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Original Research

Fuel consumption optimization of the atkinson cycle in a turbocharged SI engine using a genetic algorithm at low speed and part load

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ABSTRACT

The growing demand for cleaner fuels and improved energy efficiency in the automotive industry has intensified research into turbocharged engines, particularly those based on the Atkinson cycle. This study focuses on the optimization and implementation of a turbocharged Atkinson-cycle gasoline engine to reduce fuel consumption and emissions under low-speed and part-load operating conditions. A genetic algorithm (GA)-based multi-variable optimization framework is developed to simultaneously optimize intake valve timing, valve lift, and exhaust gas recirculation (EGR) rates, thereby enhancing engine performance across a wide range of speed–load conditions. A validated one-dimensional GT-Power simulation model, integrated with MATLAB/Simulink, is employed to analyze the influence of valve timing strategies on mixture formation, combustion behavior, and emission characteristics. Both experimental testing and numerical simulations conducted on a 1.6 L turbocharged Atkinson-cycle engine corroborate the model predictions. The optimized configuration achieves a 2-3% reduction in brake-specific fuel consumption (BSFC), an 18% decrease in NO_x emissions, and up to a 2.5% reduction in CO_2 emissions. The findings demonstrate the significant potential of the Atkinson cycle to improve thermal efficiency under low-speed and part-load conditions, particularly when combined with advanced variable valve strategies and GA-based optimization techniques. Future research should explore the hybridization of Otto and Atkinson cycles, as well as the integration of advanced turbocharging technologies, to mitigate inherent power density limitations.

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1- Introduction

The increasing demand for cleaner fuels has compelled automobile manufacturers to explore alternatives to conventional crude oil-based energy sources. Consequently, significant research efforts have been directed toward Hybrid Electric Vehicles (HEVs), which were developed to reduce fuel consumption and mitigate greenhouse gas emissions. The transportation sector accounts for approximately 66% of global oil consumption, with nearly half attributed to small passenger cars and light-duty trucks [1]. Improvements in fuel efficiency and emissions reduction in HEVs are achieved through technologies such as engine start–stop systems, regenerative braking, and advanced engine concepts including the Atkinson cycle [2, 3]. The integration of a fuel-efficient Atkinson-cycle engine into HEVs enhances overall vehicle efficiency while substantially lowering greenhouse gas emissions. Figure 1 presents the progression of carbon monoxide (CO) and carbon dioxide (CO_2) emission limits from the Euro 1 standards to the most recent Euro 6d regulations introduced in January 2020. Since the introduction of the first emission legislation, permissible pollutant levels particularly CO have been significantly reduced, with an overall decrease of approximately 63%. From the Euro 4 stage onward, the CO emission limit has remained constant at 1 g/km [3].

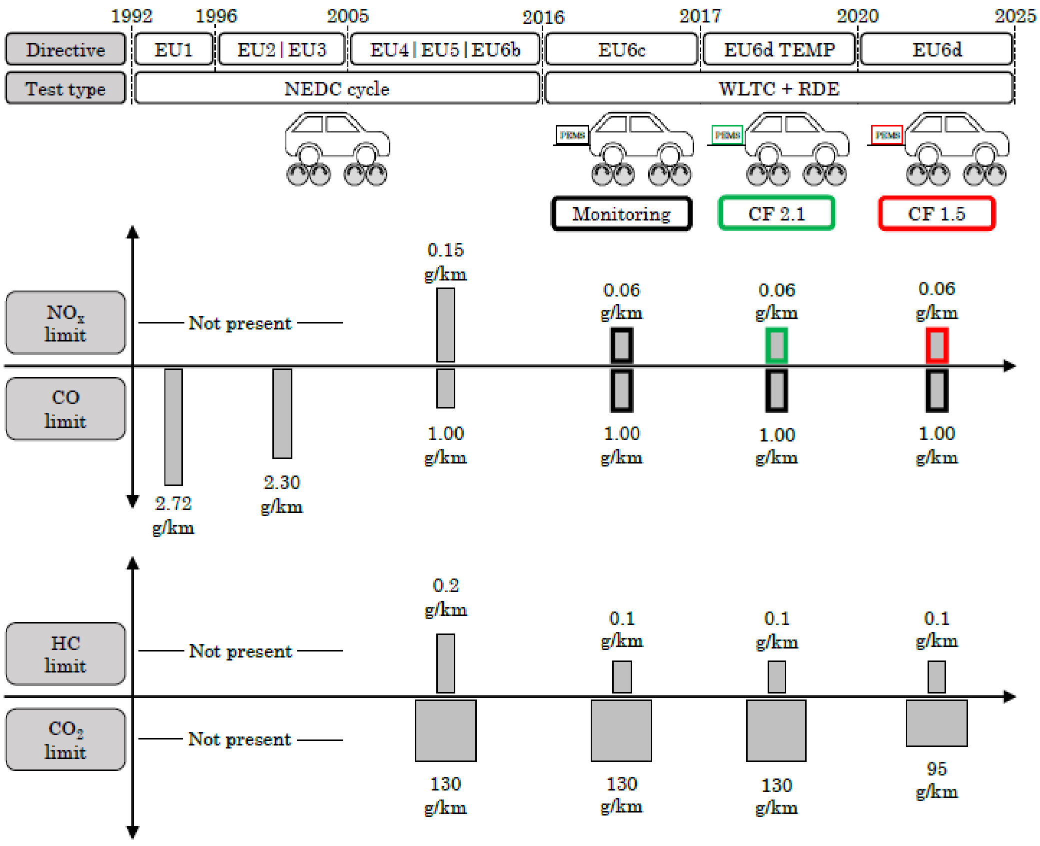


Figure 1 Emission legislation development [3]

