Optimising the Performance of 110cc Engines for Fuel-Efficient Vehicle Design in the Shell Eco-Marathon

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Article History: Received 26 July 2024; Revised 17 November 2024; Accepted 28 November 2024

Abstract
The Shell Eco-Marathon (SEM) is an internationally recognised competition that inspires higher education students to develop innovative, fuel-efficient vehicle designs, emphasising sustainability and engineering excellence. A major challenge in this endeavour lies in optimising engine performance, particularly for small-capacity engines such as the 110cc, which require precise tuning to achieve superior thermal efficiency and minimal fuel consumption. This study addresses this challenge by developing detailed brake-specific fuel consumption (BSFC) and brake thermal efficiency maps through dynamometer testing of a 110cc engine. The results demonstrated a maximum torque of 7.31 Nm at 5500 RPM, a peak brake power of 5.33 kW at 7500 RPM, and optimal operating conditions at 5000 RPM with a load of 5.42 Nm, achieving a minimum BSFC of 347.3 g/kWh and a maximum thermal efficiency of 23.87%. These findings provide practical insights into the engine's most efficient operating range, enabling the design of optimised drivetrains that enhance vehicle performance and reduce energy consumption. By harnessing these insights, SEM participants can contribute to advancing sustainable engineering solutions while achieving competitive excellence.

Keywords: Brake-Specific Fuel Consumption (BSFC), Dynamometer Testing, Engine Optimisation, Fuel-Efficient Vehicles, Thermal Efficiency

1.0 Introduction
As global energy demands continue to rise, the world faces an impending energy crisis, with oil and gas reserves projected to be depleted by the end of the century. These situations present significant challenges to energy sustainability [1]. The growing dependence on automobiles for personal transportation has led to a surge in gasoline consumption, further exacerbating the issue [2]. The 1973 Oil Crisis highlighted the vulnerabilities associated with fuel shortages, spurring a heightened interest in fuel-efficient vehicles. Although electric vehicles (EVs) are widely regarded as the future of transportation, current infrastructure limitations make a complete transition from conventional internal combustion (IC) engines unfeasible in the short term. Therefore, enhancing the efficiency of IC engines remains a critical area

of focus, especially considering the vast market potential and the ongoing demand for fuel-efficient solutions.

The Shell Eco-Marathon Challenge serves as an innovative platform for higher education students to devise solutions aimed at maximising vehicle fuel economy while minimising energy consumption [3]. This event challenges university students to design, build, and test energy-efficient vehicles, producing the most energy-efficient vehicles [4], [5]. In this competition, teams are tasked with constructing high-fuel-efficiency prototype vehicles. The Universiti Sains Malaysia (USM) team has selected a 110cc motorcycle engine as the drive train for their vehicle. This engine was chosen for its small displacement and the advantage of a fuel injection system, which allows for precise control of the fuel mass injected into the combustion chamber, enhancing efficiency compared to carbureted engines of similar displacement.

To optimise the vehicle's fuel mileage during the challenge, the engine needs to operate at peak efficiency. This requires the development of a three-dimensional Brake Thermal Efficiency (BTE) map, necessitating dynamometer testing of the engine. There are two primary types of engine dynamometer tests: wide-open throttle (WOT) tests and engine fuel consumption tests. The WOT test measures the maximum torque across the engine's operating speed range to assess overall performance.

Conversely, the engine fuel consumption test involves varying the engine's speed and torque while monitoring fuel consumption, producing valuable data on engine efficiency, including Brake Specific Fuel Consumption (BSFC) and BTE maps. BSFC is a critical metric that reflects the engine's capability to convert fuel into effective work [6]. As defined by Reif Ed [7], BSFC quantifies the amount of fuel required by an internal combustion engine to perform a specific amount of work, typically measured in grams per kilowatt-hour (g/kWh). The BSFC can be calculated as the ratio of fuel consumption rate ($\dot{m}f$ in g/h) to engine brake power (in kW), as shown in Equation (1) [8].

$$BSFC = \frac{\dot{m}f}{Pbrake} \tag{1}$$

Brake thermal efficiency (BTE) is a critical performance metric for internal combustion engines, defined as the ratio of net work output (brake power) to the heat input from the fuel. Specifically, BTE quantifies how effectively an engine converts the energy supplied through fuel into useful mechanical work [9]. In practice, internal combustion engines cannot convert all the chemical energy in the fuel into mechanical work due to inherent energy losses, such as heat dissipation and friction. According to the second law of thermodynamics, thermal engines operate by absorbing heat from a hot reservoir and releasing some of that heat to a cold reservoir, which inherently limits their efficiency—no thermal engine can achieve 100% efficiency [10].

