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Increasing thermal efficiency in internal combustion engines through automated control of operational processes

Abstract. The study aimed to analyse a closed-loop control strategy that adjusts the ignition timing and fuel injection to increase work output in the cylinder whilst ensuring knock safety and reducing cycle instability. The methodology was based on methods of energy (thermal) balance analysis, classification and analytical systematisation, structural-functional modelling, comparative analysis and analytical generalisation. It has been established that the thermal efficiency of an internal combustion engine (ICE) is the proportion of the fuel energy converted into useful work. The difference between theoretical and actual efficiency indicated the amount of energy lost due to mechanical and auxiliary processes. The energy balance reflected the distribution of fuel energy between useful work at the shaft, heat dissipation to the cooling system, losses with exhaust gases, and other types of losses, allowing the dominant directions of its utilisation to be identified. Increasing the efficiency is limited by rising pressures, temperatures and thermal loads; therefore, optimal heat release phasing is key, which must be maintained without detonation or excessive peaks. The study determined that injection and ignition parameters determine the combustion phasing and power output; and since injection alters ignition conditions, the ignition timing must be coordinated with the fuel strategy (particularly in a closed-loop system). Parameter optimisation was constrained by detonation, thermomechanical, emission and operational factors, which define the permissible range of settings. The study noted that automated control improves efficiency by optimising mixture formation and the combustion phase, and by reducing mechanical and auxiliary losses through coordinated control of the subsystems. The reduction in mechanical and auxiliary losses was achieved through a combination of tribological solutions and control of the units to avoid excessive energy consumption. The use of energy balance as a criterion and coordinated closed-loop control of ignition, fuel supply and auxiliary systems via the engine control unit (ECU) makes it possible to reduce dominant losses and improve the efficiency of the internal combustion engine within the limits of detonation and thermal load constraints. The practical significance lies in the ability of engineers to apply the results when calibrating the ECU during bench tests and engine tuning on the vehicle

Keywords: detonation; ignition; injection; restriction; combustion phasing

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INTRODUCTION

In the context of the global energy transition, internal combustion engines (ICEs) remain critical for heavy-duty transport and off-grid power generation, which necessitates further improvements in their operational and environmental performance. Improving thermal efficiency is a priority, as even a small reduction in specific fuel consumption translates into a significant reduction in costs and harmful emissions across the industry. At the same time, the potential for purely design-based improvements in many production solutions is limited by knock resistance, thermal loads and service life requirements, particularly under variable operating conditions. Under such conditions, automated control of operational processes becomes one of the most effective tools for further optimisation: intelligent control systems can maintain real-time convergence towards optimal combustion phasing, whilst simultaneously mitigating detonation risks and adapting the cycle to operation on alternative fuels, which poses a challenge for static maps and algorithms.

Scientific literature confirms that control strategies which simultaneously account for combustion phasing, detonation constraints and cycle variability are effective. The study by Q. Zhu *et al.* (2021) demonstrated the possibility of online optimisation of the ignition timing based on models of combustion phasing, detonation and the IMEP coefficient of variation. This means that the ignition optimum is formulated as a multi-criteria problem, where "efficiency" is not separated from stability and detonation limits, which is of fundamental priority for real-world control. In parallel with ignition optimisation, approaches are being developed to reduce detonation sensitivity through fuel strategy and combined ignition modes. D. Lou *et al.* (2024) demonstrated that hydrogen injection methods and spark ignition strategies alter the conditions for detonation in a hydrogen engine. In automated control, ignition should not be considered in isolation, but as an element of coordinated control of mixture formation and energy supply mode.

Y. Kou *et al.* (2022) found that the Taguchi-Grey combination (a combination of two methods for multi-criteria optimisation of process/system parameters) can be used for systematic selection of parameters that reduce the susceptibility to detonation in spark-ignition internal combustion engines. This approach confirms that even with complex process non-linearity, stable "optimal" settings can be found, but for practical application, these findings must be adapted to changing conditions in real time. V. Mittal (2024) summarised advances in detonation detection in spark-ignition engines and emphasised that improving the accuracy and speed of algorithms is critical for more aggressive ignition control strategies. In practice, this makes it possible to operate closer to the detonation limit without compromising reliability, which translates into improved thermal efficiency.

Efficiency optimisation can be achieved not only through the ignition timing but also through speed profile control. J. Song & H.H. Song (2022) noted that optimising the engine's speed profile improves net indicated efficiency and provided a quantitative explanation of the mechanisms underlying this optimisation. This indicates that automation must cover a broader set of controlled variables, rather than being limited to a single parameter. The expansion of the fuel base places greater demands on the control of operational processes. R. Menaca *et al.* (2025), using the example of an optical engine with multi-spark ignition, confirmed that multi-point/multi-cycle spark generation can sustain combustion with more complex fuels, and numerical validation enhances confidence in control models. Automated algorithms must be compatible with non-conventional ignition modes and exhibit greater sensitivity to ignition conditions. In a study by J. Park *et al.* (2023), a one-dimensional convolutional neural network with hyperparameter optimisation and data augmentation was used to determine the onset of detonation. This approach demonstrates the suitability of such models for integration into on-board systems as a "sensory layer" for adaptive control.