In 1882, British engineer James Atkinson advanced internal combustion engine development by introducing a cycle designed to achieve higher thermal efficiency than the conventional Otto cycle. Today, renewed interest in HEVs has led to the widespread adoption of the Atkinson cycle in modern powertrains. Atkinson-cycle engines extend the effective expansion stroke relative to the compression stroke, increasing thermal efficiency and reducing fuel consumption and pollutant emissions. Despite these advantages, the Atkinson cycle has an inherent limitation: reduced power density. The cycle is intentionally configured to prioritize efficiency over maximum power output. When two engines of identical displacement operate at the same speed, an Otto-cycle engine typically produces higher power and torque. In contrast, the Atkinson-cycle engine achieves superior thermal efficiency and lower fuel consumption. However, because a portion of the intake charge is effectively displaced during the early compression phase (due to late intake valve closing in practical implementations), wide-open throttle (WOT) torque and peak power output are reduced. This trade-off between efficiency and power remains a key design consideration in Atkinson-cycle engine applications [3-5].

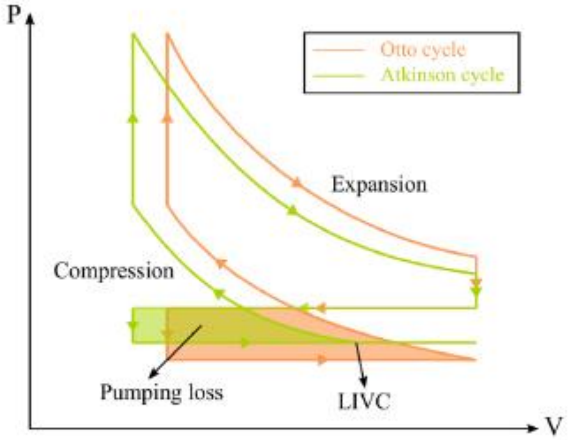


Figure 2 P-V diagram of the Atkinson cycle with LIVC mechanism [6]

Figure 3 displays both the conventional and modified pistons. They were milled using CNC technology from forgings that were nearly in their final near-net shape.

Figure 3 Piston with a compression ratio of 9.5 (left) and a compression ratio of 12 (right)

The Atkinson cycle can improve fuel economy by approximately 20–30%, making it particularly well-suited for HEVs. Its higher expansion ratio relative to the compression ratio enables superior thermal efficiency compared with the conventional Otto cycle. According to findings reported by Qingyu et al., the Atkinson cycle demonstrates clear advantages over the Otto cycle in HEV applications due to its enhanced fuel efficiency. The authors proposed a performance optimization strategy based on adjusting the compression ratio in relation to cycle efficiency. Their approach emphasized operating at a relatively low effective compression ratio while optimizing the maximum geometric compression ratio and intake valve timing within combustion pressure constraints. Experimental validation confirmed improvements in fuel economy, reduced pumping losses, and significant gains in cycle efficiency, particularly under low- and medium-load operating conditions [5, 6]. Zhao proposed that the extended Atkinson cycle is particularly well-suited for HEV applications due to its capability to achieve a high expansion ratio without increasing the risk of engine knock, while simultaneously reducing NO_x emissions. The higher expansion ratio improves thermal efficiency and lowers peak combustion temperatures, contributing to improved emission performance. Additionally, the cycle is characterized by relatively straightforward implementation through valve timing control and contributes to reduced exhaust gas temperatures, which can benefit overall engine durability and aftertreatment performance [7]. In their study, Yuanhui et al. investigated the influence of engine design parameters and performance-related factors on the Atkinson cycle. Their analysis revealed that mechanical friction contributes significantly to power losses, while higher compression ratios intensify heat transfer losses. Furthermore, increases in frictional losses and cylinder length were found to negatively affect overall cycle performance, leading to reductions in efficiency and power output [8]. Shuhn-Shyurng conducted a comparative analysis of the Otto and Atkinson cycles while accounting for heat transfer effects. The study concluded that, under identical operating conditions, an engine operating on the Otto cycle produces higher work output and greater thermal efficiency than an engine operating on the Atkinson cycle. These findings highlight the performance trade-offs between the two cycles when heat transfer losses are considered [9].

2- Atkinson cycle

In recent years, major automotive manufacturers like Toyota, Ford, and Honda have increasingly adopted Atkinson-cycle engines in their HEVs. The majority of HEVs and plug-in hybrid electric vehicles (PHEVs) in the US market now come equipped with Atkinson-cycle engines, including popular models such as the Toyota Prius, Camry Hybrid, Ford Fusion Hybrid, Honda Accord Hybrid, and Chevrolet Volt. Advanced technologies like cooled exhaust gas recirculation (EGR) have been implemented to enhance performance and reduce knocking. For example, the 2018 Camry Hybrid features Toyota's A25A-FXS engine, a naturally aspirated Atkinson-cycle engine with a high compression ratio of 14: 1, along with variable valve timing (VVT) and cooled EGR. While detailed information about this specific engine is scarce, a similar engine (A25A-FKS) optimized for non-hybrid use in the 2018 Camry has been examined [10]. The peak brake thermal efficiency of the engine is reported to reach 40%, alongside an 18.6% decrease in CO_2 emissions compared to the Model Year (MY) 2015 engine lacking the Atkinson cycle and EGR features. However, since other enhancements are also included in the updated model, these figures may overstate the isolated impact of the Atkinson cycle. Similarly, Toyota's 2ZR-FXE engine, utilized in the third-generation Prius and Lexus CT200h, incorporates the LIVC Atkinson cycle, cooled EGR, and port fuel injection (PFI), boasting the same peak thermal efficiency of 40%. Beyond the manufacturer's information, Li Y et al. investigated the potential fuel savings of an Atkinson-cycle gasoline engine in a series HEV. The overall fuel consumption dropped by 4.58% in comparison to the original Otto engine, with decreases of 46.1% in NO_x emissions and 18.37% in CO_2 emissions [11]. According to the EPA's forecast, incorporating the Atkinson cycle could potentially lower CO_2 emissions by 3%–8% when considering the impact of EGR and a high compression ratio. Yet, advancements in engine technology indicate that this reduction could be even greater, ranging from 10%–14% [12]. Moreover, fuel savings from the Atkinson cycle are projected to be 8%–10.3% by regulatory agencies, and manufacturers are on track to meet and even exceed this value [13]. It is also estimated that 20%–30% of the fuel economy improvement brought by HEVs is attributed to the Atkinson cycle [14].

