JOURNAL OF AUTOMOTIVE AND MECHANICAL APPLIED TECHNOLOGY

Vol. 3 No 1, 2026, pp. 75-86 https://journal.uny.ac.id/publications/jamat https://doi.org/10.21831/jamat.v3i1.3335

Design of an ESP32-Based Electronic Control System for Evaluating Motorcycle Fuel Injector Characteristics

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ARTICLE INFO

Article history:
Received 06.04.2026
Revised 02.05.2026
Accepted 15.06.2026

Keywords:
Electronic fuel injection; ESP32-S3 CAM; Fuel injector; Pulse-width modulation; Web-based control

ABSTRACT

The development of electronic fuel injection (EFI) technology and the growing use of ethanol-blended fuels have introduced new challenges for motorcycle fuel systems, particularly injector performance and reliability. Commercial injector testers are relatively expensive and often use closed architectures, limiting their accessibility for small workshops and educational laboratories. This study aimed to design and develop a web-based injector characteristic testing control system using an ESP32-S3 CAM microcontroller and to evaluate its performance. An engineering design method with a quantitative testing approach was applied. The system was designed to conduct fuel volume, spray pattern, and leakage tests by controlling engine speed simulation (RPM), duty cycle, and test duration through a web interface. The ESP32-S3 CAM generated pulse-width modulation (PWM) signals to actuate the injector and provided real-time visual monitoring through an integrated camera. The results showed that the system successfully executed the intended testing functions. Increasing RPM, duty cycle, and test duration produced proportional increases in injected fuel volume. Linearity analysis indicated that injector responses were generally linear with respect to changes in RPM and duty cycle. Repeatability testing produced maximum coefficient of variation values of 1% for injector 1 and 2% for injector 2, indicating good measurement consistency. Spray pattern testing showed a uniform cone-shaped atomization pattern. In contrast, leakage testing confirmed the absence of fuel droplets under inactive conditions. These findings demonstrate that the developed ESP32-based tester provides a low-cost, flexible, and practical alternative for evaluating motorcycle injector characteristics in workshop and laboratory settings, especially where standardized diagnostic equipment is not readily available.

1. Introduction

The advancement of motor vehicle technology has driven the widespread adoption of Electronic Fuel Injection (EFI) systems as replacements for conventional fuel-delivery systems. EFI systems control fuel supply more precisely by regulating injection timing, injection duration, and fuel atomization according to engine operating conditions. Compared with carburetor-based systems, EFI technology provides better adaptability to variations in engine speed, throttle position, load, temperature, and air–fuel ratio requirements. This capability contributes to improved combustion efficiency, enhanced engine performance, reduced fuel consumption, and lower exhaust emissions. In this system, the injector serves as a key actuator, atomizing pressurized fuel into fine droplets, enabling it to mix more effectively with air before combustion [1]. Therefore, injector performance directly influences the quality of mixture formation, combustion stability, engine response, and emission characteristics.

The reliability of motorcycle injectors is particularly important because motorcycles are widely used as daily transportation in Indonesia and other developing countries. In many cases, motorcycles operate in stop-and-go traffic, under high ambient temperatures, in dusty environments, and with irregular maintenance schedules. These operating conditions can accelerate injector degradation, especially when fuel quality varies or when deposits accumulate on the injector nozzle. A small disturbance in injector opening, fuel flow rate, or spray pattern can cause an imbalance in the air–fuel mixture. If the injector delivers less fuel than required, the combustion process may become lean, leading to poor acceleration, engine hesitation, and increased combustion temperature. Conversely, excessive fuel delivery may cause rich combustion, increased fuel consumption, carbon deposits, and higher hydrocarbon emissions.

The implementation of ethanol-blended fuels, which has recently begun to expand in Indonesia, creates additional challenges for fuel-system components, particularly injectors [2]. Ethanol-blended fuels are promoted because they can reduce dependence on fossil fuels and support the use of renewable energy sources. However, ethanol has different physical and chemical characteristics from pure gasoline. The hygroscopic nature of ethanol allows it to absorb moisture from the surrounding environment, increasing the risk of corrosion in metallic fuel-system components. In addition, the presence of water and oxygenated compounds in ethanol-blended fuels can influence fuel stability and promote deposit formation on injector nozzles [3]. These deposits can reduce fuel flow rate, alter the spray pattern, and deteriorate atomization quality, ultimately affecting engine performance and emissions.