The BTE is influenced by various factors, including engine design and the type of fuel used [9]. It can also be expressed with Brake Specific Fuel

Consumption (BSFC), as demonstrated in Equation (2). Here, BSFC is measured in kg/kWh, and CV represents the calorific value of the fuel, specifically its lower heating value (LHV). For gasoline, the LHV is approximately 12.06 kW/kg.

$$BTE = \frac{1}{BSFC*CV} \times 100\% \qquad (2)$$

Traditional internal combustion engines (ICE), particularly spark-ignition (SI) engines, utilise a thermodynamic cycle known as the Otto cycle to produce mechanical power [11]. However, as highlighted by Martin et al., SI engines face inherent limitations in thermal efficiency, typically achieving a maximum efficiency of around 35% [10]. This limitation arises because not all thermal energy generated during fuel combustion is converted into useful work; roughly one-third of the fuel injected into the combustion chamber is utilised for mechanical power, while the remainder is lost through engine cooling and exhaust gases [10].

To minimise fuel consumption in the vehicle, the engine must operate predominantly under its most fuel-efficient conditions, as outlined in the fuel consumption map. To contribute to this goal, the present study investigates the performance of a 110cc engine, focusing on the development of brake-specific fuel consumption (BSFC) and brake thermal efficiency maps through dynamometer testing. This approach allows the observation of fuel consumption at various torque levels and engine speeds. The throttle angle and dynamometer load settings will be controlled during these tests to gather comprehensive data. The current study offers valuable insights into the engine's operational limits and efficiency under different load conditions, which can be used to fine-tune engine performance and improve vehicle energy efficiency. Findings from this research will be useful for advancing drivetrain designs and contribute to the overall goals of SEM to foster innovation in energy-efficient vehicle design.

2.0 Methodology

To accurately assess the engine's performance and efficiency, a series of tests will be conducted. Before these tests, the 110cc engine must be removed from its original motorcycle frame and modified to facilitate efficient power transfer to the dynamometer. This involves several key steps:

2.1 Engine Specification

An internal combustion engine operates within a defined speed range, constrained by its idling speed and maximum redline speed [7]. Within this range, the engine can produce its maximum power and torque only at specific engine speeds [12]. Therefore, it is essential for the engine's rated power to align with the application requirements within the permissible speed range. The engine selected for this study is a 110cc displacement four-stroke engine, which is capable of producing a maximum output power of 6.2 kW at 7,500 RPM. Additionally, it achieves a maximum torque of 8.59 Nm at 5,500 RPM (as shown in Table 1). These specifications highlight the engine's capability to deliver optimal performance within its operational limits, making it suitable for applications where efficiency and power are critical.

Table 1: Engine specification

Type	Four-stroke
Number of cylinders	1
Bore x Stroke	50.0 mm x 55.6 mm
Displacement	109.2 cc
Compression ratio	9.0:1
Fuel system	Electronic Fuel Injection
Camshaft Configuration	Single overhead camshaft (SOHC)
Maximum torque	8.59 Nm @ 5,500 RPM
Maximum power	6.22 kW @ 7,500 RPM
Cooling system	Air-cooled

2.2 Clutch Modification

In this study, we address the inefficiencies caused by the centrifugal clutch traditionally used in the engine, which is connected to the engine output shaft. The centrifugal clutch often experiences slippage, particularly under high load and low engine speed conditions, leading to mechanical losses [13].

To mitigate these issues, we have opted to eliminate the centrifugal clutch. This involves the removal of the one-way clutch and its replacement with a weight balancer unit. By substituting the centrifugal clutch with a weight balancer, we establish a direct connection between the output shaft and the dynamometer. This modification enhances power transfer efficiency by minimising slippage and ensuring a more reliable connection [14] (see Figure 1). This approach not only optimises performance but also contributes to more accurate measurements during testing.