This study examines the implementation of a fuel-efficient, innovative Atkinson-cycle engine. Initially, an experimental investigation is conducted on a baseline Otto-cycle engine, and a corresponding one-dimensional (1D) GT-Power simulation model is developed and validated against experimental data. Subsequently, the validated Otto-cycle engine model is transformed and optimized to operate under the Atkinson-cycle principle using a Genetic Algorithm (GA)-based optimization framework. The optimization process focuses on key control parameters, including intake valve opening timing, intake valve duration, maximum intake valve lift, and exhaust gas recirculation (EGR) rate, to enhance efficiency and emissions performance.

3- Genetic Algorithm Methodology

Multiple operating conditions were analyzed through 1D CFD calculations. Various valve lift opening laws were simulated to provide additional insights into the impact of Atkinson strategies on factors such as mixture preparation, injection-air interaction, turbulence levels, and auto-ignition. The GT-Power tool was used to conduct these 1D computations [11].

For the Atkinson-cycle engine, there are four primary optimization variables: Intake Valve Opening (IVO), Intake Valve Opening Duration (IVC-IVO), Maximum Intake Valve Lift (MAX IV lift), and Exhaust Gas Recirculation (EGR). The chromosome of each individual can be represented as a vector of five real values, where each real value represents a gene in the chromosome. These five real values correspond to the five operating variables, respectively. Therefore, each individual in a population represents a specific combination of operating variables under a given speed and torque.

The fuel efficiency of each individual is assessed using the fitness function value. Through crossover and mutation operations, new offspring are generated from selected parent individuals in the reproduction pool. With each genetic generation, successive individuals progressively approach the optimal state with the lowest fitness value.

3-1- Coupling Methodology Between MATLAB–GA, Simulink, and GT-Power

The optimization framework developed in this study integrates a Genetic Algorithm (GA) implemented in MATLAB, a dynamic system model built in Simulink, and a high-fidelity engine model developed in GT-Power. The three environments are coupled within an automated co-simulation loop to enable model-based engine parameter optimization. The architecture follows a hierarchical master–slave configuration:

(1) MATLAB (GA) acts as the supervisory optimization layer.
(2) Simulink functions as the system-level integration and control platform.
(3) GT-Power operates as the high-fidelity physics-based engine simulation module.

The coupling is realized through a bidirectional data exchange mechanism, allowing iterative parameter updates and performance feedback during each optimization generation. The GA implemented in MATLAB serves as the master controller of the optimization process. The algorithm initializes a population of candidate solutions representing engine design or control parameters. Thus, a vector $\mathrm{x} = (\mathrm{IVO}, \mathrm{IVC}, \mathrm{EVC}, \mathrm{MAX\ LIFT}, \mathrm{EGR})$ is defined to represent a chromosome of an individual in the population, meaning that each chromosome contains five genetic genes. Optimizations for the operating variables were performed under the same speed–load points as those shown in Figure 2. The GA-based optimization scheme for maximizing the fuel economy at a given load point can be depicted as:

$$\text{Minimize:}\quad \mathrm{BSFC}$$
$$\text{Subject to: } 6\,\% \le EGR \le 24\,\%$$
$$0.99 \times (\mathrm{Max\ Lift})_{\mathrm{Base}} \le \mathrm{Max\ Lift} \le 1.01 \times (\mathrm{Max\ Lift})_{\mathrm{Base}}$$
$$0.80 \times (\mathrm{IVC} - \mathrm{IVO})_{\mathrm{Base}} \le (\mathrm{IVC} - \mathrm{IVO}) \le 1.20 \times (\mathrm{IVC} - \mathrm{IVO})_{\mathrm{Base}}$$
$$-30^\circ\ \mathrm{ATDC} \le \mathrm{IVO} \le 40^\circ\ \mathrm{ATDC}$$

For each individual, MATLAB transfers the parameter set to the Simulink model via workspace variables. The fitness function for the GA-based fuel economy optimization is formulated as:

$$F(x) = BSFC(x) + R\left[\sum_{i=1}^{4} max(\bar{g}_i, 0) + \left|\bar{h}(x)\right|\right] \tag{1}$$

After receiving the simulation outputs, the GA performs selection, crossover, and mutation operations to generate a new population. The procedure continues until the convergence criteria (maximum generations or fitness tolerance) are satisfied. The coupled optimization loop proceeds as follows:

- GA generates a candidate parameter set.
- Parameters are written to the MATLAB workspace.
- The Simulink model is executed programmatically.
- GT-Power performs the engine simulation within the co-simulation environment.
- Performance results are returned to MATLAB.
- The objective function is evaluated.
- GA updates the population.

This automated loop eliminates manual intervention and enables the efficient exploration of a high-dimensional parameter space.

Figure 4 shows the coupling scheme among the MATLAB (GA) program, the Simulink model, and the GT-Power model.

