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Design and implementation of an electronic fuel injection retrofit system for a four-stroke motorcycle engine

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Abstract

Fuel delivery systems play a critical role in determining combustion stability, fuel efficiency, and exhaust emission characteristics of small spark-ignition (SI) engines. Conventional carburetor-based motorcycles, which remain widely used in developing countries, inherently suffer from limited air-fuel ratio control, particularly under transient operating conditions. This study presents the design and experimental implementation of an Electronic Fuel Injection (EFI) retrofit system applied to a four-stroke carbureted motorcycle engine using original equipment manufacturer (OEM) Yamaha components. The retrofit configuration integrates a Yamaha Vixion ECU, injector and fuel pump from Yamaha Jupiter Z1, and standard engine sensors including crankshaft position, throttle position, and engine temperature sensors. Performance evaluation was conducted through chassis dynamometer testing, fuel consumption measurement, and exhaust gas analysis. Experimental results demonstrate that the EFI retrofit significantly improves fuel economy and reduces hydrocarbon (HC) and carbon monoxide (CO) emissions compared to the original carburetor system, while exhibiting a minor reduction in peak torque and power output. The observed trade-off is attributed to conservative OEM fuel and ignition mapping optimized for emission compliance rather than peak performance. The findings confirm that OEM-based EFI retrofit offers a practical and scalable pathway for enhancing combustion cleanliness and fuel efficiency in legacy motorcycle engines without extensive mechanical modification.

Keywords

Electronic fuel injection retrofit, Motorcycle engine, Mombustion efficiency, Fuel economy, Exhaust emissions

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Introduction

Small-displacement four-stroke motorcycles remain the dominant mode of personal transportation in many developing countries due to their affordability, simplicity, and low operating costs. However, a large proportion of these motorcycles still rely on carburetor-based fuel delivery systems, which provide limited control over air–fuel ratio and mixture homogeneity, particularly during transient changes in load and engine speed [1], [2]. As a consequence, carbureted engines often exhibit higher fuel consumption, unstable combustion, and elevated exhaust emissions.

Electronic Fuel Injection (EFI) technology has been widely adopted in modern motorcycles as an effective solution to address these limitations. EFI systems enable precise metering of fuel based on real-time sensor feedback, resulting in improved combustion stability, lower emissions, and better adaptability to varying operating conditions [3], [4]. Numerous studies have reported that EFI-equipped engines demonstrate superior fuel economy and reduced HC and CO emissions compared to carburetor systems, especially under urban driving conditions [5], [6].

Despite these advantages, the replacement of carbureted motorcycles with factory-installed EFI models remains economically challenging in many regions. As a result, EFI retrofit systems have attracted increasing research interest as a transitional strategy to improve the environmental performance of existing motorcycle fleets [7]. Most reported EFI retrofit studies employ programmable or aftermarket ECUs, which, while flexible, increase system complexity, cost, and calibration requirements [8].

Limited attention has been given to EFI retrofit implementations based on original equipment manufacturer (OEM) components. OEM-based systems offer inherent reliability, standardized sensor compatibility, and conservative calibration strategies designed for durability and emission compliance. However, their performance characteristics when adapted to carbureted engines with different mechanical configurations remain underexplored.

Accordingly, this study aims to design, implement, and experimentally evaluate an OEM-based EFI retrofit system for a four-stroke motorcycle engine. The investigation focuses on comparative analysis of torque and power output, fuel consumption, and exhaust emissions between the original carburetor configuration and the EFI retrofit system, thereby providing insight into the feasibility and performance trade-offs of OEM-based EFI retrofitting.

Method

This research employed an experimental comparative approach to evaluate the performance and emission characteristics of a four-stroke motorcycle engine before and after EFI retrofit. The carburetor system served as the baseline configuration, while the EFI retrofit represented the treatment condition. Such an approach is well-suited for assessing cause–effect relationships in engine system modifications [9].

The test object was a Yamaha Vega ZR 2010 four-stroke motorcycle originally equipped with a carburetor. The EFI retrofit system was constructed using OEM Yamaha components, consisting of a Yamaha Vixion ECU, fuel injector and electric fuel pump from Yamaha Jupiter Z1, crankshaft position sensor (CKP), throttle position sensor (TPS), engine operating temperature (EOT) sensor, lean angle sensor, and supporting actuators including fast idle solenoid. A custom wiring harness and fuel delivery layout were developed to ensure electrical and mechanical compatibility.