Ukrainian studies also confirm the practical benefits of precise ignition control for alternative fuels and specific power units. N.Ye. Ryaboshapka *et al.* (2023) found that changing the ignition advance angle affects the operating processes of a petrol internal combustion engine when running on fuel containing ethanol. This confirms the need for adaptive (automated) ignition adjustment for fuel mixtures, where the optimum depends on the operating mode and fuel composition. H.I. Slynko *et al.* (2022) found that installing an ignition timing variator in combination with a gas cylinder system (propane-butane) improves the performance of a specific engine. This provides practical justification for the effectiveness of ignition correction measures as an element of automated control, capable of maintaining higher thermal efficiency without altering the design.

Despite the development of individual solutions for optimising ignition and detecting knock, there is a lack of a coordinated, automated control loop within the engine control unit (ECU) that coordinates ignition and fuel injection within the constraints (knock, instability, fuel variability) and demonstrates an increase in thermal efficiency through the energy balance. Therefore, the study aimed to evaluate a closed-loop adaptation of ignition and fuel delivery aimed at improving performance indicators regarding knock and cycle variability. To achieve this objective, the following tasks were set: to identify the dominant channels of energy loss in the internal combustion engine based on the energy (thermal) balance; to justify a closed-loop ECU system for coordinated control of fuel delivery and ignition, incorporating safety constraints; to interpret the effect of automation through changes in the proportions of thermal, pumping, mechanical and auxiliary losses in the engine's overall energy balance.

MATERIALS AND METHODS

The study was of an analytical and synthetic nature and aimed to provide a theoretical justification for coordinated closed-loop control of fuel injection and ignition to improve the specific efficiency of internal combustion engines within the constraints of detonation, thermomechanical and emission limits. The conceptual framework was developed through the synthesis of energy balancing approaches, control theory and experimental data from scientific publications in the field of internal combustion engine process automation. The information base for the research consisted of scientific publications in peer-reviewed journals from 2020 to 2025, sourced from the Scopus, Web of Science and Google Scholar databases, on improving internal combustion engine efficiency and engine control, as well as works on the adaptation of control systems to alternative fuels.

The study combined methods of energy (thermal) balance analysis, classification and analytical systematisation, structural and functional modelling, comparative analysis and analytical generalisation to identify loss pathways based on the energy balance and to optimise the control actions of the electronic control unit to improve the thermal efficiency of the internal combustion engine. Using the method of energy (thermal) balance analysis, the fuel energy was decomposed into work output at the shaft and losses, which were classified into three groups: thermal, gas-dynamic (pumping), mechanical and auxiliary, based on the nature of the losses, their sources and the expected direction of reduction, as these loss groups reflect the main physically distinct energy dissipation channels in the internal combustion engine and correspond to the basic items of the energy balance, which are subject to separate control and optimisation. This approach has made it possible to structure the control object according to loss channels and establish a basis for evaluating the control effect by changing the proportions of losses in the balance whilst adhering to constraints (detonation, peak pressures/temperatures, thermal load, emissions, actuator limits).

Using a classification-based analytical systematisation of constraints, a list of key optimisation limits for ICE operating processes has been compiled, categorised as follows: thermomechanical, detonation/combustion stability, emissions, actuator and measurement, and operational variability. These constraints were selected as fundamental because they directly determine the permissible range of operating modes and settings and are decisive for ensuring performance, reliability, environmental compliance and the feasibility of control under real operating conditions. The criterion for the effectiveness of adjusting the control parameters (combustion phasing, ignition advance angle and injection characteristics) was an analytical interpretation of the increase in the proportion of fuel energy converted into energy, achieved by reducing the proportion of thermal, gas-dynamic and mechanical losses within the established limits. This approach was used to interpret the effect of automation as a conceptual redistribution of fuel energy between loss channels within the permissible range of settings, defined by thermomechanical and detonation constraints (a quantitative assessment of loss reduction was not performed within the scope of this theoretical study). Using the method of structural-functional modelling, the architecture of the ECU was generalised as a closed-loop system “sensors → algorithms (state estimation, controllers/maps, diagnostics and protection) → actuators”, with three functional levels identified (measurement, computation, execution). This formalisation made it possible to link controllable variables (fuel injection, ignition, gas exchange, component control) to the corresponding measurements, algorithms and constraints (knock, temperature limits, emissions, reliability) and to demonstrate the role of models and observers in ensuring robustness. This was done to justify the ECU as the central mechanism for implementing coordinated control to maintain the optimal combustion phase and reduce losses without exceeding the specified limits.

Using comparative analysis and the systematisation of scientific sources, the theoretical approaches to reducing heat loss have been categorised as follows: balanced (Popa *et al.*, 2022), combustion phase control (Ahmed *et al.*, 2022), early combustion suppression (Watanabe *et al.*, 2021), and process stabilisation (Björnsson & Tunestal, 2024). These approaches were selected as they correspond to the main physical “levers” governing heat loss formation in the cylinder – the phase and duration of heat release, the level of peak temperatures/pressures, and the proportion of unstable cycles – whilst also having direct, implementable control effects in the ECU. The comparison criteria were physical mechanism for reducing heat transfer (energy redistribution, changes in combustion phase/duration, peak limitation, reduction of cycle variation) and type of automated control involvement (balance-based evaluation, target phase maintenance, operation within limits, closed-loop corrections). This formulated a coordinated scheme of control actions specifically aimed at reducing heat losses in the CPG and assessed the feasibility of combining approaches within the constraints of thermomechanical and detonation limits. Analytical generalisation was used to systematise methods for increasing the overall thermal efficiency of internal combustion engines via two pathways: combustion optimisation (indicator level) and the reduction of mechanical and auxiliary losses (output shaft level), which differentiates between the contribution of processes within the cylinder and losses due to friction/drive of components, as well as the comparison of controllable parameters (injection, ignition, pump/lubrication control) within the constraints of reliability and operational safety. This approach formed the methodological basis for selecting a coordinated control strategy via the ECU and interpreting its impact on the components of energy losses.

