

# Research on the Design and Fabrication of an Electronic Fuel Injection System Model for Automotive Training Applications

Nguyen Trong Quynh, Do Huy Tung

**Abstract**— Electronic Fuel Injection (EFI) systems are currently widely applied in modern automobiles to improve engine performance, reduce fuel consumption, and satisfy increasingly stringent emission standards. However, in automotive engineering education, the teaching and practical training of EFI systems still face many difficulties due to the lack of visual models for practical study and diagnostics. This paper presents the research, design, and fabrication process of an electronic fuel injection system model for training purposes. The research methodology was conducted through theoretical analysis of the EFI system, design of the control model, and experimental testing on the fabricated model. The results show that the model operates stably and is capable of simulating basic engine operating conditions such as idling, medium load, and full load. In addition, the model allows direct observation of control signals and the fuel injection process. The model has scientific and practical significance in education, practical training, and research on modern automotive engine control systems.

**Index Terms**— EFI, ECU, training model, electronic fuel injection, engine control, automotive engineering.

## I. INTRODUCTION

In recent years, the global automotive industry has developed rapidly toward the electronicization and intelligentization of control systems in order to improve energy efficiency, enhance vehicle performance, and reduce environmental pollution. Among these systems, the engine control system plays a particularly important role because it directly determines the air–fuel mixture formation process, combustion efficiency, and emission levels of internal combustion engines. Compared with conventional carburetor-based fuel supply systems, the Electronic Fuel Injection (EFI) system enables precise control of the fuel quantity injected into the engine based on signals from sensors and the electronic control unit (ECU). Owing to its real-time control capability, the EFI system helps maintain the optimum air–fuel ratio under various operating conditions, thereby improving engine power, reducing fuel consumption, and enhancing dynamic load response [1].

In addition to performance requirements, increasingly stringent emission regulations such as Euro 4, Euro 5, and the trend toward Euro 6 standards have promoted the widespread

application of EFI systems in most modern automobiles. According to research by Robert Bosch GmbH [2], EFI systems can accurately control fuel injection timing and quantity, significantly reducing the concentration of harmful emissions such as CO, HC, and NO<sub>x</sub>. Furthermore, the integration of EFI systems with oxygen sensors and three-way catalytic converters enables the engine to maintain the excess air coefficient near the ideal value, thereby improving exhaust gas treatment efficiency and satisfying current environmental standards [3]. In addition, the development of electronic control technologies such as electronic throttle control, intelligent ignition control, and OBD-II diagnostic systems has made the structure and control algorithms of EFI systems increasingly complex, requiring automotive engineering personnel to possess advanced knowledge of electrical–electronic systems and engine control technologies.

However, practical training on EFI systems at many automotive engineering training institutions still faces several limitations. Teaching contents mainly focus on structural theory and operating principles, while direct practice on actual systems remains limited due to high equipment costs and operational safety requirements. Most existing training models are only capable of illustrating structural configurations or basic schematic diagrams and cannot adequately demonstrate signal processing and ECU control algorithms under different engine operating conditions. Consequently, students encounter significant difficulties in understanding the relationship between sensor signals, engine load conditions, and the corresponding injected fuel quantity. In addition, the capability for practical diagnosis of EFI system faults through sensor signals and ECU control data remains limited, resulting in ineffective access to modern engine control technologies [4].

In recent years, many domestic and international studies have focused on developing training models for EFI systems. Some commercial models are capable of relatively comprehensive simulation of sensor signals and injector operation; however, they involve high investment costs and closed architectures that make in-depth research on control algorithms difficult [5]. In Vietnam, several studies have initially developed EFI training models for automotive engineering education; however, most of them mainly focus on structural simulation or basic electrical circuit connections and have not fully integrated hardware systems, signal simulation, and ECU control algorithms under actual engine operating conditions [6]. Therefore, there remains a research gap in developing an EFI model capable of synchronously integrating hardware systems, electronic control, sensor signal simulation, and system diagnostic training for

**Manuscript received May 19, 2026**

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educational purposes.