Performance testing was conducted using a chassis dynamometer to measure torque and power output across the operating speed range. Fuel consumption was evaluated using a volumetric fuel measurement method over a fixed travel distance. Exhaust emissions (CO, CO_2, and HC) were measured using a calibrated automotive gas analyzer under idle, medium, and high engine speed conditions.

Baseline tests were first conducted with the original carburetor system. Subsequently, the EFI retrofit system was installed without altering the engine's mechanical components. All tests were repeated under comparable environmental conditions. Each measurement was conducted in three repetitions, and average values were used for analysis.

Comparative analysis was performed by calculating percentage changes in torque, power, fuel consumption, and emission levels between carburetor and EFI configurations. Graphical and tabular representations were employed to highlight performance trends and system differences. Research framework show in Figure 1.

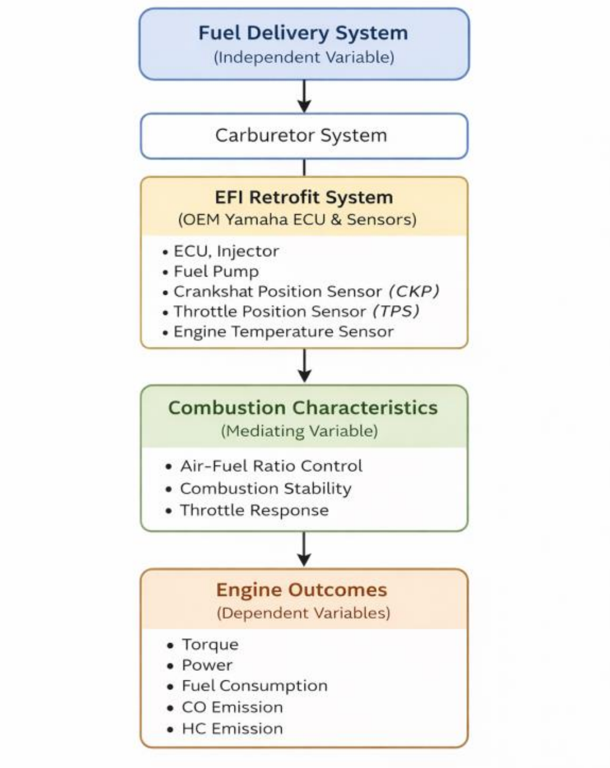

Figure 1. Research framework

The conceptual research framework illustrating the comparison between the carburetor and EFI systems with respect to torque, power, and exhaust emissions is presented in Figure 1. This framework highlights the direct relationship between the fuel delivery system and engine performance characteristics.

Results

Torque and power characteristics

The torque and power characteristics of the motorcycle engine were evaluated using a chassis dynamometer for both the original carbureted system and the retrofitted Electronic Fuel Injection (EFI) system. Each configuration was tested three times under identical operating conditions to ensure measurement repeatability, and the averaged results are summarized in Table 1 and Table 2, with the corresponding dynamometer curves presented in Figure 2 and Figure 3, respectively.

Table 1. Torque and power test results of carburetor system

Test No.	Engine Speed at Max Power (rpm)	Maximum Power (kW)	Engine Speed at Max Torque (rpm)	Maximum Torque (N·m)
1	6.660	5.54	5.100	8.85
2	6.660	5.54	4.920	8.68
3	6.760	5.54	4.880	8.77
Average	6.693	5.54	4.967	8.77