RESULTS AND DISCUSSION

Automated workflow management to improve the efficiency of internal combustion engines

The thermal efficiency of an internal combustion engine is the proportion of the fuel’s chemical energy that is converted into useful mechanical output at the crankshaft in a real-world cycle. It is assessed by the indicated and effective (braking) thermal efficiency: the indicated efficiency reflects the conversion of energy in the cylinder into gases, whilst the effective efficiency accounts for additional losses between the cylinder and the shaft (friction, drive of units, auxiliary systems); the difference between them characterises the total mechanical and auxiliary losses. A significant proportion of heat is also lost through heat exchange with the cylinder walls and the cooling system, and via the exhaust gases (Popa *et al.*, 2022). It is advisable to describe these components using the engine's energy balance, which can identify dominant loss pathways in a specific operating mode and priority control measures (Table 1).

Table 1. Classification of energy losses in internal combustion engines

Type	Characteristic	Main sources of formation	Loss reduction method
Heat-based	Heat dissipation into structural components and via the exhaust gases, and losses due to incomplete combustion	Heat exchange in the combustion chamber, elevated exhaust gas temperature, and incomplete air-fuel mixing and ignition	Optimisation of combustion phasing and heat release profile, evaluation based on the heat balance
Gas-dynamic (pump-driven)	Increase in negative gas exchange at the inlet/outlet	Restrictions in the intake/exhaust tract, throttling at partial loads, the effects of supercharging and recirculation	Control of gas exchange processes (blowing, recirculation, gas distribution phases)
Mechanical and auxiliary	Losses of mechanical energy due to friction and the drive of auxiliary units	Friction in cylinder-piston group, crankshaft-connecting rod mechanism and bearings; energy consumption of pumps, generator, and cooling and lubrication systems	Tribological/design solutions, optimal control of units with a focus on reliability

Source: compiled by the authors based on National Academies of Sciences, Engineering, and Medicine (2021), A. Gangopadhyay (2021), Z. Liu *et al*. (2022), D. Popa *et al*. (2022)

Heat losses depend on heat transfer, exhaust energy and incomplete combustion; they are therefore reduced primarily by controlling the timing and progression of combustion and are assessed via the heat balance. Pump losses are determined by gas exchange and increase at partial loads due to resistance in the ducts and throttling; their margin is linked to gas exchange control and the coordination of these effects with the load regime. Mechanical and auxiliary losses are caused by friction and the drive of the units; therefore, they are reduced by a combination of tribological solutions and optimal control of the subsystems without compromising reliability. Improving thermal efficiency is a complex process, and the benefits of automation should be justified by analysing the changes in the proportions of losses within the engine's overall energy balance.

To identify the predominant losses under different operating conditions, an energy (thermal) balance is used, within which the fuel energy is distributed between output at the shaft, heat in the cooling system, exhaust energy, and mechanical and other losses. Balance analysis provides a basis for setting priorities: if thermal losses predominate, the focus is on controlling the combustion process and heat transfer; if mechanical and auxiliary losses predominate, the focus is on reducing friction and optimising the control of systems (pumps, cooling, lubrication) (Popa *et al.*, 2022). At the same time, the potential for improving efficiency is limited by physical and design factors: an increase in efficiency is accompanied by higher peak pressures and temperatures, increased heat fluxes to components, a more acute trade-off between efficiency and emissions (particularly nitrogen oxides), as well as higher demands on the strength and thermal stability of components. This determines the practical limits of further loss reduction and the need to optimise operating processes whilst considering reliability and environmental standards (Watanabe *et al.*, 2021).

Thermodynamic efficiency in a real internal combustion engine cycle is primarily determined by when and how intensely the heat of combustion is released in relation to piston movement and changes in volume. Under identical conditions, different phasing and shapes of the heat release curve result in different amounts of output and heat losses; therefore, the key controllable factors are injection (timing, duration, pressure, pulse structure) and ignition (advance angle, spark energy, knock control). Maximum output is achieved when the main heat release occurs near top dead centre (the position of the piston in the cylinder when it is at its highest point (at the end of the compression or exhaust stroke) and before the change in direction of movement), but without excessive peak pressures/temperatures and without detonation. Late combustion increases exhaust losses, whilst excessively early combustion increases mechanical loads, heat fluxes to the cylinder walls and the risk of detonation; therefore, the optimum is a compromise that the control system must maintain across a wide range of operating conditions. This is confirmed by approaches to optimising the ignition timing with constraints (Arsie *et al.*, 2024) and closed-loop control of the combustion phase to improve stability/efficiency under inter-cylinder variations (Björnsson & Tunestal, 2024).

