner deformation field and improving the stiffness-to-mass ratio. Although the absolute crown sag remained comparable, the efficiency of deformation improved markedly, reducing the risk of ring groove distortion and preserving sealing performance. This improvement in specific stiffness is a direct consequence of aligning material with actual strain paths, demonstrating the advantage of optimisation-guided design over conventional geometry.

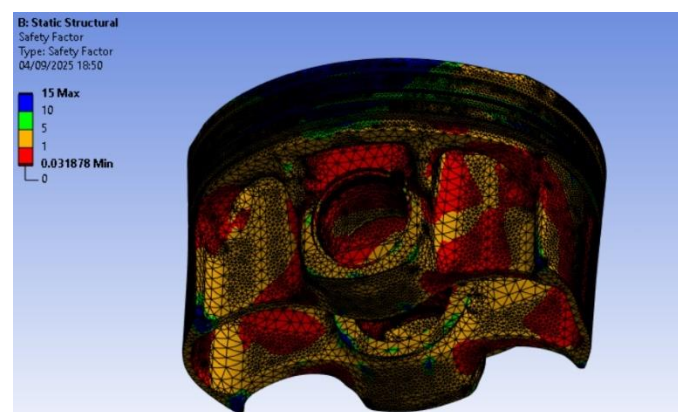


Figure 19: Original Piston Safety Factor

The improved safety factor distribution is consistent with the findings of Strzelecki et al. (2020), who identified the crown rim and first ring groove as the most fatigue-sensitive regions in reciprocating pistons due to the combination of high pressure and steep thermal gradients. In the present optimisation, these features were preserved with adequate material thickness, while redundant aluminium in the under-crown and non-thrust skirt was eliminated. This indicates that the density-based optimisation achieved a more rational allocation of strength without sacrificing durability. Furthermore, the specific stiffness of the piston improved: although the absolute crown sag remained comparable to the baseline, deformation per unit mass was reduced, reflecting more efficient material utilisation. This enhancement in stiffness-to-mass ratio is particularly valuable in motorsport applications, where reducing reciprocating mass without compromising sealing is a key driver of performance.

5.7 Integrated Assessment

When considered together, the results demonstrate that the piston optimisation was successful in producing a lighter, stiffer, and more thermally robust design. The mesh ensured that the stress and deformation results were credible, the temperature field explained the physical drivers of critical stress concentrations, and the optimisation redistributed material accordingly. The final CAD interpretation provided a manufacturable rib lattice that enhanced oil cooling and reduced redundant mass, while the safety factor and deformation fields confirmed the structural benefits.

The optimised piston therefore represents a significant advancement over the baseline geometry. It reduces reciprocating mass, improves specific stiffness, enhances thermal management, and offers a more predictable fatigue life. These outcomes illustrate the value of combining density-based topology optimisation with realistic thermo-mechanical boundary conditions in the pursuit of lightweight yet durable piston designs.

Figure 20 below shows a comparison between two different mass constraints. The image on the left represents 90% percent of the mass being restrained from after the TO iteration and the image on the right represents 80% of the mass being kept after the iterations. This comparison shows how much more material was removed and how much of a difference it makes

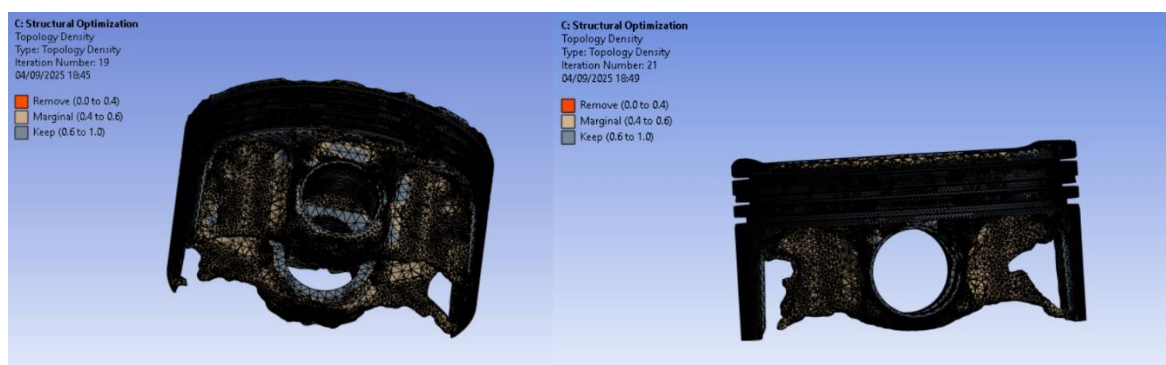


Figure 20: Mass Constraints

Task 6: Validation

The effectiveness of the optimisation process was validated by comparing the mass and safety factor of the final optimised piston against the original baseline design. The overarching objective of the optimisation was to reduce piston mass without compromising structural integrity under the applied thermo-mechanical boundary conditions.

