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Engineering Design and Performance Validation of a Low-Cost Diesel Common Rail Injector Test Bench

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ABSTRACT

High-pressure common rail (HPCR) systems are essential in modern diesel engines to meet performance and emissions requirements. However, commercial injector test benches remain costly for vocational laboratories and small-scale workshops. This study designs, develops, and preliminarily validates a low-cost diesel common rail injector test bench using the ADDIE (analysis, design, development, implementation, and evaluation) framework. The system integrates a repurposed Chevrolet Captiva high-pressure supply pump driven by a 1 hp AC motor, a high-pressure fuel circuit, and an Arduino Nano-based electronic control unit (ECU) that applies pulse-width modulation (PWM) to control pulsed injector actuation. Validation was performed using a Denso Hino RN285 injector at low, medium, and high operating stages. The bench generated rail pressures from 360 bar (36 MPa) to 850 bar (85 MPa) and delivered 18.0 to 39.0 mL of fuel over a 20 s collection window. The measured delivery volume at low and medium speeds remained within the manufacturer’s tolerance after interpolation to the actual measured rpm. In contrast, a delivery deficit was observed at the highest speed. Quantitative spray-image analysis yielded spray angles of 15.38-20.44 degrees, within the specified range. The results indicate that the developed bench is a functional laboratory-scale platform for injector diagnostics and vocational training, although further benchmarking against calibrated commercial equipment and long-term durability testing are still required.

1. Introduction

The global automotive industry has increasingly adopted high-pressure common rail (HPCR) fuel injection systems to comply with stringent emission regulations such as Euro IV and Euro VI while maintaining engine performance and fuel efficiency. The HPCR system enables independent control of injection timing and injection pressure, allowing electronically actuated injectors to deliver fuel pressures exceeding 100 MPa with high precision. Accurate injector operation significantly affects fuel atomization quality, combustion stability, fuel consumption, and exhaust emissions, particularly nitrogen oxides (NOx) and particulate matter (PM) [1], [2].

In the HPCR system, the injector is the primary component that regulates fuel delivery and spray formation. Variations in injector performance due to nozzle wear, internal leakage, solenoid degradation, or flow instability may lead to poor atomization, incomplete combustion, reduced power, and increased exhaust opacity [3], [4]. Previous studies have demonstrated that even small deviations in injection rate and spray distribution can substantially affect combustion behavior and engine efficiency [5]. Therefore, periodic injector diagnostics and performance validation are essential to ensure reliable engine operation and compliance with emissions standards.

Commercial common-rail injector test benches manufactured by companies such as Bosch, Delphi, and Denso can provide highly accurate diagnostic measurements under controlled operating conditions. These systems generally include high-pressure regulation, programmable injection control, and quantitative fuel measurement features [6]. However, the acquisition and maintenance costs of such industrial-grade equipment remain prohibitively expensive for vocational education laboratories, small-scale workshops, and academic research facilities. In addition, several existing systems require proprietary software and specialized calibration procedures, limiting their accessibility for educational and low-cost research purposes [7].

Several studies have investigated common rail injector testing, spray characterization, and injection rate validation under various operating conditions [5], [8], [9]. Other studies have explored simulation-based injector validation and pressure-response modeling to improve injection accuracy and fuel delivery prediction [2], [10]. Nevertheless, limited research has focused on developing an integrated, low-cost injector test bench capable of performing repeatable experimental evaluations using repurposed automotive components while maintaining sufficient diagnostic functionality for educational and laboratory-scale applications. In particular, the development of compact testing equipment with controllable injector actuation, stable pressure generation, and quantitative spray analysis capability remains an important engineering challenge.

To address this issue, this study proposes the development of a diesel common-rail injector test bench using a repurposed Chevrolet Captiva high-pressure supply pump integrated with an Arduino Nano-based electronic control system. The developed platform combines a high-pressure fuel delivery circuit, AC motor-driven pump actuation, pulse-width modulation (PWM)-based injector control, and spray visualization capability within a compact experimental setup. Unlike commercial systems with high operational costs, the proposed equipment is intended to provide an accessible, repeatable injector-testing platform suitable for educational, diagnostic, and laboratory-scale applications.

The objective of this research is to design, develop, and experimentally validate a diesel common rail injector test bench capable of evaluating fuel delivery characteristics and spray atomization behavior under varying operating conditions. System validation was conducted using a Hino RN285 injector by analyzing fuel delivery volume and spray angle characteristics across different rotational speeds. The obtained results were subsequently evaluated to determine the operational reliability and diagnostic capability of the developed testing equipment.

2. Methodology

2.1 System Architecture and Design Framework

The development of the diesel common rail injector test bench was conducted through sequential stages of analysis, design, fabrication, implementation, and performance evaluation to ensure the functional reliability and engineering feasibility of the developed system. The proposed platform was designed to simulate the high-pressure hydraulic environment of a diesel common rail injection system by integrating a mechanical drive unit, a high-pressure fuel delivery circuit, and an electronically controlled injector actuation module. Such integration is essential for maintaining stable injection characteristics and repeatable injector operation under varying testing conditions [1], [2].

The structural frame of the test bench was constructed using 30 mm × 30 mm × 1 mm hollow steel sections with overall dimensions of 80 cm × 50 cm × 110 cm, as shown in **Fig. 1**. The rigid frame configuration was intended to minimize excessive vibration generated by the rotating motor and high-pressure pump during operation. In addition, the compact structural arrangement was designed to simplify maintenance procedures and facilitate laboratory-scale experimental testing.