In petrol direct-injection internal combustion engines, the injection timing determines the mixture structure (homogeneous/layered), local air-fuel ratios and flame development conditions. At high loads, evaporation and mixing affect the combustion rate and duration, cyclic fluctuations and susceptibility to knock. Changes in the injection timing and pressure alter the combustion process, efficiency and emission characteristics, through a shift in the heat release phase, changes in heat losses (including to the cylinder walls) and the "efficiency-toxicity" trade-off (Wang *et al.*, 2023). For diesel modes, the start/end of injection and the division into multiple pulses are critical, as they influence ignition delay, pressure rise rate, combustion behaviour, peak temperatures and, consequently, indicated efficiency, nitrogen oxide emission limits and reliability. A promising approach is adaptive dynamic control of injection timing using deep reinforcement learning methods, which accounts for non-linearity and changing conditions and reduces the need for manual re-tuning at each operating point (Henry de Frahan *et al.*, 2022).

Ignition and injection are interrelated: the ignition timing determines the combustion phase, but the injection timing alters the ignition conditions and the rate of flame propagation, and consequently the optimum ignition angle. Therefore, modern 21st-century strategies coordinate these parameters via combustion phase targets; one example is model-predictive control, which coordinates injection and ignition influences whilst accounting for actuator limitations, stability and emissions (Ahmed *et al.*, 2022). Injection and ignition determine efficiency through mixture formation and the combustion phase/rate (and duration), which affects net output, exhaust losses and heat transfer to the cylinder walls; optimisation is implemented as automated control of the combustion phase, taking into account detonation, thermal load, emissions and actuator limits, as confirmed experimentally. However, the optimisation of combustion phasing, injection and ignition is not arbitrary: it is constrained by thermomechanical, knock, emission, actuator-measurement and operational factors. These limitations define the permissible range of settings and determine which parameters can be adjusted in a given mode (Table 2).

Table 2. Key constraints on the optimisation of ICE operating processes

Restriction class	Characteristic	Impact on selection of optimisation parameters
Thermomechanical	Peak pressure/rate of pressure rise, temperature limits and heat fluxes	They limit the "early" combustion phase, as the load and heat transfer increase
Detonation and combustion stability	For spark-ignition engines – knocking; at partial loads – stability limits	Ignition timing and lean-burn modes are restricted due to the risk of unstable combustion
Environmental (emissions)	Trade-offs between efficiency and emissions (nitrogen oxides/particulate matter)	Require a multi-criteria selection of settings
Actuators and sensors	Injector/ignition timing, sensor delays and errors, air-fuel ratio limits	Limit the range of available modes and make precise control more difficult
Operational flexibility	Non-linearity, changing conditions, differences between cylinders, ageing	Necessitates adaptability and robustness in control systems

Source: compiled by the authors based on K. Watanabe *et al.* (2021), O.Y. Ahmed *et al.* (2022), M. Henry de Frahan *et al.* (2022), I. Arsie *et al.* (2024), O. Björnsson & P. Tunestal (2024), J. Wang *et al.* (2023)

Optimising fuel injection, ignition and combustion phasing to improve thermal efficiency involves finding the optimum within the range of permissible operating conditions, rather than an "absolute" maximum. The decisive constraints are thermomechanical limits (peak pressure, rate of pressure rise, temperatures and heat fluxes), knock resistance and combustion stability for spark-ignition engines, as well as environmental trade-offs between efficiency and emissions (particularly nitrogen oxides and soot), as confirmed by experiments varying injection parameters. Furthermore, the feasibility of optimal settings is limited by the capabilities of actuators and measurement accuracy; therefore, practical efficiency improvements are achieved through control methods that explicitly account for these limitations and closed-loop combustion phase control, and in conditions of operating mode variability – through adaptive approaches subject to safety controls.

The modern 21st century internal combustion engine is a dynamic system in which efficiency, emissions and reliability depend to a large extent on the precision of real-time control of operational processes. The central element is the ECU, which, based on measurements, state assessments and safety limits, controls fuel supply, ignition, gas exchange and auxiliary systems in steady-state and transient modes and under changing operating conditions. A typical ECU architecture implements a closed-loop system with three functional levels: measurement (sensors), computation and algorithms (filtering, state estimation, maps/controllers, diagnostics and protection), and actuators (injectors, ignition, air control devices, and, where necessary, gas distribution and assemblies). In the context of improving thermal efficiency, the ECU provides control of the air-fuel mixture composition and fuel delivery, optimisation of ignition considering knock and temperature limits, maintaining the target combustion phase (maps + feedback), as well as reducing auxiliary costs through subsystem control without compromising reliability (Aliramezani *et al.*, 2021). As engine complexity increases, so does the role of models and data processing methods (tuning, state observers, adaptive control elements); however, their application requires robustness and safety guarantees (Fig. 1).