Figure 1: Engine crankcase without centrifugal clutch

2.3 Fuel Consumption Measuring System

Accurate measurement of fuel consumption under various operating conditions created by the dynamometer is crucial for this study. To quantify fuel usage, we weigh the fuel tank before and after each engine test. This weight data is recorded using an electronic fuel weight scale setup, as shown in Figure 2. The electronic fuel weight scale consists of a load cell paired with an HX711 load cell amplifier and an Arduino microcontroller. The setup utilises two 2-mm thick mild steel sheets, each measuring 30 cm x 45 cm, serving as the top and bottom plates of the scale, with the load cell positioned between them. This configuration ensures precise measurements of fuel consumption during testing, allowing for reliable data analysis across different engine operating conditions.

Figure 2: Electronic fuel weight scale setup

Figure 3 shows the fuel weight scale schematic diagram with the Arduino pins connection for the load cell amplifier and the load cell. An Arduino programming code is developed to measure the mass of the fuel in the tank in real-time. Thus, in each dynamometer run, the mass of the fuel consumed can be calculated [15].

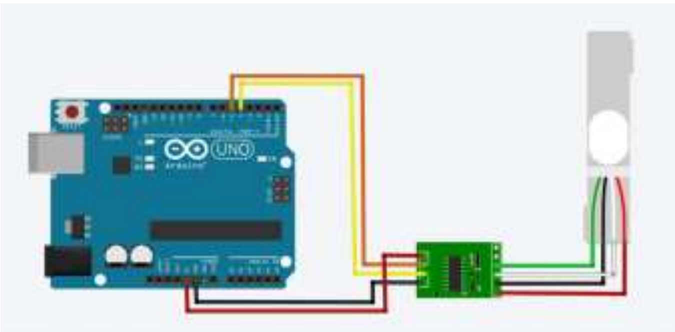

Figure 3: Fuel weight scale schematic diagram

2.4 Throttle Body Control Unit

The throttle body butterfly valve regulates the airflow into the combustion chamber, directly impacting fuel injection and engine power output. In the engine utilised for this project, the throttle is traditionally mechanical, with the throttle opening adjusted by the user through a throttle cable. To enhance control during testing, we have developed an electronic throttle controller as shown in Figure 4. This system allows the user to adjust and maintain the desired throttle angle while simultaneously managing dynamometer settings.

The integration of electronic control improves precision and responsiveness, facilitating more accurate assessments of engine performance under varying operational conditions.

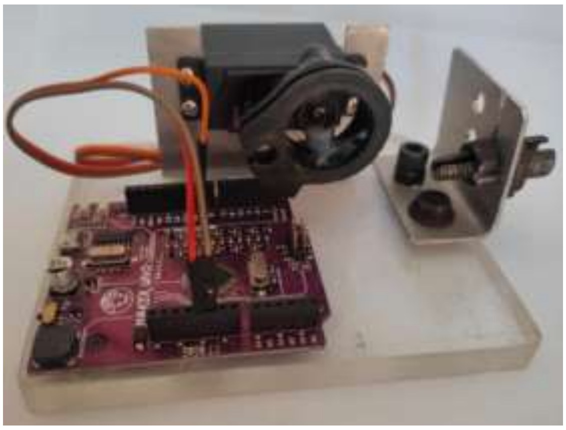

Figure 4: Fully assembled throttle controller

Figure 5 illustrates the schematic diagram of the electronic throttle controller. An Arduino microcontroller is employed to manage the servo motor, adjusting it according to the throttle angle set by the user while simultaneously displaying the real-time throttle angle. This setup ensures precise control over airflow into the combustion chamber, enhancing engine performance evaluation.