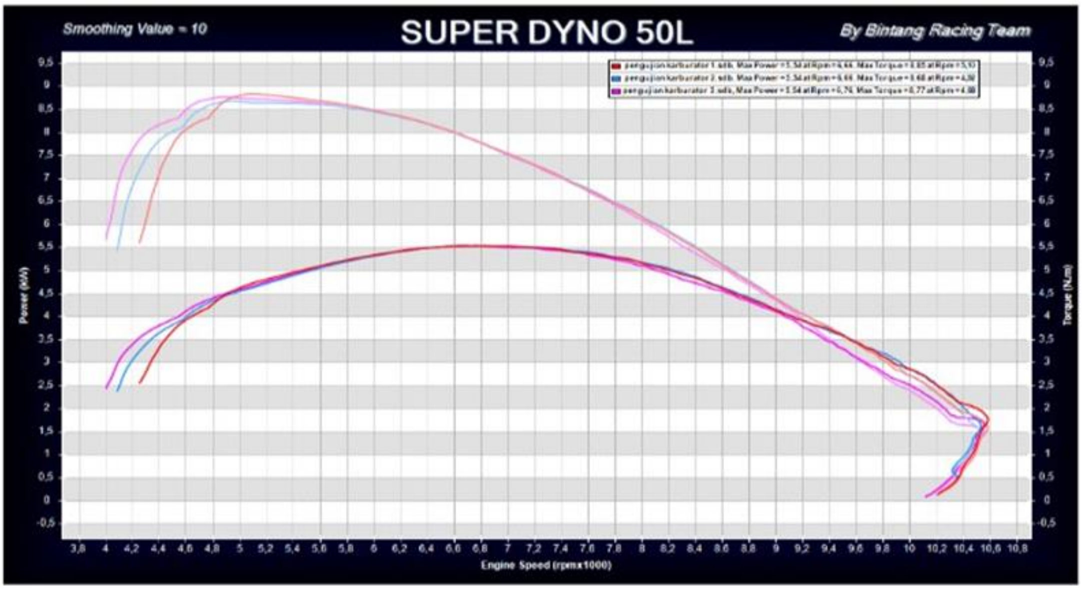

Figure 2. The carburetor torque power curves

Table 1. Torque and power test results of EFI retrofit system

Test No.	Engine Speed at Max Power (rpm)	Maximum Power (kW)	Engine Speed at Max Torque (rpm)	Maximum Torque (N·m)
1	6.530	5.32	5.610	8.20
2	6.740	5.35	5.480	8.18
3	6.740	5.27	5.440	8.22
Average	6.670	5.31	5.510	8.20

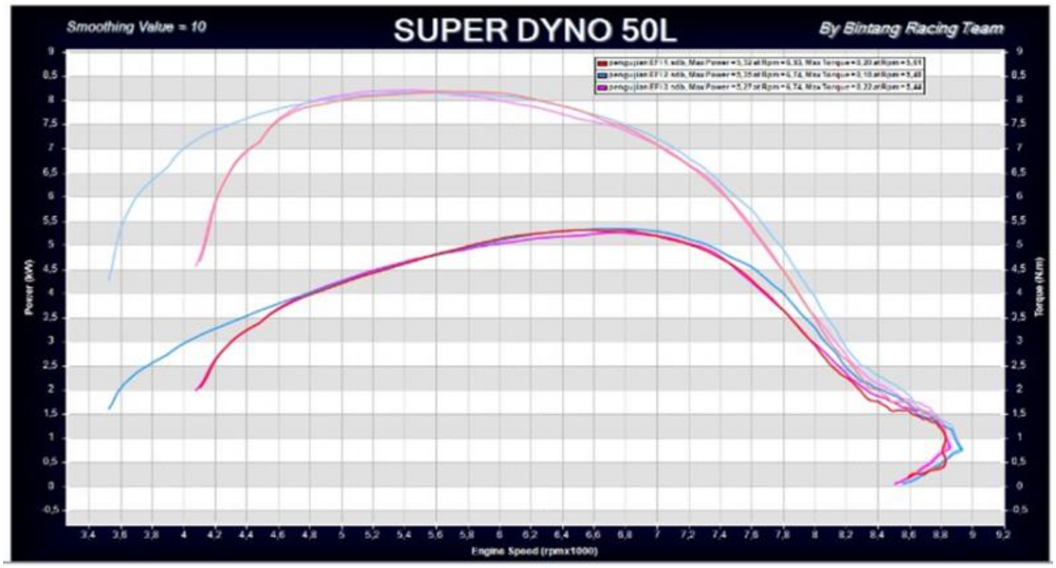

Figure 3. The EFI torque power curves

For the carbureted configuration, the engine delivered an average maximum power of 5.54 kW at 6693 rpm and a maximum torque of 8.77 N·m at approximately 4967 rpm, as reported in Table 1. The torque power curves shown in Figure 2 exhibit a conventional carburetor response, characterized by relatively higher torque at lower engine speeds but with noticeable fluctuations along the speed range. This behavior reflects less precise air–fuel ratio control and reduced combustion stability, particularly during transient operating conditions.