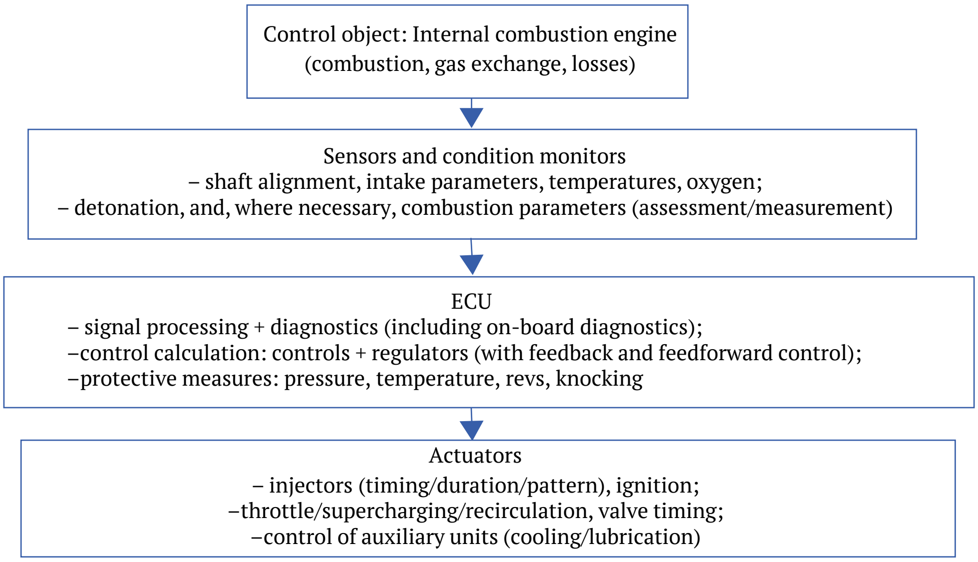

Figure 1. Generalised structure of ECU
Source: compiled by the authors based on M. Aliramezani *et al.* (2021), B.C. Pereira *et al.* (2023)

The ECU implements a closed-loop system of "sensors → algorithms (state/limit estimation) → actuators", aligning combustion parameters with efficiency, emissions and reliability requirements, and ensuring coordinated control of fuel delivery, ignition, gas exchange and auxiliary systems. As engine complexity increases, so does the role of models and data processing methods; however, their application requires resilience to disturbances and uncertainties, as well as safety guarantees.

The results of the study showed that the energy (thermal) balance serves as a practical tool for identifying the dominant loss pathways in a specific operating mode and selecting priority control actions. Injection parameters act as a key lever which, by altering the heat release rate and combustion phase, redistributes energy between output and losses. A similar interpretation of the balance approach is demonstrated by M. Güler & M. Özkan (2022), who found that the energy balance is not merely a descriptive framework but a practical optimisation tool: for a direct-injection diesel engine with multi-pulse injection, the authors performed a breakdown of fuel energy across loss channels and demonstrated that the selection of timing/number of pilot pulses alters the distribution between output and losses (exhaust/cooling/other components). Therefore, the balance analysis provides a quantitative basis for optimising injection parameters: it can be used not only to improve thermal efficiency but also to identify which specific loss channel (exhaust, cooling or other components) is responsible for the gains achieved in a particular operating mode.

G. Kaltakkıran *et al.* (2022) performed an instantaneous energy balance during the warm-up of a spark-ignition petrol engine and demonstrated that, particularly under transient thermal conditions, the balance can be used to quantitatively elucidate relationship between thermal management strategies and the structure of losses. This is consistent with the results of presented study, which emphasises the mode-dependent nature of the dominant loss channels and the need to evaluate the effect of control via the balance in a specific mode, rather than based on an averaged picture. The selection of priority control actions in transient thermal conditions should be based on a mode-oriented balance analysis, which can direct control towards those loss channels that are decisive in the specific engine state.

The results of the study established that an increase in thermal efficiency through combustion control constitutes an optimisation within a feasible region bounded by thermomechanical and emission limits, as well as actuator and measurement constraints, disturbances and operational variability. The effectiveness of ECU is determined by the ability of algorithms to robustly maintain the combustion phase and key process indicators under conditions of noise and incomplete observability without violating safety limits. This is consistent with the approach of P. GhafGhanbari *et al.* (2024), who proposed a model-predictive control scheme with output feedback for a compression-ignition engine and emphasised that uncertainties, disturbances and limited measurements render "ideal" optimisation without explicit consideration of constraints potentially unstable or unsafe. Accordingly, improved thermal efficiency is achieved by optimising combustion control within permissible constraints, and the practically achievable effect is determined by the robustness of the algorithms and compliance with safety requirements. Z. Chen *et al.* (2025) demonstrated that combining model-predictive control with reinforcement learning is a practical approach for transitioning from static maps to adaptive multi-criteria control in transient conditions: model-predictive control is used as a guiding mechanism for the learning process, and the objective is set as a trade-off between nitrogen oxide emissions and engine performance indicators via the control of fuel delivery parameters (in particular, fuel rail pressure and injection parameters). This is consistent with the results of the current study, which emphasises that, due to non-linearity, variable operating conditions and "efficiency-emissions" trade-offs, there is a growing need for adaptive control approaches that explicitly consider constraints and safety requirements. Thus, the energy balance can be used to determine which losses dominate in a given engine operating mode and, accordingly, to select priority control actions. Improved thermal efficiency is achieved by optimising combustion and reducing auxiliary losses within thermomechanical, environmental and actuator constraints, which requires robust and adaptive control.