- Population size: 50
- Number of generations: 300
- Crossover probability: 0.8 (GT-Power default)
- Mutation probability: 0.01 (GT-Power default)

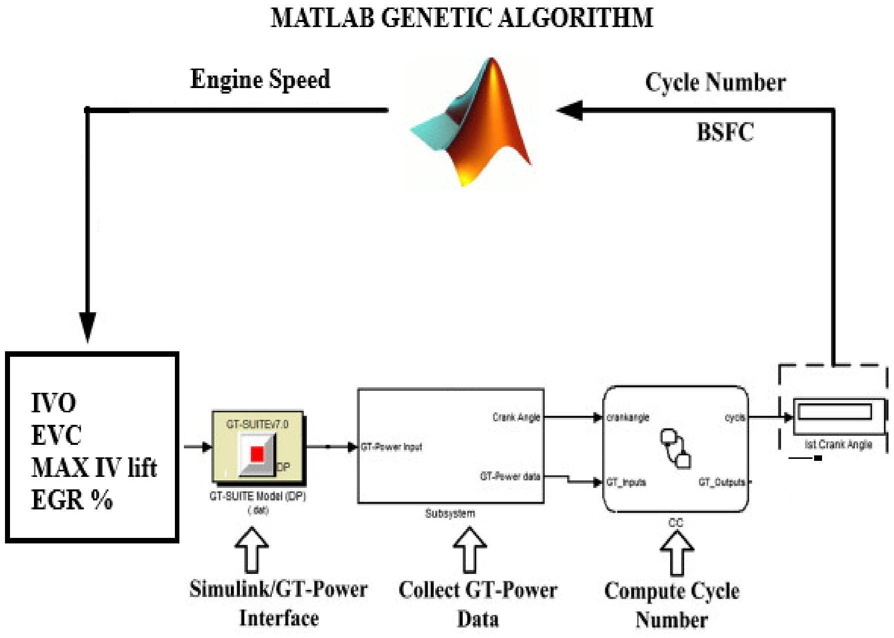


Figure 4 Coupling scheme among the MATLAB (GA) program, Simulink model, and GT-Power model

Figure 5 displays the flowchart of the fuel economy optimization procedure based on the coupled MATLAB–GA, Simulink, and GT-Power framework. The algorithm initializes the population, evaluates each individual through GT-Power co-simulation, computes the fitness function (e.g., BSFC-based objective), and applies genetic operators (selection, crossover, and mutation) iteratively until the stopping criterion is satisfied, yielding the optimal engine calibration parameters. The flowchart illustrates the closed-loop optimization procedure used for fuel economy improvement via the integrated framework. The process follows a population-based evolutionary structure combined with high-fidelity engine simulation.

The procedure begins with the initialization of the Genetic Algorithm (GA) and the Simulink model. During this stage:

- Decision variables and their bounds are defined.
- GA parameters (population size, mutation rate, crossover probability, maximum generations) are specified.
- The Simulink model is prepared for co-simulation with GT-Power.

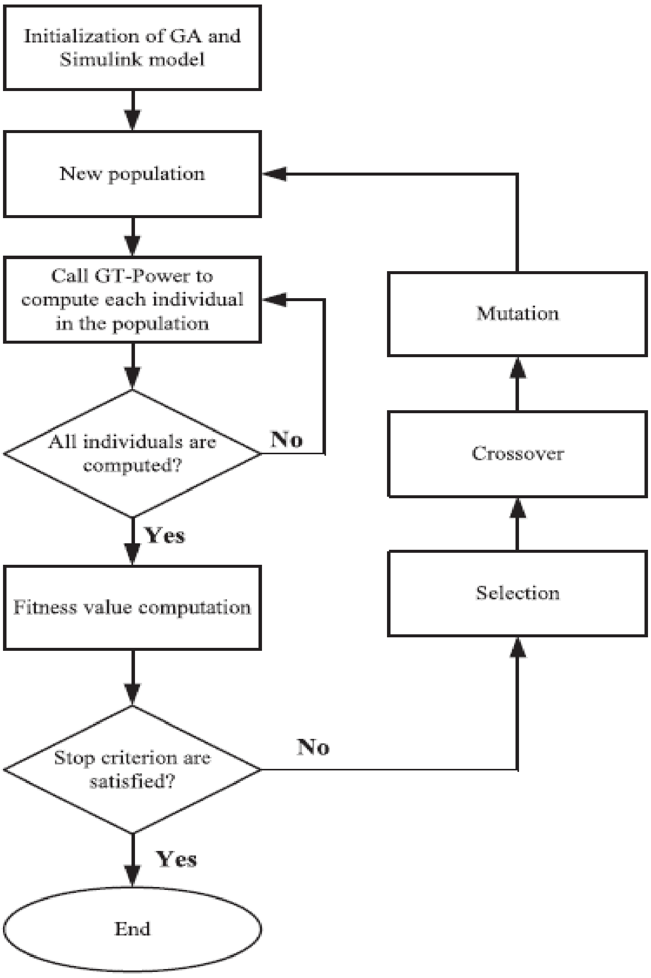


Figure 5 Flowchart for fuel economy optimization via MATLAB(GA)/Simuling/GTPower

This step establishes the optimization environment and initializes the first generation.

3-2- Analysis of optimization results

Figures 6–10 present the optimization results of the engine operating variables at 2000 rpm and 2 bar load using the Genetic Algorithm (GA). Under the defined constraints—intake valve opening (IVO), intake valve closing (IVC), exhaust valve closing (EVC), maximum valve lift, and exhaust gas recirculation (EGR)—all parameters converged to their optimal values. The corresponding optimal brake-specific energy consumption (BSEC) was reduced to 333 g/kW.h, representing a 3.36% improvement compared to the baseline condition prior to optimization. It is noteworthy that, based on the convergence trends of the best fitness value of individuals and the mean fitness of the population, the optimization process terminated before reaching the predefined limit of 370 generations. This occurred because a stopping criterion was implemented in the MATLAB-based GA program: if the best fitness value remains unchanged for 10consecutive generations, the population is considered to have converged sufficiently. At that point, the algorithm automatically terminates to avoid unnecessary computational effort. Figure 11 illustrates the baseline and Atkinson intake valve cam profiles versus crank angle after optimization with the genetic algorithm. Maximum lift and intake valve opening duration are increased.