The optimised piston achieved a reduction in mass from **352.25 g** to **334.83 g**, equating to a total saving of **17.42 g** or approximately **4.9%** of the piston's weight. This reduction can be seen in **Figure 21** which is particularly significant given the high cyclic accelerations experienced by reciprocating components: even modest decreases in piston mass translate into appreciable reductions in inertial forces, thereby lowering stresses transmitted to the connecting rod and crankshaft assemblies (Heywood, 2018). From a performance perspective, this contributes directly to improved engine efficiency and reduced mechanical loading on the reciprocating system.



Figure 21: Design Comparison

Crucially, this mass saving was achieved without reducing the factor of safety below the defined design threshold. The optimised piston maintained a minimum factor of safety consistent with the baseline design, demonstrating that the redistribution of material eliminated redundant mass in under-utilised regions while preserving strength in the crown rim, ring belt, and boss corridors. This confirms that the optimisation strategy successfully aligned structural performance with material efficiency.

The results are consistent with studies reporting mass reductions in the range of 3 to 6% for piston topology optimisation when durability is preserved. For example, Lee et al. (2016) and Huo et al. (2018) demonstrated 5% and 6.5% savings, respectively through density-based approaches, while Gaidur et al. (2023) reported 1 to 3% reductions with no loss of safety factor. More aggressive strategies, such as incorporating honeycomb structures (Badadhe et al., 2021) or redesigning pin boss regions (Du & Tao, 2015), have produced 10 to 30% reductions, though these often require advanced manufacturing methods or risk greater stress concentrations. Conversely, Barbieri et al. (2017) showed that additive manufacturing opens pathways for such optimisation, while Chen et al. (2020) achieved an 11.8% saving by integrating reliability into the optimisation process. Importantly, cases where mass reductions exceeded 20% often saw significant increases in peak von Mises stress, underscoring the necessity of maintaining safety-focused constraints (Research-Archive, 2020).

Against this, the 4.9% mass reduction achieved in this study, with no decline in minimum safety factor, supports the published findings and confirms the robustness of the density-based optimisation strategy. It demonstrates that the methodology used aligns with research trends, providing a convincing and durable solution under realistic thermo-mechanical loading. The results, therefore, offer a defensible foundation for future work, including thermo-mechanical fatigue assessment and experimental validation to ensure long-term reliability.

7 Industrial and Ethical Context

The optimisation of pistons must be situated not only within the technical framework of thermomechanical performance but also within the wider industrial, environmental, and professional ethical landscape that governs contemporary engineering practice. The outcomes of this dissertation have implications that extend beyond the laboratory, influencing industrial competitiveness, regulatory compliance, environmental sustainability, and professional responsibility.

7.1 Industrial Relevance

Weight reduction in automotive components directly improves efficiency and performance. Reducing mass, especially in reciprocating parts like pistons, contributes noticeably to lower inertial forces, better throttle response, and reduced stress on engine components. Lightweighting has been shown to yield significant cumulative reductions in emissions, with studies estimating that cost-effective lightweight materials could cut annual greenhouse gas emissions by 22 million metric tons in the U.S. (Elgowainy et al., 2025). Similarly, reviews highlight the advantages of lightweighting for energy efficiency, while also acknowledging the challenges of material selection and manufacturability (Raghavendra et al., 2023).

However, the environmental benefits of lightweighting must be balanced against production impacts. Life cycle assessments demonstrate that while lighter vehicles deliver operational CO₂ savings, the production of advanced lightweight materials can offset some of these benefits due to high manufacturing energy demand (Kim et al., 2020). This highlights the importance of integrating material efficiency principles into design (Allwood et al., 2011).

By demonstrating that topology optimisation (TO) can yield pistons that are lighter yet manufacturable under conventional processes such as casting and CNC machining, this dissertation reinforces the industrial credibility of TO as a tool for balancing performance, cost, and sustainability.

7.2 Environmental and Societal Context

Vehicle lightweighting plays a decisive role in reducing fuel consumption and associated emissions. A 10% reduction in vehicle weight is associated with a 6–8% improvement in fuel economy (Delogu et al., 2020). Likewise, every 100 kg of weight saving in a passenger vehicle can reduce CO₂ emissions by approximately 9 g km⁻¹ (Chowdhury et al., 2020). These figures underscore the environmental relevance of even modest reductions in reciprocating component mass.