Based on the practical requirements mentioned above, this paper focuses on the research, design, and fabrication of an electronic fuel injection system model for automotive engineering training. The research contents include hardware model development, design of control algorithms for EFI system operation simulation, and evaluation of the model performance under idling, medium-load, and full-load conditions. The research results contribute to improving practical training effectiveness, supporting students in gaining intuitive access to modern engine control systems, and providing a foundation for further studies on automotive diagnostics and electronic control technologies.

## II. THEORETICAL BASIS OF THE EFI SYSTEM

### 2.1. Structure of the Electronic Fuel Injection System

The Electronic Fuel Injection (EFI) system is a fuel supply control system for engines that delivers fuel through a controlled injection process managed by an electronic control unit (ECU). Compared with conventional carburetor systems, EFI enables precise control of the fuel quantity supplied according to engine operating conditions, thereby improving combustion efficiency, reducing fuel consumption, and minimizing harmful emissions [1]. A typical EFI system consists of major components such as the ECU, fuel injectors, input sensors, fuel pump, and electronic throttle control mechanism.

In the EFI system, the Electronic Control Unit (ECU) serves as the central processing and control unit. The ECU receives electrical signals from sensors mounted on the engine, processes the data according to pre-programmed algorithms, and generates appropriate control signals for the fuel injectors and other actuators [2]. The real-time processing capability of the ECU enables the system to respond rapidly to variations in engine load and speed.

The fuel injector is an important actuator of the EFI system. The injector operates based on the electromagnetic principle, in which the ECU controls the injector valve opening duration to determine the amount of fuel delivered into the intake manifold or combustion chamber. The longer the injector opening duration, the greater the injected fuel quantity [3].

To enable the ECU to accurately calculate the required fuel quantity, the EFI system employs various types of sensors. The Crankshaft Position Sensor (CKP) provides information on engine speed and crankshaft angular position in order to determine fuel injection and ignition timing. The Camshaft Position Sensor (CMP) helps the ECU identify the engine operating cycle for synchronizing the sequential fuel injection process [4].

The Throttle Position Sensor (TPS) is used to determine the throttle opening angle, thereby reflecting the driver's load demand. The Manifold Absolute Pressure (MAP) sensor or Mass Air Flow (MAF) sensor is used to determine the amount of air entering the engine. Meanwhile, the Engine Coolant Temperature (ECT) sensor enables the ECU to adjust fuel quantity during cold-start conditions or low engine temperatures. In addition, the Oxygen Sensor installed

in the exhaust system measures the residual oxygen content in exhaust gases to support closed-loop air–fuel ratio control [5].

The electric fuel pump is responsible for generating stable fuel pressure supplied to the injectors. Fuel pressure is maintained through a pressure regulator to ensure accurate fuel delivery under different operating conditions. Furthermore, in modern engines, the EFI system is often integrated with an Electronic Throttle Control (ETC) system, allowing the ECU to regulate intake airflow according to an optimal control strategy [6].

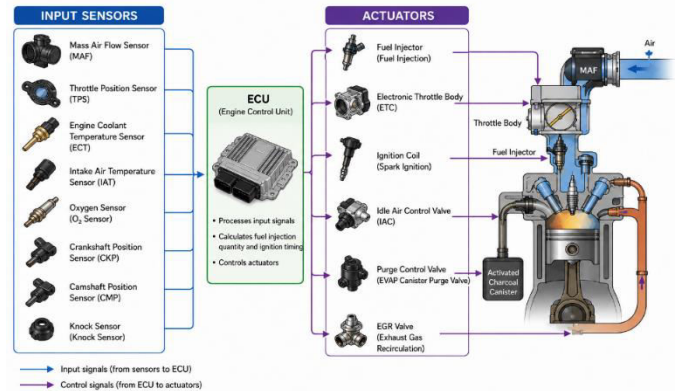


Figure 1. General diagram of the EFI system.

### 2.2. Fuel Injection Control Principle

The fundamental operating principle of the EFI system is based on the ECU receiving signals from sensors to determine the engine operating condition, and then calculating the required fuel quantity corresponding to each operating mode [7]. During operation, the ECU continuously receives signals from sensors such as TPS, MAP/MAF, CKP, CMP, ECT and the oxygen sensor in order to determine engine load, rotational speed, operating temperature, and exhaust gas composition.