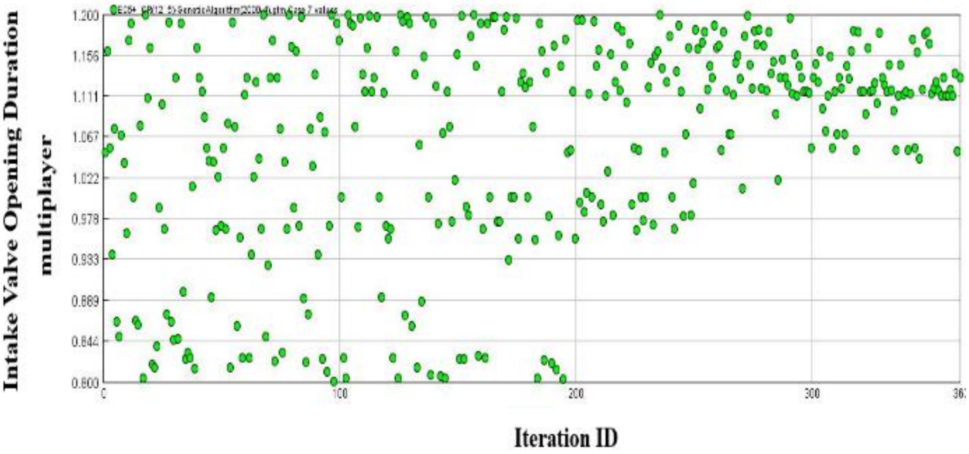


Figure 6 intake valve opening multiplayer vs. iteration

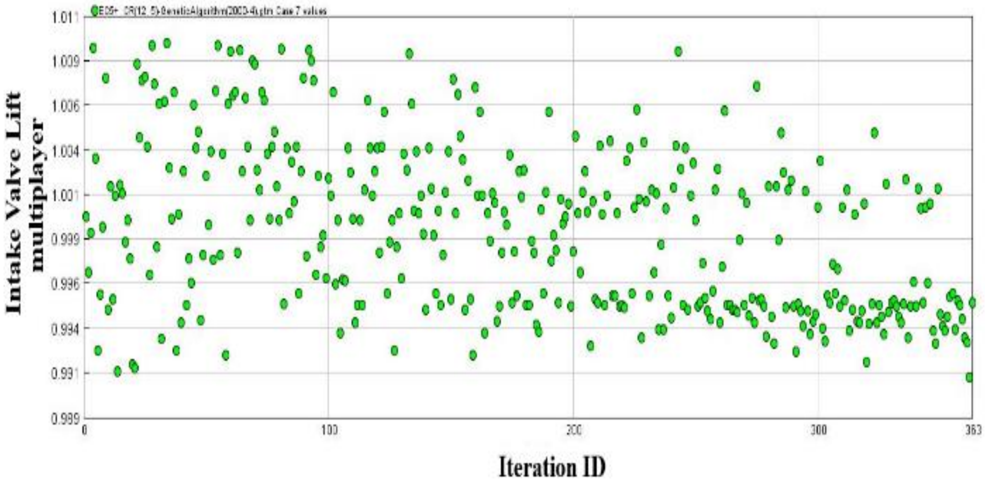


Figure 7 intake valve lift multiplayer vs. iteration

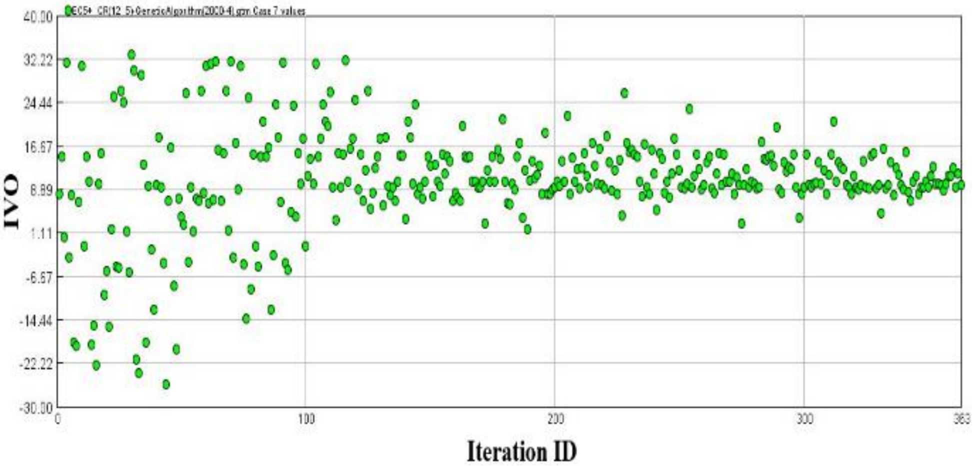


Figure 8 intake valve opening vs. iteration

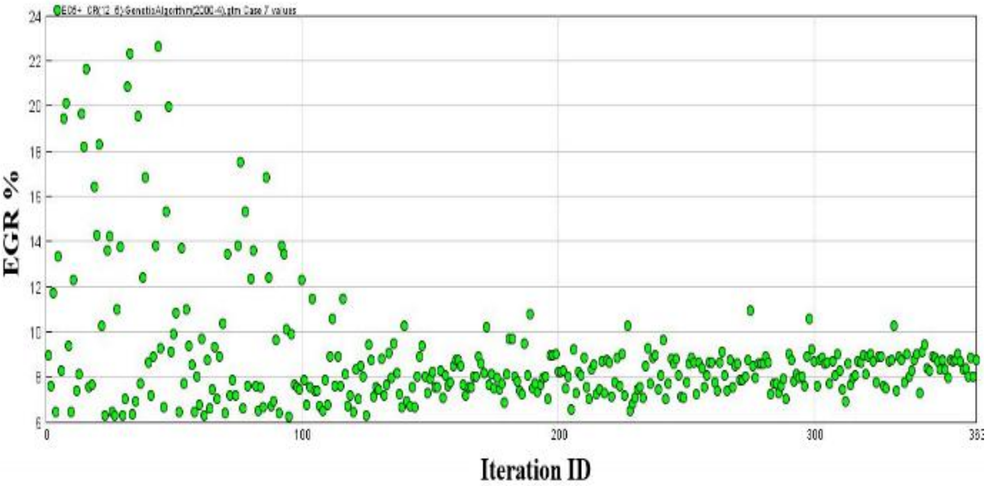


Figure 9 EGR vs. iteration

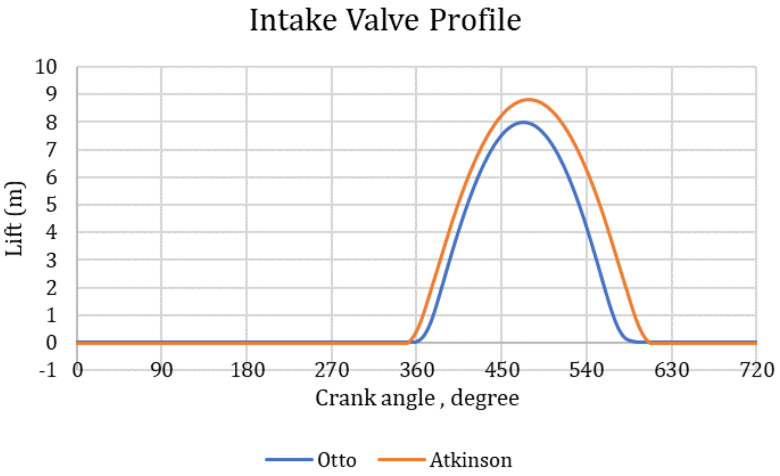


Figure 10 Custom and final intake valve profiles after optimization with GA

3-3- Validation of numerical 1D modeling

Figure 11 presents a comparison between the experimental and 1D numerical data for the cylinder pressure profile at 2000 rpm and a 2 barload. The results confirm the accuracy of the numerical model.

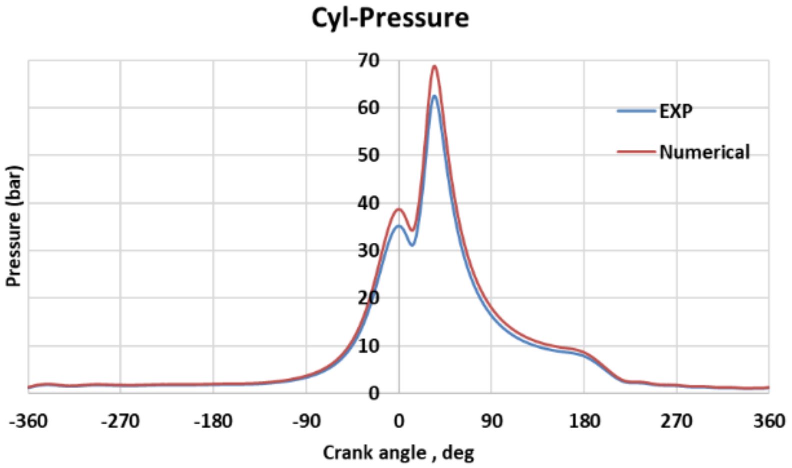


Figure 11 Comparison of experimental and 1D numerical data for the pressure profile

4- Engine rig and test equipment

Figure 12 shows the schematic of the 1.6 L four-cylinder turbocharged Atkinson-cycle gasoline engine studied in this work. The schematics of the basic engine functioning components are presented, including the air filter, throttle, intake manifold, the four cylinders, the exhaust manifold, and the Three-Way Catalyst. The Atkinson-cycle engine is a Port Fuel Injection (PFI) gasoline engine, and an FC2210Z intelligent fuel consumption meter with an accuracy of ±0.5% is installed to measure fuel consumption. The engine is equipped with a DYNAS3 LI 250 high-dynamic electric dynamometer, and the speed, engine oil temperature, coolant temperature, and intake air temperature were recorded automatically from the dynamometer control console.