Comprehensive optimisation of operational processes and the energy balance of internal combustion engines

Optimisation of injection and ignition parameters is one of the most effective ways of improving the thermal efficiency of an internal combustion engine, as these controllable factors influence mixture formation, the heat release curve and the combustion phase. In practice, the task boils down to selecting parameters (injection timing/duration, pressure and pulse structure, ignition advance angle) that minimise specific fuel consumption or maximise efficiency whilst simultaneously meeting constraints regarding knock, emissions, thermal load, service life and the capabilities of the actuators. The basic formulation is constrained optimisation: an objective function (fuel consumption/efficiency) and a system of constraints (knock, peak pressure and its rise rate, temperature limits, emission limits, combustion stability, actuator constraints) (Yu *et al.*, 2022; Vlaswinkel *et al.*, 2025). For spark-ignition internal combustion engines, this manifests as optimisation of the ignition timing, where the optimum is constrained by knock and thermal load; for high-load modes with direct injection, changes in injection timing and pressure simultaneously affect both efficiency and emissions, resulting in a multi-criteria problem.

In practice, map calibration (RPM/load) is used in conjunction with optimisation algorithms (gradient, heuristic, surrogate and multi-criteria methods) to reduce the number of bench tests and account for constraints (Yu *et al.*, 2022). To improve the validity of the results, model-based optimisation is employed, which formalises the relationship between "control → combustion phase → losses → efficiency" (in particular for selecting the ignition timing whilst accounting for detonation). Data-driven approaches are also used, where machine learning models act as surrogates for predicting efficiency/emissions and for state estimation (Aliramezani *et al.*, 2021), whilst Bayesian optimisation with constraints ensures safe exploration of settings during costly experiments, considering the risk of exceeding limits (Vlaswinkel *et al.*, 2025). The need for multi-criteria optimisation is particularly evident under high-load conditions. The largest proportion of heat losses occurs in the cylinder-piston group due to heat exchange at high temperatures; improving thermal efficiency requires a targeted influence on the combustion process. Theoretical approaches to reducing these losses through automated control are summarised in Table 3.

Table 3. Theoretical approaches to reducing heat loss in the cylinder-piston group through automation

Method	Mechanism of effect on heat loss	Role of automated control
Balance approach	The conversion of energy from "wall/cooling" into output (or into exhaust)	Quantitative assessment of the effect based on the energy balance
Combustion phase control	Reduction in duration of high temperatures → lower total heat transfer	Maintenance of target combustion phase under different operating conditions
Restrictions on early burning	Avoiding excessive pressure/temperature peaks → lower heat fluxes in the component	Operation within thermomechanical limits
Stabilisation of process	Reduction of "bad cycles" (delays/instability) → lower average losses	Closed-loop combustion parameter control

Source: compiled by the authors based on M. Aliramezani *et al.* (2021), K. Watanabe *et al.* (2021), O.Y. Ahmed *et al*. (2022), D. Popa *et al.* (2022), O. Björnsson & P. Tunestal (2024)

The reduction in heat loss within the cylinder-piston assembly through automation is achieved not so much by a direct "reduction in heat exchange" as by a controlled modification of the combustion process, which redistributes energy within the engine's thermal balance in favour of output. The key factor is combustion phase control: maintaining the target phase reduces the duration of high-temperature conditions and minimises the probability of deviations that lead to increased losses. At the same time, the potential of this approach is limited by the need to avoid excessively early combustion, which sharply increases peak pressures/temperatures and heat fluxes in the component; therefore, optimisation inevitably takes place within thermomechanical limits. In this context, the balance approach serves as a tool for verifying the results: it can be used to quantitatively confirm that stabilising and optimising combustion does indeed reduce the proportion of energy dissipated into the walls and cooling, thereby translating into an increase in efficiency.

Improvements in effective thermal efficiency of internal combustion engines are determined not only by the quality of combustion, but also by the level of mechanical and auxiliary losses, which reduce the proportion of net output reaching the output shaft. Therefore, reducing friction in engine components and lowering the energy consumption of auxiliary systems (lubrication and cooling systems) represents a critical reserve for improving efficiency, particularly when combustion parameters are already close to optimal. In contrast to the "aggressive" approach of achieving thermodynamically favourable combustion conditions, reducing mechanical losses often improves efficiency without directly exacerbating trade-offs regarding emissions or knock resistance; however, it requires strict consideration of reliability and lubrication requirements. It is advisable to consider mechanical losses in two components: friction losses in the main assemblies (primarily in the cylinder-piston group and bearings) and losses in the drive of auxiliary units. In many configurations, the largest contribution comes from friction in the "piston-ring-cylinder liner" zone, so improving efficiency begins with tribological solutions. Coatings, optimisation of surface roughness and design changes in the power cylinder reduce friction losses and, consequently, improve efficiency by reducing the gap between rated and actual performance (Gangopadhyay, 2021). At the same time, the actual effect of such solutions depends on the temperature regime and the properties of the oil, which determine the nature of the lubrication.

The most direct method of increasing efficiency through automation relates to the control of auxiliary units, primarily the lubrication system. The oil pump ensures the necessary minimum permissible oil pressure and flow rate; however, an excess of these increases the energy consumption of the drive and reduces efficiency. Therefore, pump control must maintain pressure/flow at or above the limits set by the requirements of hydrodynamic lubrication and heat dissipation in bearings and the crankshaft, whilst avoiding excessive flow in operating modes where it is not required (Liu *et al.*, 2022). Pump control should be viewed as an optimisation problem with constraints: minimising energy consumption while maintaining lubrication safety and the permissible thermal state of friction components. In practice, this is achieved by adapting the pump's operating mode to oil temperature, speed and load, and by integrating this logic into the overall motor control system. Thus, reducing mechanical losses to improve thermal efficiency involves combining tribological measures to reduce friction with automated control of auxiliary units (in particular the lubrication system), whilst strictly adhering to service life and reliability constraints.