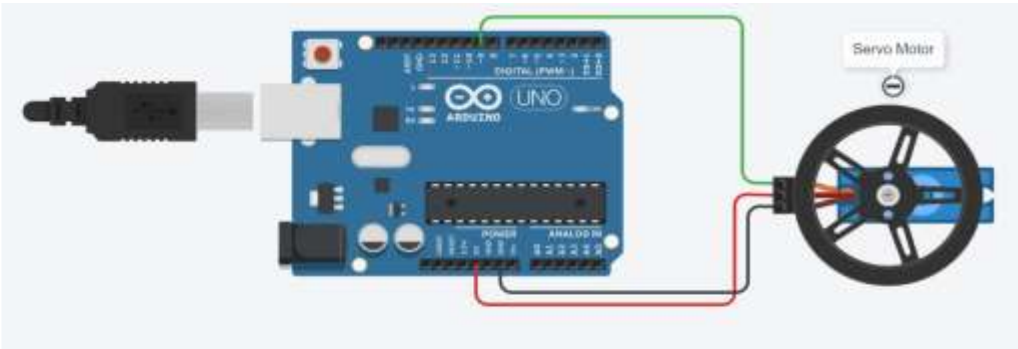

Figure 5: Electronic throttle controller schematic diagram

2.5 Dynamometer Tests

The dynamometer tests conducted in this study include wide-open throttle (WOT) assessments and fuel consumption measurements. The WOT engine test is essential for evaluating engine performance; it measures engine torque across a range of speeds from idle to maximum, with the throttle fully open. During this test, only torque and engine speed data from the dynamometer are collected. The results are used to plot curves representing engine torque and brake power against engine rotational speed, providing insights into the engine's performance characteristics under WOT conditions. These plots will help to analyse the relationship between torque, power, and engine speed, crucial for understanding the engine's efficiency and capabilities.

The engine fuel consumption test is carried out by operating the engine at the targeted engine operating conditions (i.e. the speed and the torque) while fuel consumption data are taken. In this test, a LabView data acquisition program is developed to log the engine torque, the rotational speed, the throttle angle, and the fuel mass consumed. Based on the engine fuel consumption test results, the engine brake specific fuel consumption (BSFC) and the engine thermal efficiency 3D maps are developed.

3.0 Results and Discussion

The WOT engine performance test measures the maximum torque over a range of engine rotational speeds. Figure 6 shows the maximum engine torque versus engine speed, obtained from the WOT engine test. The engine attains the maximum rotational speed of 10,000 RPM before reaching the rev limiter. Based on the engine torque curve, the engine torque increased as the engine speed increased from 2,000 RPM, reaching the peak torque of 7.31 Nm at 5,500 RPM, and then decreased as the engine speed continued to increase.

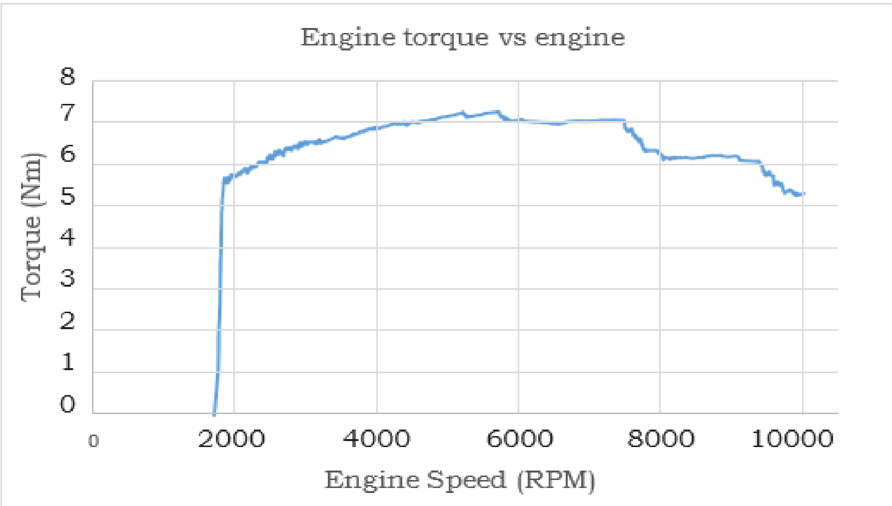

Figure 6: Engine maximum torque curve based on the WOT engine test

Figure 7 shows the engine brake power plotted against the engine speed, obtained from the WOT engine test. As the chart demonstrates, the engine brake power increases linearly as the engine speed increases from 2,000 RPM to 7,000 RPM. Then, the engine power decreases at the engine speed of 8,000 RPM and then begins to increase again until the engine speed reaches 9,500 RPM before decreasing again at the maximum speed of 10,000 RPM. Based on the WOT engine test, the peak engine brake power is 5.68 kW at the engine speed of 9,500 RPM.