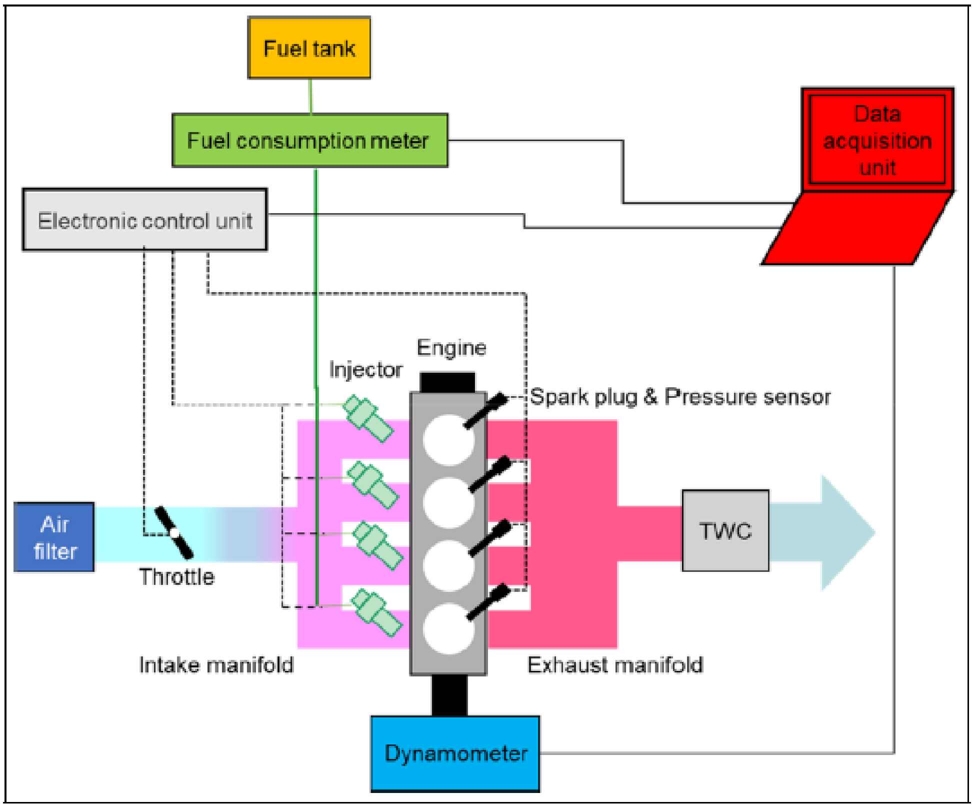


Figure 12 Schematic setup of the Atkinson-cycle engine

A Kistler 6117B pressure sensor combined with a spark plug is used to measure each cylinder's pressure with an accuracy of ±1.25 bar, and a Kistler 2613B crank angle encoder with an accuracy of ±0.1° CA is installed at the free end of the crankshaft to specify the crank angle position. The cylinder pressure and crank angle are monitored and recorded by the electronic control unit. A high-speed data acquisition unit (AVL 621 combustion analyzer) is employed to receive the data from the fuel consumption meter, the dynamometer, and the electronic control unit. Besides, the data acquisition unit also includes a Horiba MEXA-730L tester with an accuracy of ±0.1 to control the air-fuel ratio. The fuel tested in this study is pure gasoline without any blends. All experimental measurements are conducted after the engine warms up at idle speed and reaches a steady state, with the oil temperature between 90°C and 65°C and the coolant temperature between 80°C and 65°C. During the entire experiment, the oil temperature is kept below 135°C, the coolant outlet temperature is controlled at 88°C–65°C, and the exhaust temperature is controlled below 850°C.

Table 1 shows the original Otto-cycle engine's basic specifications. The engine installed in the test rig is shown in Figure 13.

Table 1 Original Otto-cycle engine basic specifications

Type	Inline, water cooled
Number of cylinders	4
Bore (mm)	0.0785
Engine speed (rpm)	3500
Stroke (mm)	0.082
Connecting rod length(mm)	0.1335
Compression ratio	9.5-12
Diameter on intake valve	3 cm
Diameter on exhaust valve	2.4 cm
Maximum torque/Speed	230 Nm/2500 rpm
Rated power/Speed	112 kW/6000 rpm
Intake valve opening timing	365
Exhaust valve opening timing	156

Figure 13 Engine in the test rig

5- Results and Discussion

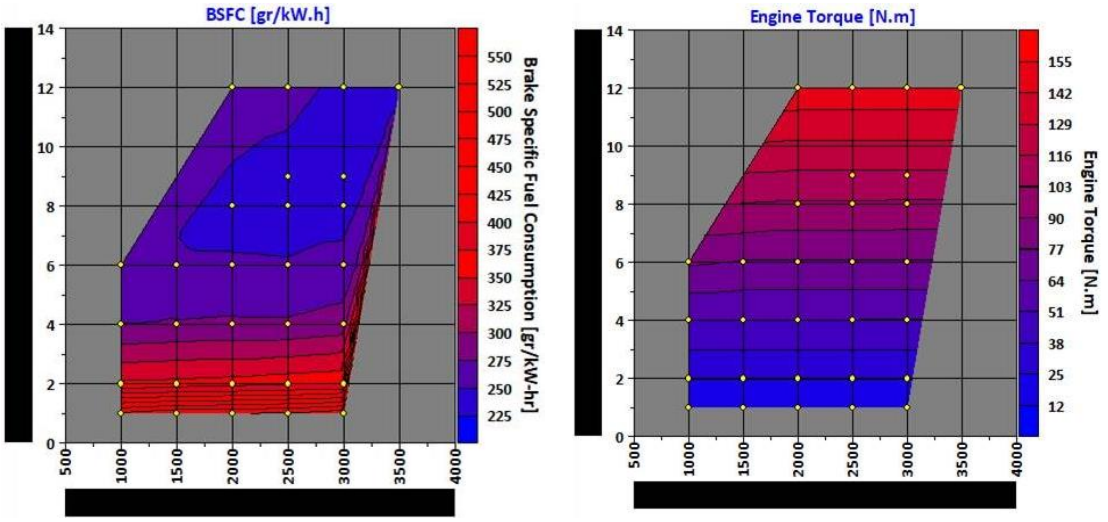
Figure 14 presents the engine performance and emission maps of brake specific fuel consumption (BSFC), thermal efficiency, torque, fuel consumption rate, HC, and NOx across a speed range of 1000–3500 rpm under various load conditions. Based on the results, the following conclusions can be drawn:

(a) After optimization, the average BSFC decreases by approximately 2–3%. The minimum BSFC of 238 g/kW·h occurs at 3000 rpm and 1 bar, while the maximum value of 545 g/kW·h is also observed at 3000 rpm under low-load conditions.

(b) Thermal efficiency varies significantly with load. At 3000 rpm and 1 bar, the minimum thermal efficiency is 16%, whereas the maximum thermal efficiency reaches 36% at 3000 rpm and 9 bar.