Injector deposits may appear in the form of varnish, gum, or carbonaceous residues around the nozzle orifice. Although these deposits are often small, their effect can be significant because injector nozzles are designed with very narrow passages to produce controlled atomization. Partial blockage of the nozzle can reduce the injected fuel volume, disturb the spray cone, and create uneven droplet distribution. Poor atomization can lead to incomplete combustion, unstable idle operation, increased fuel consumption, and higher exhaust emissions. In severe cases, injector leakage may occur when the needle valve fails to seal properly, leading to fuel droplets even when the injector is inactive. This condition can create starting difficulties, excessive fuel odor, and potential safety risks.

Therefore, periodic inspection of injector condition is required by evaluating fuel spray volume, spray pattern, and leakage. These three parameters represent the main indicators of injector performance. Fuel spray volume indicates whether the injector can deliver fuel under the required operating conditions. Spray pattern observation provides information on the quality and uniformity of atomization, while leakage testing determines whether the injector maintains sealing performance under fuel pressure when no activation signal is applied. A reliable injector testing system should be able to simulate injector operation across different engine speeds, duty cycles, and test durations, enabling consistent evaluation of changes in injector characteristics.

However, most commercial injector testers are relatively expensive and use proprietary closed-system architectures, making modification, maintenance, and further development difficult. Commercial equipment is generally designed as a ready-to-use diagnostic tool with limited access to the control algorithm and system configuration. This condition limits its use for educational, experimental, and small-scale workshop applications where flexibility and affordability are important. As a result, small-scale workshops generally rely on manual injector cleaning without standardized measurement or evaluation procedures. Manual inspection is often based solely on visual judgment, making it difficult to quantitatively compare injector performance before and after cleaning or maintenance. The absence of standardized measurement also reduces the reliability of injector diagnosis.

The development of low-cost microcontroller-based control systems offers an alternative solution for injector testing applications. Microcontrollers can be programmed to generate Pulse Width Modulation (PWM) signals that represent injector activation under simulated engine operating conditions. By adjusting the signal frequency and duty cycle, the injector's opening and closing behavior can be controlled according to specific test parameters. In addition, integrating wireless communication and web-based interfaces enables users to operate the system without additional desktop software. This approach is suitable for small workshops, vocational education, and laboratory-scale testing because it combines affordability, flexibility, and ease of use.

To address these challenges, this study developed a web-based injector characteristic testing control system utilizing the ESP32-S3 CAM microcontroller. The ESP32-S3 CAM was selected because it integrates microcontroller-based signal processing, Wi-Fi connectivity, and camera-based monitoring in a compact platform. The system was designed to control key testing parameters, including simulated engine speed (RPM), duty cycle, and test duration, while providing real-time monitoring through an integrated camera and web server. Through the web interface, users can enter test parameters, activate the injector and fuel pump, and observe the spray process in real time.

The main objective of this study was to design, develop, and evaluate an ESP32-based electronic control system for motorcycle fuel injector characteristic testing. The evaluation focused on the system's ability to control injector operation, measure fuel volume output under varying parameters, observe spray patterns, and identify leakage conditions. The proposed system is expected to provide a practical and low-cost alternative for injector testing, particularly for small-scale workshops, vocational education laboratories, and research applications related to motorcycle EFI systems.

2. Methods

The research was conducted systematically, following the workflow illustrated in **Fig. 1**. The study began with problem identification based on field-encountered issues, followed by a literature review and requirements analysis to establish the theoretical foundation and determine the specifications of the system to be developed. Based on this analysis, the system planning and design phase was carried out, encompassing the development of the system concept and architecture, and the selection of appropriate components in accordance with the research objectives.

The subsequent stage involved hardware assembly and software programming to transform the design into an operational prototype. The prototype was then subjected to a series of tests to evaluate its performance based on predefined parameters. If discrepancies were identified, improvements were made to both the system design and programming until the prototype operated as intended. Finally, the test results were analyzed and evaluated as the basis for drawing conclusions and formulating the study findings.