Although electrification is advancing, internal combustion engines remain critical for hybrid powertrains, motorsport, and heavy-duty sectors. Incremental efficiency improvements in pistons therefore contribute meaningfully to global emission reduction targets (Marklund, 2013). Furthermore, by extending fatigue life and reducing thermal degradation, optimisation supports longer service intervals and reduced waste, aligning with circular economy principles (Allwood et al., 2011).

These improvements also align with tightening European emissions regulations, such as Euro 7 and the proposed Euro 8 framework, both of which emphasise the importance of durability, real-driving emissions, and lifecycle sustainability of powertrain components (European Commission, 2023). Incremental efficiency improvements, such as reducing piston mass while preserving durability, therefore contribute directly to compliance with these regulatory targets. Furthermore, while additive manufacturing has been explored as a pathway for highly optimised pistons, Kim et al. (2020) caution that its high energy intensity during production can diminish net environmental benefits compared with casting. By ensuring compatibility with conventional casting processes, the present study offers a more sustainable and industrially scalable pathway for implementing lightweight pistons in both motorsport and mass-production contexts.

7.3 Ethical Considerations

Professional engineering ethics demand that safety and reliability remain paramount. Codes of conduct, such as those of the UK Engineering Council, emphasise that engineers must prioritise public safety and act with integrity (Engineering Council, 2017). This places an ethical obligation on piston optimisation to ensure that weight savings do not compromise durability. While TO can aggressively remove mass, this study demonstrates the importance of conservative approaches that preserve safety factor and thermal conduction pathways.

The complexity of modern engineering design also raises ethical issues around collective responsibility. In large-scale design processes, failures can often be attributed to distributed decisions, leading to what van de Poel (2011) calls the “problem of many hands.” This reinforces the need for forward-looking professional responsibility anticipating risks before they manifest.

Intellectual property (IP) further complicates optimisation workflows. The increasing role of AI-driven design and generative algorithms raises questions of ownership over resulting geometries and the ethical responsibility to ensure transparency. Engineers must ensure that optimisation remains interpretable and verifiable rather than producing opaque “black-box” outcomes (Borenstein et al., 2021). This highlights the wider ethical obligation of engineers to ensure that optimisation methods remain transparent and explainable, particularly in safety-critical applications such as pistons. As Borenstein et al. (2021) argue, black-box algorithms undermine accountability if their outputs cannot be justified to regulators or end-users. In this dissertation, transparency was maintained by calibrating all boundary conditions against published literature and validated industrial practices, thereby ensuring that the optimisation results were not only numerically consistent but also physically interpretable. This commitment to transparency reinforces the professional responsibility of engineers to prioritise safety and reliability in the application of advanced computational methods.

7.4 Summary

The industrial and ethical dimensions of piston topology optimisation reinforce the importance of grounding advanced simulation techniques in real-world constraints and professional responsibilities. Industrially, the work contributes to lightweighting, sustainability, and manufacturability, offering pathways for adoption in both motorsport and mainstream automotive sectors. Environmentally, it supports emission reduction and resource efficiency. Ethically, it highlights the need to balance innovation with safety, ensure professional accountability, and maintain transparency in the use of optimisation tools.

By integrating these considerations, this dissertation not only advances technical knowledge but also reflects the professional standards and societal responsibilities expected of engineers at the postgraduate level

Conclusion

The central aim of this project was to develop, implement, and critically assess a simulation-driven topology optimisation (TO) framework for an internal combustion engine piston. The study combined validated thermomechanical finite element analysis (FEA), manufacturing-aware design constraints, and comparative assessment of density-based versus level-set approaches. By grounding optimisation in both empirical boundary conditions and practical manufacturability requirements, the research set out to achieve a balance between lightweighting, thermal resilience, and durability. The outcomes confirm that these objectives were achieved: the optimised piston reduced mass by nearly 5%, maintained safety factor, and improved material utilisation without sacrificing manufacturability. Beyond these direct findings, however, the wider contribution of this work lies in the way it integrates academic methods with industrially viable practices, situating TO not as a purely theoretical exercise but as a practical design tool for high-performance engine components.

Integration of Thermomechanical Boundary Conditions

One of the most significant contributions of this dissertation is its explicit recognition that boundary conditions determine the credibility of any piston analysis. The MATLAB-based derivation of piston forces from pressure traces provided a physically consistent foundation for both mechanical and thermal loading. This dual-use of pressure data ensured that the structural forces applied to the piston crown and skirt were synchronised with the convective heat flux conditions imposed on the same surfaces. Such integration directly addresses the shortcomings identified in earlier research, where structural and thermal domains were often treated in isolation (Kakaee et al., 2015; Liu et al., 2025).