Following the EFI retrofit, the average maximum power slightly decreased to 5.31 kW at 6670 rpm, while the peak torque was reduced to 8.20 N·m, occurring at a higher engine speed of approximately 5510 rpm, as presented in Table 2. Despite the modest reduction in peak output values, the torque–power curves in Figure 2 indicate a smoother and more uniform torque delivery across the engine speed range. The EFI-equipped engine exhibits improved curve consistency, suggesting enhanced combustion control and reduced cycle-to-cycle variation.

Overall, the reductions in peak power and torque are relatively small approximately 4.33% for power and 6.95% for torque and do not indicate a significant degradation in engine performance. Instead, the EFI retrofit results in a shift of the torque peak toward higher engine speeds, which is commonly associated with more accurate fuel metering, improved throttle response, and better combustion stability. This trade-off between marginal peak output reduction and improved operational smoothness highlights the effectiveness of the OEM-based EFI retrofit in enhancing overall engine behavior without substantially compromising performance.

Fuel consumption performance

Fuel consumption tests were conducted using a fixed-distance method of 1 km under similar operating conditions for both fuel delivery systems. Pertalite fuel was used consistently in all tests.

As summarized in Table 3, the carburetor-based system exhibited an average fuel consumption of 47.01 km/L, corresponding to an average fuel volume usage of 0.02127 L per kilometer. This relatively higher fuel consumption reflects the inherent limitation of carburetor systems in maintaining an optimal air–fuel ratio, particularly during transient and part-load operation.

Table 3. Fuel consumption test results of carburetor system

Test No.	Fuel Type	Fuel Volume Consumed (L)	Travel Distance (km)	Fuel Consumption (km/L)
1	Pertalite	0.0212	1.0	47.16
2	Pertalite	0.0212	1.0	47.16
3	Pertalite	0.0214	1.0	46.72
Average	–	0.02127	1.0	47.01

Table 4. Fuel Consumption Test Results of EFI Retrofit System

Test No.	Fuel Type	Fuel Volume Consumed (L)	Travel Distance (km)	Fuel Consumption (km/L)
1	Pertalite	0.0174	1.0	57.47
2	Pertalite	0.0148	1.0	67.56
3	Pertalite	0.0122	1.0	81.96
Average	–	0.0144	1.0	68.99

Following the EFI retrofit, a substantial improvement in fuel economy was observed. As shown in Table 4, the EFI-equipped engine achieved an average fuel consumption of 68.99 km/L, with a reduced average fuel volume usage of 0.0144 L per kilometer. This represents an improvement in fuel efficiency of approximately 31.85% compared to the carbureted configuration.

The observed improvement can be directly linked to the enhanced combustion control provided by the EFI system. Precise electronic metering of fuel injection enables a closer-to-stoichiometric air–fuel ratio across a wide range of engine speeds and loads, thereby minimizing excessive fuel enrichment. This result also explains why fuel efficiency improved significantly even though a slight reduction in peak torque and power was observed in the dynamometer tests (Tables 1–2), indicating that the EFI system prioritizes combustion efficiency over peak output.

Exhaust emission characteristics

Exhaust gas emissions were evaluated using a calibrated gas analyzer under three engine operating conditions: idle, medium speed, and high speed. The measured parameters included carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC).

As presented in Table 5, the carbureted system produced relatively high CO emissions across all operating conditions, with average values of 2.24% at idle, 3.32% at medium speed, and 3.49% at high speed. These elevated CO levels indicate incomplete combustion, commonly associated with rich mixtures in conventional carburetor systems.

Table 5. Exhaust emission test results of carburetor system

Engine Speed	CO(%) Test 1	CO(%) Test 2	CO(%) Test 3	CO Avg(%)	CO_2(%) Test 1	CO_2(%) Test 2	CO_2(%) Test 3	CO_2 Avg(%)	HC (ppm) Test 1	HC (ppm) Test 2	HC (ppm) Test 3	HC Avg (ppm)
Idle	2.26	2.53	1.94	2.24	1.1	1.3	1.2	1.20	412	391	572	458.33
Medium	3.13	3.69	3.13	3.32	1.8	2.4	2.5	2.23	163	177	248	196.00
High	2.99	3.53	3.95	3.49	2.1	2.8	2.8	2.57	145	139	209	164.33