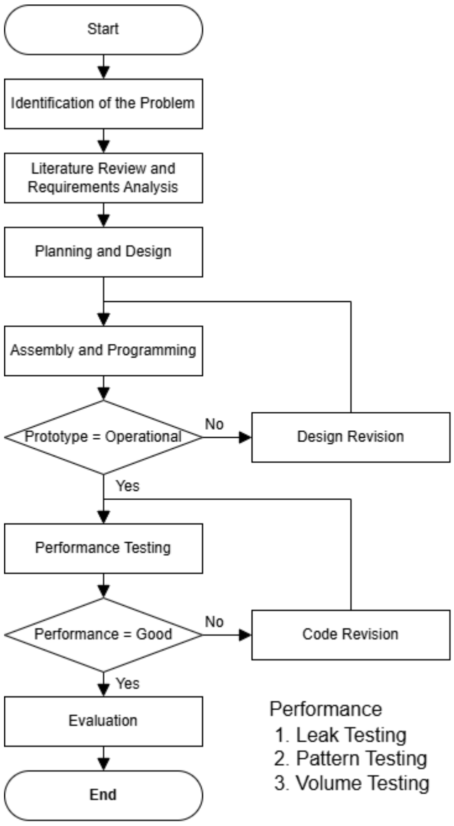


Figure 1. Research flowchart

2.1 Testing Procedure

The testing procedure was conducted to evaluate injector performance under several operating conditions. The tests consisted of evaluations of fuel volume, spray pattern, and leakage. Fuel volume testing was performed by varying RPM (1000-6000 rpm), duty cycle (15-45%), and test duration (30, 60, and 90 s), while the resulting fuel volume was measured using a graduated cylinder. Spray pattern testing was conducted by visual observation using the real-time monitoring feature integrated into the ESP32-S3 CAM web server. Leakage testing was performed by applying fuel pressure to the injector without an activation signal and observing whether fuel droplets appeared for one minute. Each test was repeated three times to assess measurement consistency.

2.2 Data Analysis

Injector performance was evaluated based on fuel volume, spray pattern, and leakage characteristics. The relationships among RPM, duty cycle, test duration, and resulting fuel volume were analyzed using graphical representations to observe trends in injector operating characteristics. Measurement consistency was assessed through repeatability testing using the coefficient of variation (CV), as shown in **Eq. 1**.

$$CV = \frac{S}{\bar{x}} \times 100\% \quad (1)$$

where S represents the standard deviation, and x-bar represents the mean value of the measurement results. A lower CV value indicates greater measurement consistency and repeatability. In addition, spray pattern and leakage characteristics were evaluated qualitatively based on visual observations during testing.

3. Results and Discussion

The electronic architecture of the injector characteristic testing control system is shown in **Fig. 2**. The system consists of input, processing, driver, actuator, monitoring, and measurement sections. The ESP32-S3 CAM serves as the central controller, receiving web-based user input, converting it into PWM timing parameters, controlling the injector and fuel pump via driver circuits, and transmitting camera images for real-time spray observation. The main technical specifications of the prototype are summarized in **Table 1**, the indicative component-level cost is shown in **Table 2**, and the physical components of the developed injector tester are presented in **Table 3**.