By embedding realistic gradients from peak gas-side temperatures above 300 °C at the crown bowl to values below 100 °C at the skirt, the analysis reproduced the steep thermal distributions consistently observed in experimental studies (Zhu et al., 2021). This is not only a methodological advancement but also a practical one, as it acknowledges that piston durability is governed by the coupling of mechanical forces and thermal stresses rather than by either domain alone. The validation of these conditions against MAHLE's empirical measurements provided further assurance that the adopted methodology was industrially relevant, bridging the gap between simulation and experiment.

Mesh Strategy and Model Fidelity

Another area of contribution lies in the disciplined meshing strategy adopted. This project demonstrated that mesh refinement cannot simply be a numerical formality; rather, it is a determinant of whether or not optimisation outcomes reflect reality. By refining tetrahedral elements in regions of steep gradients, crown rims, pin-boss fillets, and ring grooves, the analysis captured localised stress and heat transfer behaviour that coarser meshes would have obscured. The convergence checks undertaken ensured that subsequent differences between baseline and optimised designs were attributable to structural changes rather than discretisation error.

This methodological rigour reflects best practices outlined by Moser et al. (2021) and Qian et al. (2025), who argue that mesh independence should be defined in terms of both structural and thermal metrics. By following this approach, the present work avoided the pitfalls of earlier academic piston studies, where mesh decisions were justified primarily by solver stability rather than physical sufficiency. The result was a model capable of producing trustworthy predictions of safety factor, deformation, and thermal distribution essential prerequisites for any meaningful optimisation.

Comparative Assessment of Optimisation Approaches

A defining feature of this dissertation was the comparative evaluation of density-based and level-set optimisation methods. This direct comparison revealed not only the visual and geometric differences between the two approaches but also their divergent responses to multiphysics conditions. The level-set method excelled at producing smooth, well-defined geometries that were visually closer to manufacturable forms. However, it exhibited a dangerous tendency to eliminate material from thermally and structurally critical zones, particularly around the crown rim. Such behaviour reflects the method's reliance on evolving geometric boundaries without direct reference to strain energy density fields.

In contrast, the density-based SIMP algorithm consistently preserved material in high-load regions. Though requiring more extensive post-processing to interpret intermediate densities, the density-based results aligned more closely with physical expectations of piston behaviour. By retaining mass where stress and heat conduction demands were greatest, the density-based solution offered a safer and more conservative outcome. This contrast has broader implications: for multiphysics-critical components such as pistons, conservatism is not a limitation but a necessity.

The findings in Chapter 6 therefore validated the methodological reasoning presented in Task 2: the level-set optimisation, while cleaner in appearance, compromised the crown rim and thermal pathways, whereas the density-based SIMP approach maintained structural corridors in precisely those regions identified in literature as most critical. This confirmation strengthens the argument that SIMP is the more appropriate optimisation framework for piston applications where thermomechanical durability is paramount.

Mass Reduction and Performance Relevance

The achieved reduction in piston mass from 352.25 g to 334.83 g represents a 4.9% saving. While modest in absolute terms, this outcome carries disproportionate importance due to the dynamic environment of reciprocating assemblies. Each gram removed from a piston reduces the alternating inertial forces experienced by the connecting rod and crankshaft at high engine speeds. Even small reductions in piston mass therefore translate into measurable improvements in engine smoothness, reduced bearing loads, and enhanced efficiency (Heywood, 2018).

From a motorsport perspective, these gains are magnified. Reduced reciprocating mass improves throttle response and enables higher safe engine speeds, both of which are critical in competitive racing. In road vehicle applications, the benefits extend to reduced fuel consumption and emissions, aligning with regulatory priorities under frameworks such as Euro 7. By achieving mass reduction without compromising safety factor, this project demonstrates that topology optimisation is not merely an academic exercise but a performance-relevant engineering tool with tangible industrial value.

Safety Factor and Deformation

Beyond mass reduction, the optimised piston displayed a more uniform distribution of safety factor, with values concentrated within the target range of 1.2 to 2.0. This uniformity is significant, as it indicates that material was allocated where it was actually needed rather than being wasted in redundant zones. By contrast, the baseline piston displayed an inefficient distribution: vast under-crown areas with excessively high safety factors and critical rim regions approaching the material limit. The optimised distribution therefore represents a more rational and predictable structural design, reducing the likelihood of unexpected fatigue crack initiation.