Automated control improves the thermal efficiency of internal combustion engines through two interrelated mechanisms: increasing the indicated fraction output by optimising mixture formation, the heat release law and combustion phasing; and reducing mechanical and auxiliary losses, which account for the difference between indicated power and output shaft. Real efficiency gains are achieved through coordinated control of fuel delivery, ignition, combustion parameters and auxiliary subsystems, considering reliability constraints and environmental requirements. At the indicator level, maintaining optimal combustion timing and process stability is key. At high loads, direct injection parameters influence the combustion process, efficiency and emissions; therefore, their selection is crucial in critical operating modes (Wang *et al.*, 2023). For spark-ignition engines, optimising the ignition timing is a constrained optimisation problem, where efficiency gains are limited by knock resistance and thermal load (Arsie *et al.*, 2024). To maintain optimal conditions across a wide range of operating modes, closed-loop combustion phase control algorithms are employed: model-predictive control coordinates process parameters whilst accounting for constraints, and closed-loop combustion phase optimisation reduces inter-cylinder variation and the probability of deviations from the effective zone. Promising learning-based approaches demonstrate the possibility of adaptive control of injection timing in complex multi-pulse processes, increasing adaptability to changing conditions (Henry de Frahan *et al.*, 2022).

At the output shaft level, automation delivers benefits by reducing friction losses and the power required to drive the units. Tribological solutions in the cylinder-piston assembly (coatings, surface roughness, design optimisations) reduce friction losses and directly improve efficiency. Optimal control of the units, particularly the lubrication system, is a key factor: the energy consumption of the oil pump drive depends on the operating mode and can be reduced provided that lubrication safety is maintained, which imposes constraints on the control algorithms. Such measures improve efficiency without directly exacerbating combustion trade-offs, but require integration into the control logic, incorporating resource and temperature limits (Gangopadhyay, 2021).

Practical gains in efficiency are impossible without high-quality calibration; optimisation algorithms make it possible to reduce the scope of testing and bring control maps closer to the optimal ones whilst adhering to constraints. Bayesian optimisation methods that take constraints into account further reduce the risk of breaching detonation and temperature limits whilst searching for efficient settings, and data-driven models reinforce these approaches in modelling and diagnostic tasks. At the same time, automation does not eliminate physical limits: as efficiency levels approach high values, thermomechanical and emission barriers dominate, defining the practical limit to further growth. Therefore, a correct assessment of the effect of automated control must be based on the energy balance, which determines which loss channel has contributed to the efficiency gain. Thus, the energy balance determines the dominant losses in the internal combustion engine and the priorities for reducing them. Automated control via the ECU improves efficiency by optimising fuel injection and ignition and managing subsystems within specified limits (knock, emissions, thermal load, service life), whilst the effect is assessed by changes in the proportions of losses in the balance.

The results of the study revealed that improving the thermal efficiency of internal combustion engines essentially boils down to optimising fuel injection and ignition as a constrained optimisation problem (involving constraints such as knocking, emissions, thermal load, service life and the limits of actuators), as well as to reducing the volume of bench testing through the use of models and optimisation procedures (in particular Bayesian optimisation) whilst maintaining safety requirements. This logic is supported by K. Esaki *et al.* (2022), demonstrating the practical implementation of automated machine learning for engine control parameters: during operation, the system autonomously collects data and adapts control to changes in the type/ratio of fuel mixtures, improving combustion efficiency and reducing the need for manual calibration. The application of algorithmic optimisation in calibration tasks can reduce the labour intensity of selecting control parameters and improve engine stability under changing operating modes and conditions.

The study by B. Hu *et al.* (2024) demonstrates the rapid calibration of a diesel engine injection map using grid-adaptive Bayesian optimisation, i.e., a practical tool for finding optimal settings with a limited number of tests. In contrast to the authors' focus on the online calibration procedure for a specific map, presented study considers optimisation calibration as part of the general formulation of "constrained optimisation", where the prior objective is not only to find parameters but also to explain through which loss channel (exhaust, cooling, mechanical/auxiliary) the gain is generated. Accordingly, algorithmic calibration is interpreted not merely as a means of reducing the number of experiments but as a mechanism for controlled entry into the permissible operating range, with the possibility of quantitatively verifying the effect via the energy balance. J.C. Peyton Jones *et al.* (2025) summarised feedback-based detonation control strategies and demonstrated that such control loops are a key mechanism for maintaining engine operation near optimal settings without breaching detonation and thermal limits. These findings are consistent with the present study; however, the present study includes detonation stability within a broader set of constraints (thermomechanical, emissions, actuator-measurement and operational variability) that define the feasible optimisation domain. Therefore, the practical improvement in efficiency is interpreted as the result of consistently maintaining the combustion phase within this range, where detonation feedback is a necessary but not the only element of safe control.

J. Tang *et al*. (2021) interpreted "Safe" search as a controlled approach to the detonation threshold: stochastic Bayesian optimisation is used to predict the detonation threshold and account for uncertainty, to approach the limit conditions without an uncontrolled transition into the detonation regime. In the results of this study, safety is formulated more broadly – as optimisation within a permissible operating region, where detonation is merely one of the constraints alongside peak pressure and its rate of rise, boundary temperatures/heat fluxes, emission limits, actuator limits and operational variability. Accordingly, whilst the authors' work addressed risk management regarding the violation of a single critical constraint (detonation), the presented study interprets the selection of optimal settings as ensuring simultaneous compliance with a set of constraints that collectively determine a practically achievable compromise between efficiency, toxicity and reliability. In both studies, the necessity of searching for settings near the boundary conditions is justified, with explicit consideration of uncertainty and the risk of constraint violation.