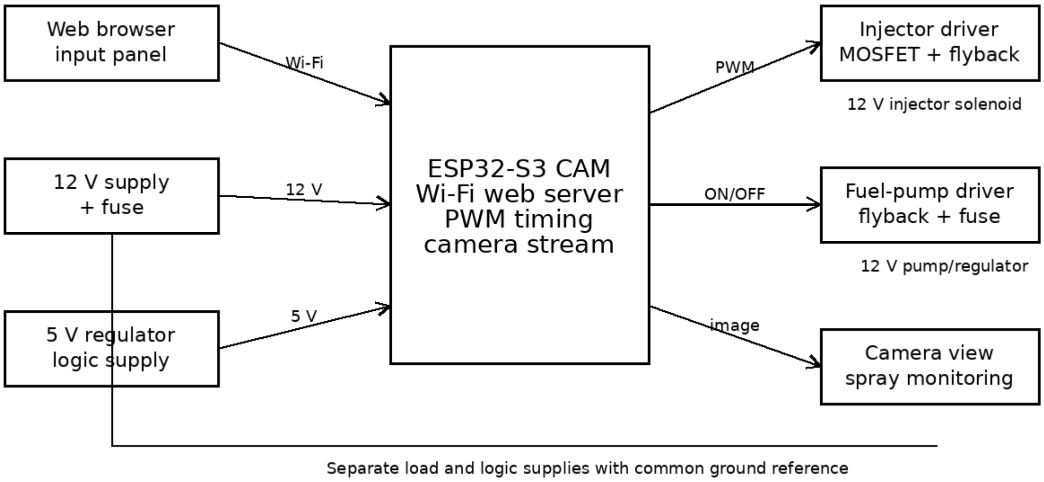


Figure 2. Control system schematic

Table 1. Main technical specifications of the developed injector tester

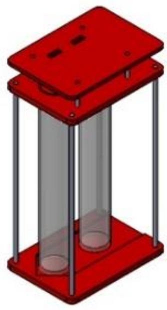
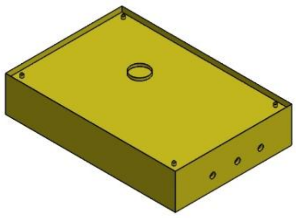
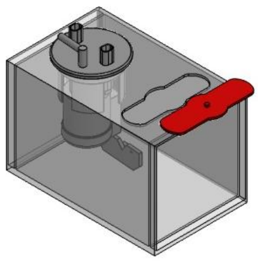
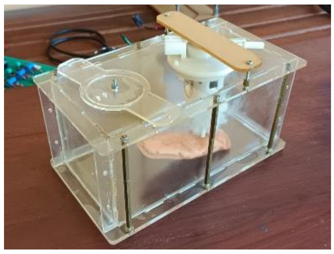
Item	Specification/description
Controller and interface	ESP32-S3 CAM; Wi-Fi web server; camera monitoring
Control variables	Simulated RPM 1000-6000; duty cycle 15-45%; duration 30-90 s
Injector and fuel supply	Two 12 V high-impedance motorcycle injectors; nominal fuel pressure approximately 300 kPa
Driver and protection	Low-side driver, flyback suppression, gate/pull-down resistor, fuse, insulated wiring
Power architecture	Separate 12 V load supply and 5 V logic supply with common ground
Measurement method	Collected volume measured with graduated cylinder; spray and leakage assessed visually
Limitation	No continuous pressure logging, oscilloscope validation, or commercial reference-tester comparison

Table 2. Developed injector tester components

Component group	Estimated cost (IDR)	Notes
Controller, driver, protection, and power electronics	550,000	ESP32-S3 CAM, driver components, fuse, wiring, regulator, supply
Fuel-delivery subsystem	350,000	Pump, regulator, hoses, and fittings

Component group	Estimated cost (IDR)	Notes
Mechanical parts and enclosure	500,000	Frame, tank, PCB housing, and fabrication materials
Miscellaneous assembly items	100,000	Fasteners and accessories
Total estimated prototype cost	1,500,000	Excluding labor, smartphone/computer, fuel, and reusable injectors

Table 3. Developed injector tester components

No	Part Name	Design	Result
1	Frame		
2	PCB housing		
3	Tank		

The signal generation algorithm implemented in the ESP32-based injector characteristic testing control system begins with microcontroller initialization, including Wi-Fi connection setup, web server configuration, and output pin assignments for the injector and fuel pump. After the system is activated, the user enters the testing parameters through the web interface, including RPM, duty cycle, and test duration. The RPM value is converted into a PWM signal frequency to determine the injector operating period. At the same time, the duty cycle defines the pulse width (Ton), representing the duration during which the injector remains active. The ESP32 microcontroller then processes these parameters using its PWM module to generate periodic digital signals that control injector opening and closing. At the same time, the system calculates the total testing duration as the execution time limit for signal generation. The fuel pump is activated during testing to maintain stable fuel pressure and simulate EFI operating conditions. The PWM signal is continuously transmitted until the specified testing duration is reached, after which the system automatically stops the output signal, deactivates the injector, and turns off the fuel pump. This signal generation process enables the injector to operate under conditions that resemble actual engine operation, allowing injection volume, spray pattern, and leakage to be evaluated.