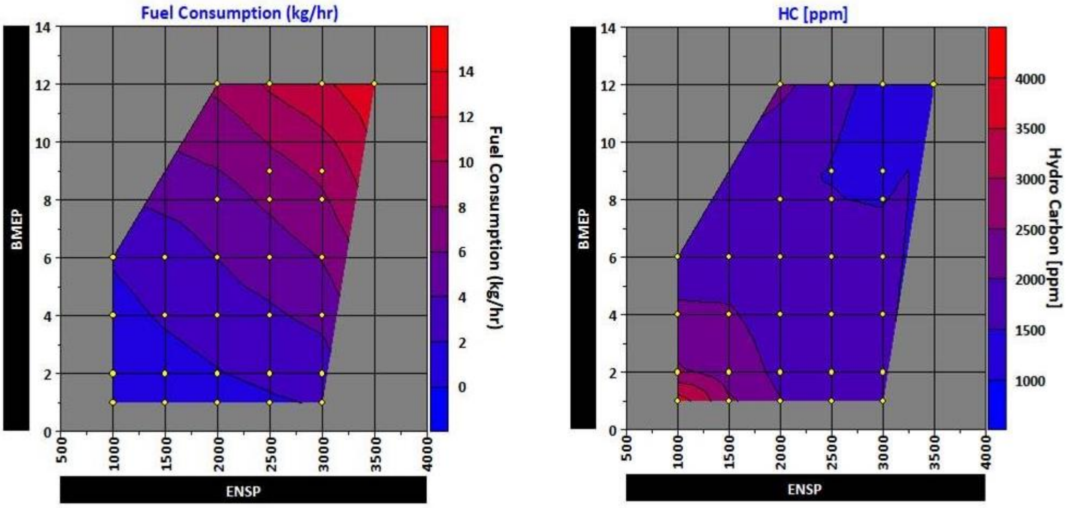
(c) Engine torque increases with both speed and load. The minimum torque of 12.6 N·m is recorded at 3000 rpm and 1 bar, while the maximum torque of 151.6 N·m is achieved at 3500 rpm and 12 bar.

(d) Fuel consumption ranges from a minimum of 0.7 kg/h at 1000 rpm and 1 bar to a maximum of 13.7 kg/h at 3500 rpm and 12 bar. The overall reduction in fuel consumption is approximately 2.5% after optimization, indicating improved fuel economy under the evaluated operating conditions.



(a) BSFC

(b) Engine torque



(c) Fuel consumption

(d) HC (ppm)

Fig 14 Map of performance change rate

6- Conclusions and recommendations for further research

In this study, the performance of an Atkinson-cycle gasoline engine and its fuel-saving potential at low speed and part load are systematically investigated. Initially, an experimental study is conducted, and a corresponding one-dimensional (1D) GT-Power simulation model is developed and validated for a baseline Otto-cycle engine. The validated Otto-cycle model is then optimized using a Genetic Algorithm (GA) to operate as an Atkinson-cycle engine by adjusting key parameters, including intake valve opening timing, intake valve duration, maximum intake valve lift, and exhaust gas recirculation (EGR) rate. Finally, the optimized engine performance maps are integrated into a series-parallel HEV platform to evaluate the impact of the Atkinson-cycle engine on overall vehicle fuel efficiency and emission performance.

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مقاله پژوهشی

بهینه‌سازی مصرف سوخت چرخه اتکینسون یک موتور اشتعال جرقه‌ای پرخوران با روش وراثت در سرعت کُند و بار جزئی

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اطلاعات مقاله

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کاهش انتشار آلاینده‌ها

چکیده

دستیابی به سوخت‌های پاک‌تر و افزایش بهره‌وری انرژی در بخش خودرو، علاقه به خودروهای دورگه برقی، بویژه آن‌هایی که از موتورهای چرخه اتکینسون استفاده می‌کنند، را افزایش داده است. این مقاله بهینه‌سازی و پیاده‌سازی موتور بنزینی پرخوران با چرخه اتکینسون را با هدف کاهش مصرف سوخت و انتشار گازهای گلخانه‌ای در سرعت و بار کم را بررسی می‌کند. یک چارچوب بهینه‌سازی چند متغیره مبتنی بر روش وراثت با تمرکز بر زمان‌بندی دریچه ورودی، دامنه دریچه و بازخورانی گازهای خروجی برای بهبود عملکرد موتور در شرایط مختلف سرعت–بار به کار گرفته شده است. یک الگوی شبیه‌سازی یک بعدی جی‌تی‌پاور معتبر، همراه با شبیه‌ساز متلب، برای ارزیابی اثرات راهبردهای زمان‌بندی دریچه بر تشکیل مخلوط، ویژگی‌های احتراق و انتشار گازهای گلخانه‌ای استفاده شده است. آزمایش‌های تجربی بر روی یک موتور ۱.۶ لیتری پرخوران اتکینسون، یافته‌های شبیه‌سازی را تأیید می‌کنند و بهبود ۲ تا ۳ درصدی در مصرف سوخت ویژه ترمزی، کاهش ۱۸ درصدی در انتشار اکسیدهای ازت و کاهش تا ۲.۵ درصدی در انتشار دی اکسید کربن را نشان می‌دهند. نتایج، ظرفیت چرخه اتکینسون را برای افزایش قابل توجه بازده در سرعت و بار کم را، بویژه هنگامی که با راهبردهای دریچه متغیر و بهینه‌سازی مبتنی بر روش وراثت بهبود می‌یابد، برجسته می‌کند. توصیه‌هایی برای تحقیقات آینده شامل دورگه‌کردن چرخه‌های اتو و اتکینسون و ادغام مجموعه‌های پرخوران پیشرفته برای رفع محدودیت‌های چگالی توان است.

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