Based on these input signals, the ECU calculates the injector opening duration according to a pre-programmed control algorithm. The fuel injection duration can be expressed as a function dependent on engine operating parameters:

$$t_{inj} = f(\text{TPS}, \text{MAP}, \text{CKP}, \text{ECT}, \lambda)$$

Where:

- $t_{inj}$ : fuel injection duration;
- TPS: throttle position signal;
- MAP: intake manifold pressure;
- CKP: engine speed;
- ECT: engine temperature;
- $\lambda$ : excess air coefficient.

When the engine load increases, the ECU increases the injector opening duration to provide a greater amount of fuel. Conversely, when the engine operates under idling or deceleration conditions, the fuel quantity is correspondingly reduced to save fuel and reduce emissions [8]. In addition, the ECU performs correction algorithms based on engine temperature, ambient pressure, and feedback signals from the oxygen sensor to maintain the air–fuel ratio near the ideal value.

### 2.3. Control Strategies in EFI Systems

One of the most important control strategies of the EFI system is closed-loop control based on oxygen sensor

feedback. In this mode, the ECU uses feedback signals from the oxygen sensor to adjust the injected fuel quantity in order to maintain the optimum air–fuel ratio, typically close to the stoichiometric ratio ( $\lambda \approx 1$ ), thereby improving combustion efficiency and reducing harmful emissions [9].

During acceleration, the intake airflow increases rapidly, causing the air–fuel mixture to become lean. To compensate for this phenomenon, the ECU implements an acceleration enrichment strategy by temporarily increasing the fuel injection duration to ensure adequate engine load response [10]. Conversely, during deceleration or sudden throttle release, the ECU may activate a fuel cut-off mode to reduce fuel consumption and minimize emissions.

Under cold-start conditions, because fuel vaporization is difficult at low temperatures, the ECU increases the injected fuel quantity to improve engine starting capability. After the engine reaches stable operating temperature, the fuel quantity is adjusted back to normal operating conditions [11].

In addition, modern EFI systems are integrated with a fail-safe mode. When certain sensors malfunction or lose signal, the ECU uses pre-programmed substitute data to temporarily maintain engine operation while simultaneously storing fault codes for diagnostic and repair purposes [12].

#### 2.4. Educational Significance of the EFI Model

In automotive engineering education, the EFI system model plays an important role in improving the effectiveness of practical teaching and research on engine control systems. Through the model, students can directly observe control signals from the ECU to the fuel injectors and input sensors, thereby gaining a clear understanding of the operating principles of modern EFI systems.

Furthermore, the EFI model supports practical sensor measurement using specialized equipment such as VOM meters, oscilloscopes, or OBD diagnostic tools. Students can analyze the relationship between sensor signals and fuel injection quantity under different engine operating conditions [13].

In addition to its basic educational function, the model also supports ECU fault diagnosis practice, electrical circuit inspection, and simulation of common failures in EFI systems. This helps improve students' analytical skills, diagnostic thinking, and ability to approach modern engine control technologies in automotive engineering.

### III. DESIGN AND FABRICATION OF THE EFI MODEL

#### 3.1. Model Design Requirements

The electronic fuel injection system model for training purposes must be designed to simultaneously satisfy both technical and pedagogical requirements in order to accurately simulate the operating principles of EFI systems used in modern automobiles. First, the model must operate stably, and the control signals from the ECU to the injectors and sensors must maintain high accuracy and provide reliable responses under various engine operating conditions.

In addition, the model should fully reproduce the actual control principles through the integration of important

sensors such as CKP, CMP, TPS, MAP/MAF, and oxygen sensors. This enables learners to clearly understand the processes of signal acquisition, data processing, and fuel injection control performed by the ECU.

Besides technical requirements, the model should possess a visual and intuitive structure that facilitates observation, measurement, and diagnostic practice. Component assemblies, electrical circuit diagrams, and sensor connection positions must be arranged appropriately to effectively support teaching activities. At the same time, the system must ensure electrical safety through suitable insulation and overload protection solutions.