Based on the implemented signal generation algorithm, injector operating time is represented in milliseconds (ms) and consists of two states: injector active (Inj On) and injector inactive (Inj Off). The operating time is automatically calculated from the RPM value entered via the web interface. This value is converted to the injection-cycle period by accounting for the characteristics of a four-stroke engine, in which one combustion cycle occurs every two crankshaft revolutions. Consequently, the number of injection cycles per second is obtained by dividing RPM by 120. For example, at 2000 RPM, approximately 16.67 injection cycles occur per second. This value determines the duration of a single injection cycle, which is then converted to milliseconds to obtain the total injector operating period (PWM period).

After the period (T) is determined, the system divides it into two components: active injector time and inactive injector time. This division is based on the specified duty cycle, where T_{on} is calculated as a percentage of the total period, and T_{off} is the remaining period after subtracting T_{on}. This relationship is expressed in **Eq. 2**.

$$Duty\ cycle = \frac{Ton}{T} \times 100\%$$

Or

$$Ton = (\frac{Duty\ Cycle}{100}) \times T \qquad (2)$$

$$Toff = T - Ton$$

As an example, at 2000 rpm, the injector operating period is approximately 60 ms. With a duty cycle of 25%, T_{on} is 15 ms, and T_{off} is 45 ms. **Table 4** provides representative theoretical timing values generated from the conversion algorithm. These values clarify the interpretation of RPM and duty cycle: increasing RPM increases the number of injection events per unit time, whereas increasing duty cycle increases the active injector pulse width within each cycle. External oscilloscope-based waveform validation was not included in the current experimental stage; therefore, the reported timing values should be interpreted as program-calculated setpoints rather than traceable timing-calibration results.

Table 3. Developed injector tester components

RPM	Injection frequency (Hz)	Period T (ms)	Duty cycle (%)	T_{on} (ms)	T_{off} (ms)
1000	8.33	120.00	25	30.00	90.00
2000	16.67	60.00	25	15.00	45.00
4000	33.33	30.00	25	7.50	22.50
6000	50.00	20.00	25	5.00	15.00

After assembly and programming were completed, preliminary testing was conducted to verify that all system components operated according to the design specifications before use for injector characteristic testing. The preliminary evaluation consisted of functional testing of the control system, repeatability testing, and leakage testing. The functional test results demonstrated that the ESP32-based system could receive and process RPM, duty cycle, and test duration parameters via the web interface. The generated PWM signals successfully controlled the injector and fuel pump according to the specified commands and responded appropriately to parameter adjustments.

During the repeatability test, the system produced consistent outputs under identical RPM and duty cycle settings. Repeated measurements showed stable injector timing responses (Inj On and Inj Off) with minimal deviation, indicating that the system could provide reliable and repeatable test results. In addition, leakage testing confirmed that no unintended fuel flow was detected when the injector was inactive (Inj Off). The system maintained stable fuel pressure and stopped fuel injection in response to control commands, without any indication of leakage during repeated testing. These results demonstrate that the developed control system exhibits stable performance and is suitable for injector characteristic testing applications.

The test results indicate that increasing the duty cycle led to a corresponding increase in the fuel volume delivered by both injectors, as shown in **Fig. 3**. The fuel volume increased progressively with each duty-cycle increment. Under all tested duty-cycle conditions, injector 1 produced a higher fuel volume than injector 2. However, both injectors exhibited similar increasing trends.