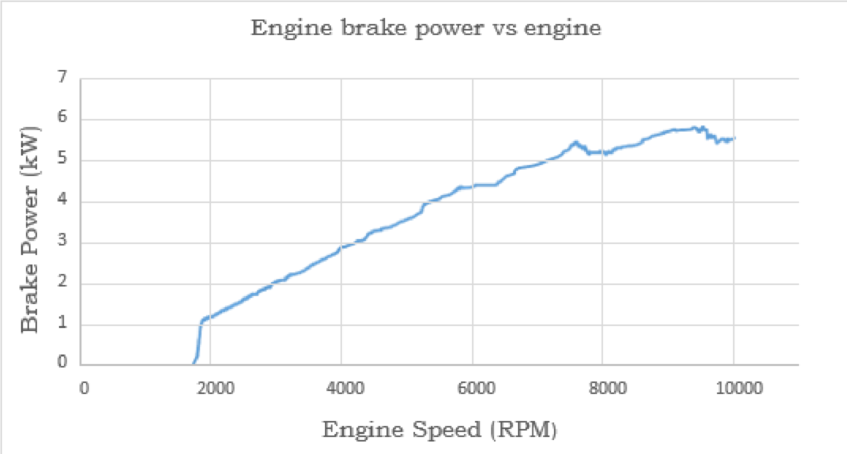

Figure 7: Engine brake power curve based on the WOT engine test

The engine fuel consumption test gathers engine fuel consumption data at different engine operating conditions. Figure 8 shows the fuel consumption in fuel mass flow rate at different engine speeds and torque. The lowest fuel consumption recorded is 3.41 g/min, at the engine speed of 2,000 RPM and with the torque of 1.08 Nm. The highest fuel consumption recorded is 46.96 g/min, at the engine speed of 8,000 RPM and with a torque of 6.50 Nm.

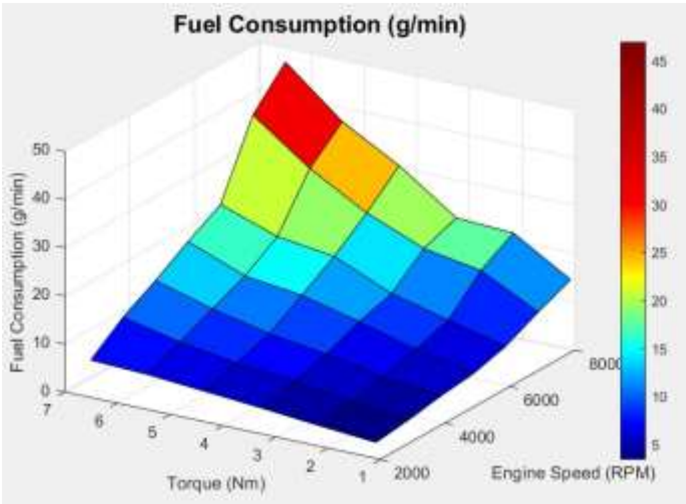

Figure 8: Fuel consumption map with engine speed (RPM) and engine torque (Nm)

The lowest fuel consumption occurs when the engine is operated at relatively low engine speed with low torque, while the highest fuel consumption occurs when the engine is operated at relatively high engine speeds with high torque. In a constant-load scenario, the fuel consumption increases with increasing engine speed. At a constant engine speed, the fuel consumption increases as the engine load is increased. Both revving the engine to a higher speed and overcoming higher loads require higher power output. Producing high power requires a higher volume of air and consumes more fuel.

Another parameter that shows how well the engine works at a given fuel consumption is the brake thermal efficiency (BTE). The BTE is defined as the ratio of the work done by the engine to the heat input [6]. The heat input, in this case, is the fuel consumed mass flow rate ($\dot{m}_f$) multiplied by the fuel calorific value (C_v) (eq. 1).