#### 3.2. Development of the Electronic Fuel Injection System Control Diagram

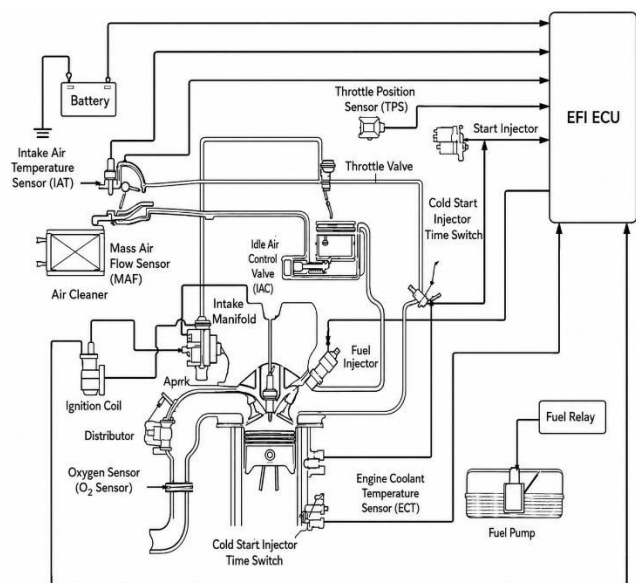


Figure 2. EFI system diagram

Figure 2 presents the general schematic of the Electronic Fuel Injection (EFI) system used in modern gasoline engines. In this system, the ECU acts as the central control unit, receiving and processing signals from sensors such as the intake air flow sensor, throttle position sensor, intake air temperature sensor, engine coolant temperature sensor, and exhaust oxygen sensor. Based on these input signals, the ECU calculates the appropriate fuel quantity and controls the injector opening duration in order to maintain the optimum air–fuel ratio under each engine operating condition. The fuel supply system consists of an electric fuel pump, control relay, and fuel injectors, which are responsible for maintaining fuel pressure and delivering fuel to the engine. In addition, the system integrates supporting components such as the ignition system, spark plugs, and cold-start injector to improve engine starting capability and stabilize the combustion process.

#### 3.3. Experimental Evaluation of Fuel Injection Control Modes

To evaluate the operating capability of the electronic fuel injection control model, the system was tested in Proteus software under three representative operating conditions: idling, medium load, and full load. The parameters displayed on the LCD include throttle opening angle, crankshaft angle, camshaft angle, and intake air temperature.

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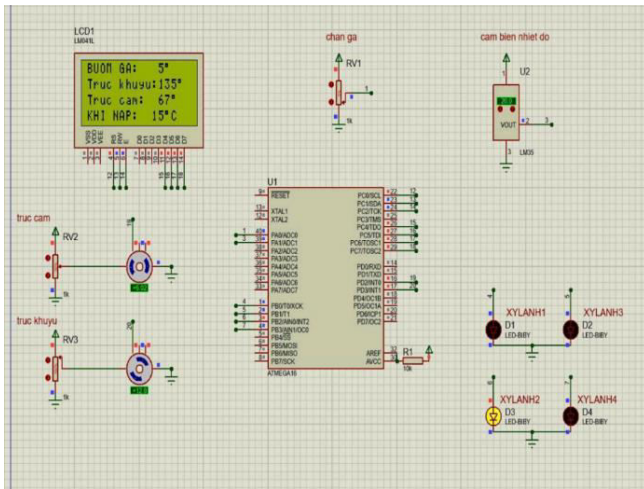