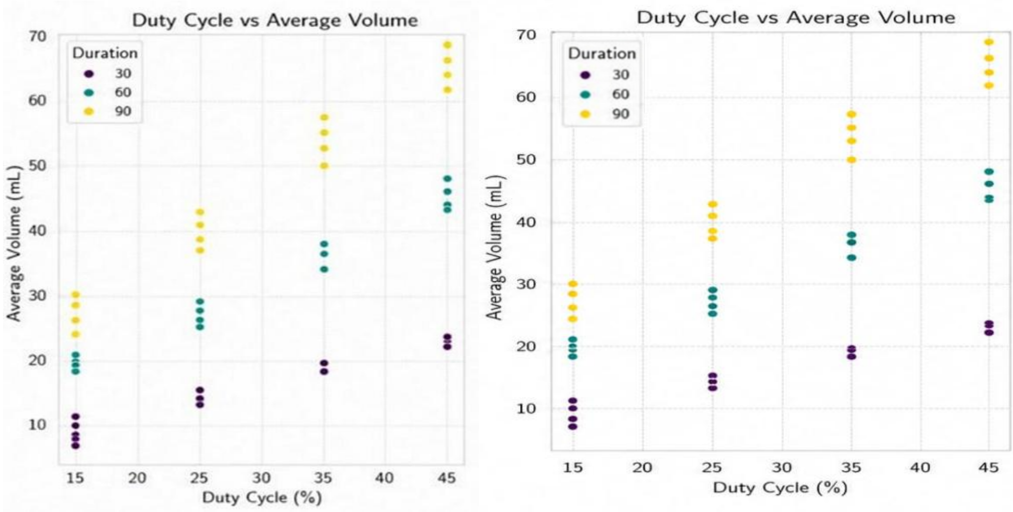


Figure 3. Effect of duty cycle on fuel volume of injectors 1 and 2

The increase in fuel volume resulting from a higher duty cycle is consistent with the operating principle of PWM. Duty cycle represents the ratio of the active signal duration to the total signal period. As the duty cycle increases, the injector remains open for a longer duration during each operating cycle. Increasing the duty cycle increases the average energy delivered to the load, thereby extending the actuator's operating duration [4]. In an electronic fuel injection system, this condition allows fuel to flow through the injector nozzle for a longer period, resulting in a greater volume of fuel being injected.

The relationship between duty cycle and injection volume exhibited a generally linear characteristic (**Fig. 3**). Good linearity reflects an injector's ability to respond consistently and predictably to variations in the control signal [5]. Differences in electromagnetic and mechanical characteristics may influence the amount of fuel delivered, even when identical control signals are applied [6]. This phenomenon explains the difference in fuel volume observed between injector 1 and injector 2 despite being operated under the same testing conditions. The findings of this study are consistent with previous studies showing that increasing the injector control signal increases the volume of fuel delivered [5], [7].

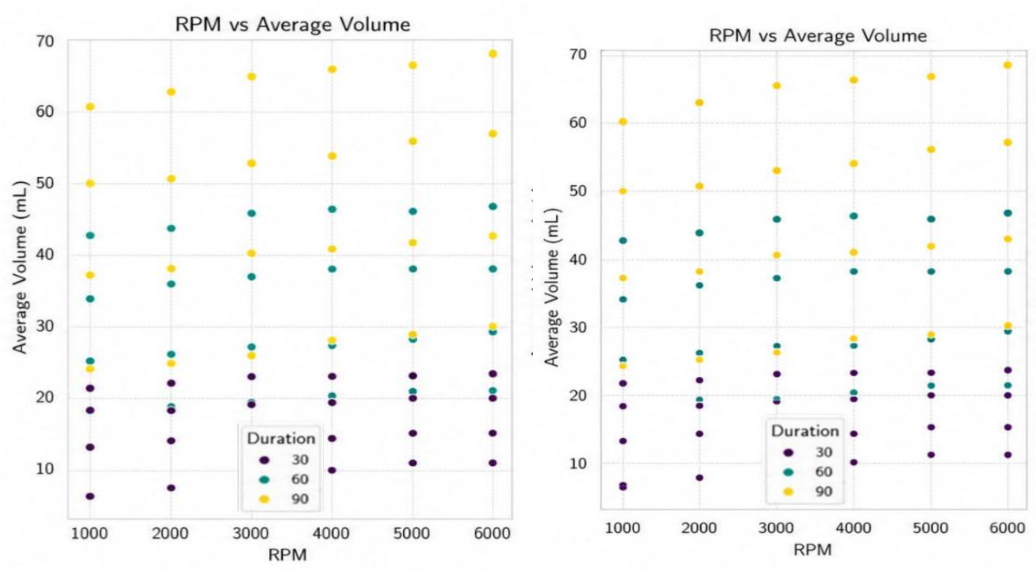


Figure 4. Effect of RPM on fuel volume of injectors 1 and 2

The experimental results indicate that an increase in engine speed (RPM) led to a corresponding increase in the fuel volume delivered by both injectors (**Fig. 4**). The injected volume increased gradually across the applied RPM variations. The plotted data demonstrate a positive correlation between RPM and injection volume: higher simulated engine speeds correspond to greater fuel accumulation in the measuring tube over the same testing duration. Across all tested RPM conditions, injector 1 consistently produced a higher fuel volume than injector 2.