The highest BTE reading in this study is 23.4 %, recorded at the engine speed of 5,000 RPM and with 5.42 Nm of torque. The lowest BTE value is 9.22 %, recorded at the engine speed of 2,000 RPM and with 1.08 Nm of torque. An IC engine's BTE is generally low, due to the energy lost during fuel combustion, as well as heat loss taking place in the form of exhaust gases and heat convection through the engine cylinder wall [10].

The engine brake thermal efficiency 3D map is shown in Figure 9. The engine operates optimally at speeds ranging between 4,000 RPM and 5,200 RPM with a 5.42 Nm torque. It can be achieved by maintaining the throttle opening angle between 32 % and 36 % at the above-mentioned rotational speed range. Since the engine has a small displacement, with a short stroke of only 55.6 mm, the torque generated is relatively small. Thus, it is recommended to operate the engine at the rotational speed of 5,000 RPM and 34% throttle to achieve the best fuel economy. In short, the engine can generally attain relatively high BTE when it is operated at relatively high torque.

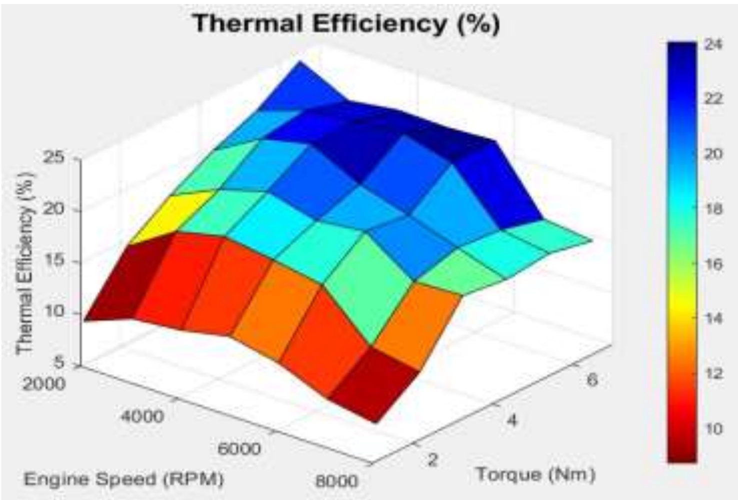

Figure 9: Engine thermal efficiency map corresponding to engine speed (RPM) and engine torque (Nm)

4.0 Conclusion

This study evaluates the performance of a 110cc motorcycle engine integrated into a Shell Eco-Marathon vehicle, focusing on identifying its optimal operating conditions through dynamometer testing. The engine achieved a peak power output of 5.33 kW at 7,500 RPM and maximum torque of 7.31 Nm at 5,500 RPM. Optimal efficiency was determined by constructing a brake thermal efficiency (BTE) 3D map, revealing a maximum efficiency of 23.87% at 5,000 RPM and 5.42 Nm torque, achieved with a throttle opening angle between 32% and 36%. The lowest efficiency, 9.22%, was recorded at 2,000 RPM and 1.08 Nm torque. These findings provide critical insights for determining the ideal transmission final drive ratio and driving conditions, including throttle positioning and engine speed, enabling the Shell Eco-Marathon team to maximise vehicle performance and fuel economy effectively. In terms of potential commercialisation, the results could significantly benefit industries focused on small-capacity engine optimization, particularly in sectors like urban transportation and fuel-efficient vehicle development. These insights could help manufacturers create engines with better fuel economy and lower emissions, aiding in compliance with stringent environmental regulations. Future work could focus on evaluating the long-term performance of these optimized engine conditions under real-world driving scenarios, investigating alternative fuels or hybrid systems to enhance sustainability, and developing advanced engine control systems that adapt to dynamic driving conditions, improving both fuel efficiency and engine longevity.

Acknowledgement

The authors wish to thank the Department of Mechanical Engineering, Politeknik Ungku Omar, and the School of Mechanical Engineering, Universiti Sains Malaysia for their technical support and for facilitating this research work.

Author Contributions

K. A. Idris: Conceptualization, Methodology, Software, Writing-Original Draft Preparation; **M. I. Ramdan**: Data Curation, Validation, Supervision; **M. Y. Idroas**: Software, Validation, Writing-Reviewing and Editing.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest in the manuscript.

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