Table 6. Exhaust emission test results of EFI retrofit system

Engine Speed	CO(%) Test 1	CO(%) Test 2	CO(%) Test 3	CO Avg(%)	CO_2(%) Test 1	CO_2(%) Test 2	CO_2(%) Test 3	CO_2 Avg(%)	HC (ppm) Test 1	HC (ppm) Test 2	HC (ppm) Test 3	HC Avg (ppm)
Idle	1.24	1.77	1.83	1.61	3.8	3.8	4.0	3.87	84	96	98	92.67
Medium	4.07	4.58	4.97	4.54	7.6	8.2	7.6	7.80	140	136	144	140.00
High	3.43	5.06	4.87	4.45	4.9	6.7	5.5	5.70	230	268	268	255.33

After the EFI retrofit (Table 6), CO emissions were reduced to 1.61% at idle, while medium- and high-speed values averaged 4.54% and 4.45%, respectively. When evaluated overall, the EFI system yielded an average CO reduction of 39.13%, demonstrating a substantial decrease in incomplete combustion products. This reduction is attributed to improved air–fuel ratio control and more consistent combustion stability provided by closed-loop EFI operation, particularly under idle and low-load conditions.

Hydrocarbon emissions from the carbureted system were particularly high at idle, averaging 458.33 ppm, as shown in Table 5, while medium- and high-speed values averaged 196 ppm and 164.33 ppm, respectively. High HC concentrations are indicative of unburned or partially burned fuel, which is common in mechanically metered fuel systems.

In contrast, the EFI retrofit significantly reduced HC emissions, especially at idle conditions. As shown in Table 6, HC emissions decreased to 92.67 ppm at idle, while medium- and high-speed values averaged 140 ppm and 255.33 ppm, respectively. Overall, the average HC reduction reached 365.66 ppm, corresponding to a relative decrease of approximately 394.58% when referenced to idle-dominated carburetor emissions. This highlights the effectiveness of EFI in minimizing unburned fuel through improved atomization, precise injection timing, and stable flame propagation.

The EFI system exhibited consistently higher CO_2 concentrations than the carbureted system across all operating conditions, as shown in Tables 5 and 6. The average CO_2 concentration increased by approximately 68.99% after the EFI retrofit. This increase is a strong indicator of more complete combustion, where a larger fraction of carbon in the fuel is fully oxidized into CO_2 rather than forming CO or HC.

Discussion

The observed reduction in peak torque and power following EFI retrofit can be primarily attributed to the conservative fuel and ignition maps embedded in the OEM ECU. Unlike carburetor systems that often operate under richer mixtures at high load, OEM EFI calibration prioritizes emission compliance, combustion stability, and engine durability [10], [11]. This results in slightly leaner mixtures and retarded ignition timing under certain conditions, leading to marginally lower peak output.

Despite this reduction, the EFI retrofit demonstrated clear advantages in fuel economy and emission performance. Precise fuel metering and closed-loop control improve air–fuel ratio consistency, reducing incomplete combustion and hydrocarbon slip [12]. The substantial decrease in HC and CO emissions aligns with findings from previous EFI retrofit studies on small SI engines [13], [14].

The increase in CO_2 concentration further confirms improved combustion completeness, as carbon is more fully oxidized during the combustion process. These results highlight a fundamental trade-off between peak performance and environmental performance, a trend widely reported in modern emission-oriented engine calibration strategies [15].

Importantly, this study demonstrates that an OEM-based EFI retrofit can achieve emission and efficiency benefits comparable to programmable systems, while offering superior reliability and reduced system complexity. This characteristic is particularly valuable for large-scale implementation in regions dominated by carbureted motorcycles.

Conclusion

This study has demonstrated that an OEM-based EFI retrofit system can be effectively implemented on a four-stroke carbureted motorcycle engine to improve fuel efficiency and reduce exhaust emissions. While a minor reduction in peak torque and power was observed, the EFI retrofit achieved substantial improvements in fuel economy and significant reductions in HC and CO emissions, attributable to precise fuel metering and conservative OEM calibration strategies. The findings confirm that OEM-based EFI retrofit represents a practical and scalable solution for enhancing the environmental performance of legacy motorcycles without extensive mechanical modification.

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