The increase in fuel volume is closely related to the relationship between engine speed and injector operating frequency. In this study, RPM values were converted into the control signal frequency generated by the ESP32 microcontroller. According to Heywood [8], in a four-stroke engine, one operating cycle occurs every two crankshaft revolutions. Thus, the injection operating frequency can be expressed as RPM divided by 120. As RPM increases, the injector operating frequency also increases, resulting in a higher number of injection cycles per unit time.

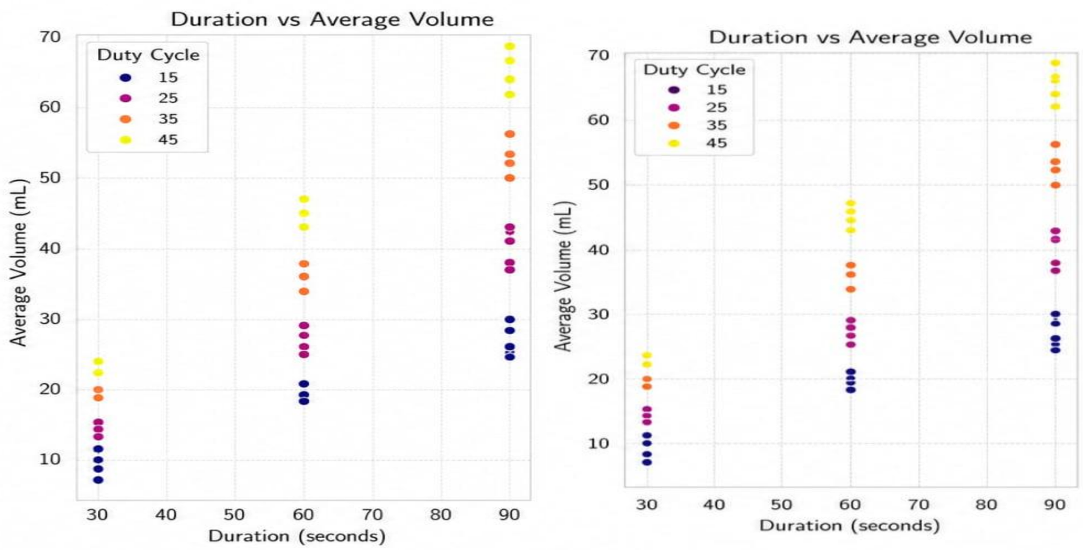


Figure 5. Effect of test duration on fuel volume of injectors 1 and 2

Increasing the number of injection cycles results in a higher total fuel volume delivered during the testing period. At a constant duty cycle, each injection cycle maintains a relatively consistent opening duration. However, when RPM increases, the number of injection events within the same test duration also increases, resulting in higher accumulated fuel volume. The relationship between RPM and fuel volume exhibited an approximately linear trend. According to Liu et al. [5], a linear relationship indicates that variations in control parameters yield proportional, predictable system responses. In this study, increases in RPM consistently led to increases in injection volume, demonstrating that the control system could generate stable frequency signals according to user-defined parameters via the web interface.

The test results indicate that increasing the test duration increased the fuel volume delivered by both injectors (**Fig. 5**). The longer the test, the greater the fuel volume accumulated in the measuring tube. Fuel volume increased gradually across all test-duration variations. Injector 1 consistently produced a higher fuel volume than injector 2 under all tested duration conditions.

The increase in fuel volume with longer test durations is attributed to the greater number of injection cycles during the test. Under constant RPM and duty-cycle conditions, the injector continuously sprays fuel. At the same time, the system remains active, allowing the discharged fuel to accumulate in the measuring tube. Consequently, a longer testing duration results in a larger fuel volume. This phenomenon is consistent with the fundamental principle of fluid flow, which states that volume is determined by the product of flow rate and time [9].

Based on the experimental results, increases in test duration were consistently followed by proportional increases in fuel volume. This behavior indicates that the developed system can operate consistently over different testing periods. The differences in fuel volume produced by the two injectors at each duration variation suggest differences in their respective flow characteristics. Nevertheless, both injectors exhibited similar increasing trends with increasing test duration, indicating that their responses to changes in operating time remained stable, predictable, and within normal operating conditions.