Figure 3. No-load mode

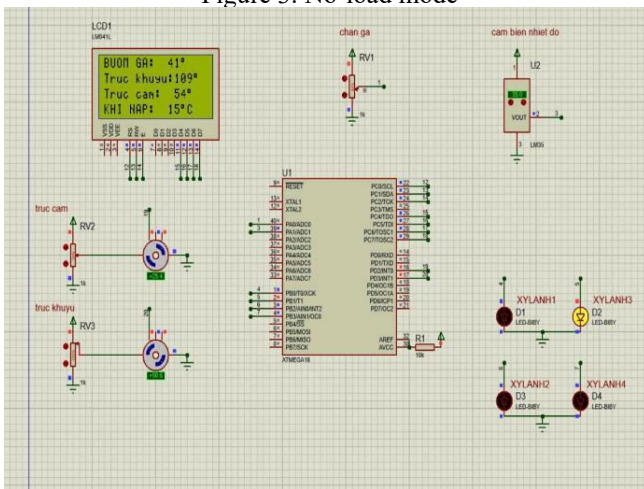


Figure 4. Medium-load mode

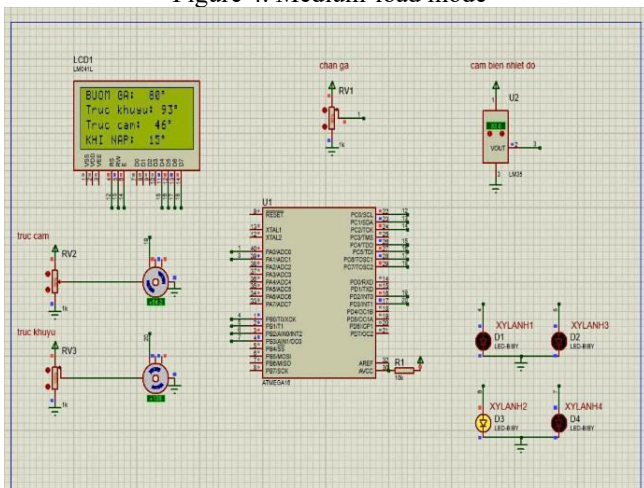


Figure 5. Full-load operating mode

## Idling Mode

- Throttle opening angle: 5°
- Crankshaft angle: 135°
- Camshaft angle: 67°
- Temperature: 15°C

Under this operating condition, the throttle valve is opened only slightly, and the intake airflow into the engine remains at a minimum level. The ECU controls a small fuel injection quantity in order to maintain stable engine operation.

Relationship between camshaft and crankshaft angles:

$$\theta_{cam} \approx \frac{\theta_{ck}}{2} = 67^\circ$$

The model accurately reflects the operating principle of a four-stroke engine and ensures signal synchronization.

## Medium-load Mode

- Throttle opening angle: 41°
- Crankshaft angle: 109°
- Camshaft angle: 54°
- Temperature: 15°C

As the throttle opening angle increases, the intake airflow also increases; consequently, the ECU increases the fuel injection quantity to meet the load demand. This represents the most common operating region of the engine.

- Relationship between camshaft and crankshaft angles:

$$54^\circ \approx \frac{109^\circ}{2}$$

The system continues to maintain an accurate relationship between CKP and CMP signals.

In addition, the sequential change in the LED states of the cylinders indicates that:

- The system successfully synchronizes the control signals.
- The injection process is activated in the correct sequence.

## Full-load Mode

- Throttle opening angle: 80°
- Crankshaft angle: 93°
- Camshaft angle: 46°
- Temperature: 15°C

Under this operating condition, the throttle valve is opened widely, causing the intake airflow to approach its maximum level. Consequently, the ECU increases the fuel injection quantity to generate higher engine power.

- Relationship between camshaft and crankshaft angles:

$$46^\circ \approx \frac{93^\circ}{2}$$

The model continues to maintain the correct mechanical characteristics of the engine.

Note: the reduction in crankshaft angle compared with the previous mode is due to this value representing an instantaneous angular position at the testing moment rather than engine speed (RPM).

## 3.4. Fabrication and Integration of the Model

### Selection of Components

The selection of components for the electronic fuel injection system model must be based on several fundamental criteria, including suitability for educational objectives, representativeness of actual systems, market availability, ease of installation, ease of maintenance, and reasonable cost. In addition, the components must be compatible with one another in terms of operating voltage, signal characteristics, and control methods.


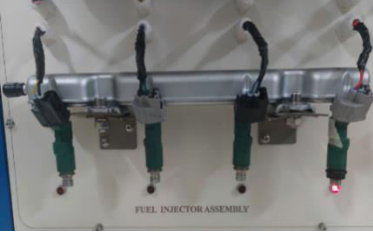



In this model, the selected components focus on three main groups: the central control unit, input sensors, and fuel

injectors. These are the core components that determine the capability of reproducing the operating principles of the electronic fuel injection system.



visualization for teaching purposes. The components should be capable of displaying signals or allowing easy measurement using instruments such as multimeters or oscilloscopes, thereby enabling students to observe signal variations under different engine operating conditions

Furthermore, during the component selection process, special attention should be given to simulation capability and