Similarly, the deformation behaviour of the optimised piston revealed improvements in stiffness-to-mass ratio. Whereas the baseline crown sag reflected diffuse and inefficient webbing, the optimised rib lattice channelled forces into concentrated corridors, producing a cleaner deformation profile. This reduced the risk of ring groove distortion and associated sealing failures, thereby enhancing both performance and durability. These findings confirm that optimisation not only reduces weight but also fundamentally improves structural efficiency.

Industrial and Academic Implications

This dissertation contributes to both academic discourse and industrial practice. Academically, it demonstrates the importance of multiphysics-aware optimisation. Too often, TO studies in the literature have prioritised compliance reduction under purely mechanical loads, producing geometries that may be structurally efficient but thermally unviable. By integrating realistic thermal gradients and pressure cycles, this work demonstrates that optimisation outcomes can be made both credible and durable.

For industry, the findings provide a validated framework for translating optimisation into manufacturable reality. By incorporating casting constraints, minimum feature sizes, and post-processing rationalisation, the final CAD model was not only lighter and stronger but also compatible with established production methods. This manufacturability-aware approach addresses a common gap between academic optimisation and industrial adoption, ensuring that optimised geometries can be realised without excessive cost or redesign.

Limitations

Like all research, this study is subject to limitations. The analysis focused on steady-state thermomechanical conditions, whereas real engine operation is inherently transient, with cyclic combustion pressures, fluctuating cooling, and variable load spectra. Although the applied boundary conditions were calibrated against experimental data, further work is required to capture fully transient effects such as knock, ignition timing variation, and cycle-to-cycle variability.

Similarly, fatigue analysis was limited to strain-life screening methods rather than full cycle-resolved assessments. While the safety factor distribution indicated improved durability, only long-term cyclic testing can confirm fatigue life. Additionally, this study assumed isotropic material properties, whereas real-world manufacturing methods such as additive manufacturing may introduce anisotropy that affects both thermal and mechanical behaviour.

Future Work

Future research should address these limitations by pursuing several avenues:

1. **Transient Multiphysics Analysis** - Fully coupled CFD-FEA simulations would enable cycle-resolved thermal and mechanical loading, improving accuracy in predicting crown temperatures, heat flux, and stress evolution.
2. **Fatigue Testing** - Both computational strain-life models and physical durability testing (e.g., >100-hour dynamometer tests) should be employed to confirm fatigue life under realistic duty cycles.
3. **Material Exploration** - Expanding optimisation studies to alternative alloys (e.g., Ti-based or hybrid composites) would provide insights into how different thermal conductivities and stiffness profiles affect optimisation outcomes.
4. **Hybrid Optimisation Approaches** - Combining density-based conservatism with level-set clarity may produce geometries that are both robust and manufacturable. Integration with emerging machine learning frameworks, such as physics-informed neural networks (Zhang et al., 2024), offers opportunities for real-time optimisation.
5. **Experimental Validation** - Ultimately, simulation must be validated against physical data. Instrumented pistons with thermocouples and strain gauges would provide the most direct means of verifying predictions, ensuring that optimised geometries perform as intended in real engines.

Wider Contribution

In broader terms, this dissertation positions topology optimisation as a credible, practical tool for advancing piston design. By bridging the gap between academic simulation and industrial feasibility, the study demonstrates how advanced optimisation can support the dual imperatives of modern powertrains: enhanced performance and reduced environmental impact. Even as the automotive industry transitions towards electrification, lightweighting of internal combustion engines remains relevant in hybrid and motorsport contexts, where efficiency and responsiveness are paramount. The framework presented here is therefore not limited to pistons but applicable to any thermally loaded, structurally critical component requiring mass efficiency and durability.

Final Remarks

In summary, this dissertation has demonstrated that density-based topology optimisation, when informed by validated thermomechanical boundary conditions and manufacturability constraints, can deliver pistons that are lighter, more efficient, and structurally robust. The optimised design reduced mass, preserved safety factor, improved deformation behaviour, and maintained essential thermal conduction pathways. Beyond these technical achievements, the study contributes methodologically by embedding calibration, mesh discipline, and empirical constraints into the optimisation loop, thereby elevating TO from a purely academic exercise to an industrially viable design tool.

While limitations remain and further experimental validation is necessary, the findings of this project represent a meaningful step towards the integration of advanced optimisation into mainstream piston development. The work confirms that careful alignment of simulation with physical reality produces outcomes that are not only numerically optimal but also practically meaningful. In doing so, it advances the case for topology optimisation as a cornerstone of next-generation engine component design, bridging the gap between computational possibility and engineering reality.

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