These findings are supported by Fawzi et al. [9], who reported that injection volume is directly related to injection duration in fuel control systems. An increase in injection time results in a higher delivered fuel volume, making duration one of the primary factors affecting the accumulation of injected fuel. Therefore, the results of the present study are consistent with those findings, demonstrating that increasing test duration directly increases the fuel volume delivered by the injector.

Although both injectors exhibited similar increasing trends, differences in the resulting injection volumes were observed. Injector 1 consistently produced higher fuel volumes than injector 2 at all duration variations. These differences may be attributed to variations in injector flow characteristics caused by wear, spring condition, manufacturing tolerances, or nozzle condition.

Table 5. Repeatability test results for injectors 1 and 2

Injector	Test condition	Number of repetitions	CV range (%)	Maximum CV (%)	Interpretation
1	Identical RPM, duty cycle, and duration settings	3	0-1	1	Low dispersion in repeated volume measurement
2	Identical RPM, duty cycle, and duration settings	3	0-2	2	Low dispersion in repeated volume measurement

The repeatability test was conducted to evaluate the consistency of fuel volume measurements when the experiment was repeated under identical operating conditions (**Table 5**). In this study, multiple tests were performed with the same RPM, duty cycle, and test duration. The resulting data were analyzed using the mean, standard deviation, and coefficient of variation (CV) to assess the degree of dispersion relative to the mean.

Based on the test results, all CV values were below the maximum acceptable limit of 5%. Injector 1 exhibited a maximum CV value of 1%, while injector 2 exhibited a maximum CV value of 2%. These results indicate that variation in measurement outcomes was relatively small, demonstrating high data uniformity and measurement consistency. According to the Joint Committee for Guides in Metrology (JCGM) [10], the coefficient of variation is a statistical measure used to assess measurement consistency by comparing the standard deviation to the mean. A lower CV value indicates greater repeatability within a measurement system. The low CV values obtained in this study demonstrate that the control system generated stable PWM signals during repeated tests, resulting in fuel volume measurements with minimal deviation.

Figure 6. Spray patterns of injectors 1 and 2

Based on spray pattern observations across all RPM, both injectors produced a uniformly distributed cone-shaped spray pattern (**Fig. 6**). These results indicate that the fuel atomization process occurred effectively under all test conditions. According to Jiang et al. [11], a good spray pattern is characterized by a fine, uniformly distributed fuel mist, which enhances the mixing of fuel and air. Standardized fuel-spray characterization generally requires defined illumination, imaging geometry, calibration scale, and image-based data reduction [12], [13]. Therefore, **Fig. 6** should be interpreted as workshop-level visual evidence rather than a complete quantitative spray analysis.

The leakage test results showed no leakage from the injector, fuel hoses, or system connections during the testing process. The injectors maintained fuel pressure when not activated, preventing fuel droplets from forming during inactivity. These findings are consistent with the leakage test acceptance criteria, which state that an injector should not exhibit fuel dripping at operating pressure without activation. This condition indicates that the needle valve can seal properly and that the developed system operated safely during the leakage evaluation.

4. Conclusions

This study designed and preliminarily evaluated a web-based control system for motorcycle injector testing using an ESP32-S3 CAM microcontroller. The system can receive RPM, duty cycle, and test duration inputs via a web interface, convert these inputs into injector timing commands, operate the injector and fuel pump via driver circuits, and provide camera-based spray monitoring. The results showed that increases in duty cycle, simulated RPM, and test duration increased the accumulated fuel volume by increasing injector pulse width, injection frequency, or cumulative opening time. Repeatability testing produced maximum CV values of 1% for injector 1 and 2% for injector 2, indicating stable short-term operation under repeated settings. No visible leakage was observed during the inactive-injector test, and the spray pattern was visually cone-shaped. The conclusion has been moderated because the prototype has not yet been validated against a commercial reference tester, fuel pressure was not continuously logged, only two injectors were tested, and spray-pattern assessment remained qualitative. Thus, the developed system is best positioned as a reconfigurable educational and preliminary diagnostic prototype. At the same time, future work should include pressure transducer integration, oscilloscope-based PWM validation, quantitative spray-image analysis, larger injector samples, and comparison with standardized injector-testing equipment.

Conflict of Interest

The authors declare that they have no conflict of interest.

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