Table 1. Assembly of components

Steps	Element	Description
Installation of the ECU control unit		The ECU control unit is responsible for controlling the operating process of the system and is susceptible to damage under impact conditions. Therefore, during the installation of the four mounting bolts, careful handling is required to ensure adequate clearance between the ECU unit and the mounting bracket, as well as to facilitate convenient connection of the three wiring harness connectors to the ECU terminals.
Installation of the fuel injector rail		Fuel injector: The fuel injector delivers fuel into the combustion chamber according to the control signals from the ECU. The injector is controlled based on injection duration and injection frequency. The fuel injection assembly is securely mounted to the lower corners of the frame using four M6 bolts. In addition, LED indicators are integrated to represent the fuel injection quantity supplied to the engine under different operating conditions.
Installation of the throttle body assembly		A real TPS sensor or a linear potentiometer may be used. This signal reflects the engine load demand and is highly convenient for manual operation on the training model. The throttle body assembly is mounted on the frame structure and must be firmly secured while allowing clear observation of its operating condition during operation. Four M6 bolts are used for mounting to ensure structural rigidity, and sufficient space must be provided around the connector area to facilitate electrical connection.
Installation of the intake air flow sensor		Mass Air Flow (MAF) sensor: The MAF sensor measures the amount of air entering the engine and transmits this information to the ECU, thereby enabling accurate adjustment of the injected fuel quantity. The intake air flow sensor is installed at the center of the frame structure and must be securely mounted. Four M6 bolts are used to ensure rigid attachment to the bracket, while sufficient space must be provided around the connector area to facilitate electrical connection.
Installation of the fuel pump		Fuel pump: The fuel pump supplies fuel to the system at a stable pressure, ensuring sufficient fuel delivery to the injectors. The fuel pump is securely mounted on the frame using a retaining clamp. Its function is to deliver fuel from the fuel tank to the engine and generate the required pressure for the fuel injection system.

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Installation of the oxygen sensor		<p>Oxygen (O<sub>2</sub>) sensor: This sensor is used to regulate the air–fuel ratio (AFR) by measuring the oxygen content in the exhaust gases and transmitting feedback signals to the ECU for fuel quantity adjustment.</p> <p>The oxygen sensor is securely mounted using two M6 bolts, and sufficient space is provided around the connector area to facilitate electrical connection.</p>
VVT-i sensor installation		<p>The VVT-i sensor provides camshaft position information to the ECU. The ECU uses this information to control the intake valve opening and closing timing, thereby optimizing engine performance, improving fuel economy, and reducing exhaust emissions.</p> <p>The VVT-i sensor is securely mounted to the bracket using two M6 bolts, and sufficient space is provided around the connector area to facilitate electrical connection.</p>

### IV. CONCLUSION

#### *Completed Model*

The components of the fuel injection system, after being installed and integrated with the ignition system, form the completed model as shown in the following figure:



Figure 6. Complete model

This paper presented the research, design, and fabrication process of an Electronic Fuel Injection (EFI) system model for automotive engineering training. Based on the analysis of the operating principles of actual EFI systems, the model was developed with all essential components, including the ECU, fuel injectors, sensors, and fuel supply system, thereby ensuring the capability to accurately simulate the control principles of electronic fuel injection engines.

Experimental results show that the model operates stably under idling, medium-load, and full-load conditions. Input signals such as throttle opening angle, crankshaft position signal, and engine temperature are accurately processed by the ECU to control the fuel injection duration in accordance with the engine load condition. The synchronization relationship between crankshaft and camshaft signals is consistently maintained in accordance with the operating principle of a four-stroke engine, while the injector control signals operate sequentially and stably.

In addition, the model enables visualization of the EFI control process, supports practical sensor measurement, control signal analysis, and investigation of fuel injection strategies under different operating conditions. The system possesses a compact structure, is easy to operate, has low fabrication cost, and is suitable for practical training conditions at automotive engineering training institutions.

However, the current model still has several limitations, including the absence of an OBD diagnostic system, lack of integration with an actual engine, and incomplete implementation of closed-loop control strategies based on

oxygen sensor feedback. In future studies, the model may be further developed by integrating electronic ignition control, adding OBD-II diagnostic communication, and developing a control system based on modern microcontrollers in order to enhance the simulation capability and practical applicability of the model.

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