In general, an increase in the thermal efficiency of an internal combustion engine is achieved by optimising fuel injection and ignition as a constrained problem, where the determining factors are detonation, thermomechanical, emission and actuator-measurement limits. Practical efficiency gains are achieved not by seeking an "absolute maximum", but through the controlled selection of parameters within the permissible range, using models and algorithmic optimisation methods that reduce the labour intensity of calibration. Therefore, a key condition for implementing this potential is robust closed-loop control capable of maintaining operation near the boundary conditions, considering uncertainties and the risk of exceeding limits.

CONCLUSIONS

The results of the study showed that the energy (thermal) balance forms the basis for classifying losses by channel in a specific operating mode and for the informed selection of control measures. Varying the injection parameters, by influencing the heat release law and the combustion phase, alters the distribution of energy between output and losses, whilst the balance approach makes it possible to quantitatively determine which specific loss channel has contributed to the increase in efficiency. For transient thermal states, the study confirmed that the application of instantaneous energy balance can ling thermal control strategies to changes in the loss structure, thereby highlighting the mode dependence of the dominant components. The selection of injection, ignition and combustion phasing parameters should be viewed as a search for the optimum within the permissible operating range, defined by a set of constraints. Thermomechanical limits, detonation resistance and combustion stability, as well as environmental trade-offs between efficiency and emissions, are central. The practical feasibility of optimal settings is further determined by the capabilities of the actuators and the accuracy of measurements, necessitating robust and adaptive control algorithms with safety monitoring.

The role of the ECU as a closed-loop system ("sensors → algorithmic modules → actuators") has been summarised; this system coordinates fuel supply, ignition, gas exchange and auxiliary systems, whilst explicitly accounting for constraints. A correct assessment of the effect of automation must be based on changes in the proportions of losses in the overall energy balance, which distinguishes contribution of combustion control from contribution of reduced auxiliary and mechanical losses. For practical implementation, high-quality calibration is required, and optimisation algorithms (in particular Bayesian ones) reduce the volume of testing and lower the risk of violating constraints during the search for settings. In general, an increase in thermal efficiency is achieved through coordinated control of the combustion process and auxiliary subsystems within thermomechanical, environmental and actuator constraints, provided that control is stable and adaptive. A limitation of the study is its theoretical nature without bench validation. Future research should experimentally verify proposed approaches and develop coordinated closed-loop control of ignition and injection, with an assessment of the effect on the energy balance.

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Підвищення теплової ефективності двигунів внутрішнього згоряння шляхом автоматизованого керування робочими процесами

Анотація. Метою дослідження було проаналізувати замкнену стратегію керування, що коригує момент іскроутворення та подачу палива для зростання корисної роботи в циліндрі за умови детонаційної безпеки та зменшення циклової нестабільності. Методологія базувалась на методах енергетичного (теплового) балансового аналізу, класифікаційно-аналітичної систематизації, структурно-функціонального моделювання, порівняльного аналізу та аналітичного узагальнення. Встановлено, що теплова ефективність двигуна внутрішнього згорання (ДВЗ) — це відсоток енергії палива, який перетворюється в корисну роботу. Різниця між теоретичними і реальними показниками ефективності показує, скільки енергії втрачається через механічні та допоміжні процеси. Енергетичний баланс відображає розподіл енергії палива між корисною роботою на валу, тепловідведенням у систему охолодження, втратами з вихлопними газами та іншими видами втрат, дозволяючи визначити домінуючі напрями її використання. Підвищення коефіцієнту користної дії обмежується зростанням тисків, температур і теплових навантажень, тому ключовим є оптимальне фазування тепловиділення, яке треба утримувати без детонації та надмірних піків. Виявлено, що параметри упорскування та запалювання формують фазування згоряння й індикаторну роботу, а оскільки упорскування змінює умови займання, кут запалювання має узгоджуватися з паливною стратегією (зокрема у замкненому контурі). Оптимізацію параметрів обмежують детонаційні, термомеханічні, емісійні та експлуатаційні чинники, які формують допустиму область налаштувань. Зазначено, що автоматизоване керування підвищує ефективність через оптимізацію сумішоутворення/фазування згоряння та через зменшення механічних і допоміжних втрат узгодженим керуванням підсистемами. Зниження механічних і допоміжних втрат досягається поєднанням трибологічних рішень і керування агрегатами для уникнення надлишкових енерговитрат. Застосування енергетичного балансу як критерію та узгоджене замкненоконтурне керування запалюванням, паливоподачею й допоміжними системами через електронний блок керування двигуном (ЕБКД) дає змогу зменшувати домінуючі втрати та підвищувати ефективність ДВЗ в межах детонаційних і термонавантажувальних обмежень. Практична значимість полягає у можливості застосування результатів інженерами з калібрування ЕБКД під час стендових випробувань і налаштувань двигуна на транспорті

Ключові слова: детонація; запалювання; упорскування; обмеження; фазування згоряння