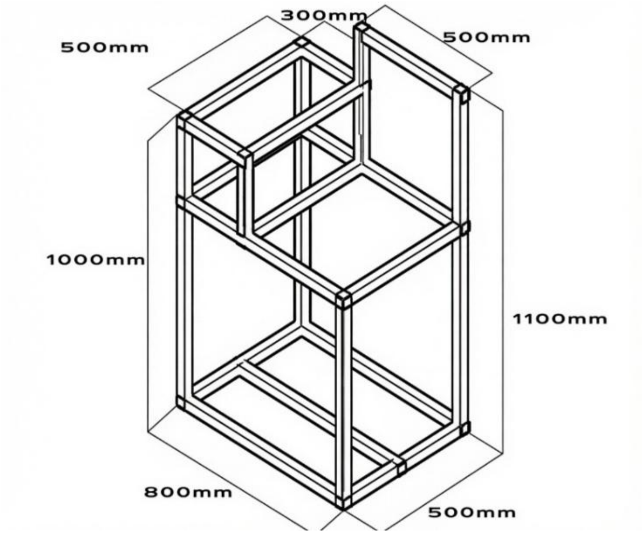

Figure 1. Frame dimensions of the test bench

2.2 Mechanical and Hydraulic Configuration

The configuration of a diesel common rail injector test bench is shown in Fig. 2. The high-pressure fuel generation system used a repurposed Chevrolet Captiva FL C140 supply pump with a radial three-piston configuration arranged at 120° intervals. This type of pump architecture is widely used in common rail systems due to its ability to deliver stable, high-pressure fuel flow under continuous operation [3]. The supply pump was driven by a 1-HP AC electric motor operating at 220 V and 50–60 Hz with a maximum rotational speed of 1,472 RPM. Power transmission from the electric motor to the supply pump was achieved using an aluminum pulley and V-belt system with a 1:1 transmission ratio to maintain rotational synchronization between the drive motor and the pump assembly.

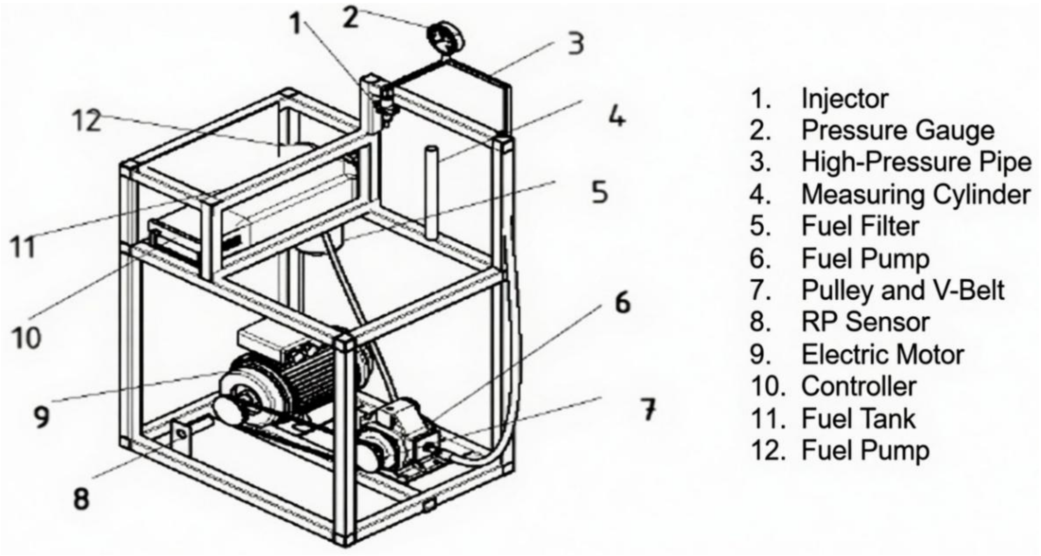

Figure 2. The configuration of a diesel common rail injector test bench

The fuel delivery system consisted of low-pressure and high-pressure circuits. On the low-pressure side, fuel was supplied from a 5-liter reservoir via a Denso 12 V electric fuel pump, then filtered through a Yanmar TF 85 fuel filter before entering the supply pump. The high-pressure circuit employed ASTM A312 stainless steel tubing with an outer diameter of 6 mm and an inner diameter of 2 mm to withstand pressures exceeding 1,000 bar during injector testing. High-pressure-resistant piping is essential in common rail experimental systems to ensure pressure stability and operational safety under cyclic injection loading [4]. An analog pressure gauge with a 0–1,000 bar measurement range was integrated into the rail line to monitor pressure fluctuations during operation.

For safe operation at pressures up to 850 bar (85 MPa), the high-pressure section was assembled with metal-to-metal sealing, copper crush washers, and mechanically supported pipe routing to reduce vibration-induced leakage. Before injector testing, the system was leak-checked at low pressure and then progressively pressurized. During operation, the operator remained outside the direct spray direction, the injector area was shielded from hand contact, and the line was depressurized before loosening any fitting. These precautions were implemented because high-pressure diesel spray can penetrate skin and because small leaks can rapidly destabilize rail pressure.

2.3 Electronic Control System

Injector actuation and testing parameters were controlled using an Arduino Nano-based electronic control system. The controller regulated injection duration and pump operating conditions via Pulse Width Modulation (PWM), which is widely used in electronically controlled injector systems due to its ability to provide stable, adjustable injector pulse characteristics [5].

The electronic system was powered by a Switch Mode Power Supply (SMPS) delivering a stabilized 12 V DC output with a maximum current capacity of 25 A. Injector triggering was performed using IRFZ44N MOSFET drivers to accommodate the high-current requirements of the injector solenoid during repeated actuation cycles. To monitor rotational speed, a Hall-effect proximity sensor was installed near the motor pulley to provide real-time RPM feedback to the microcontroller. The measured rotational speed was subsequently displayed on a 16 × 2 LCD interface. At the same time, push-button controls were used to adjust the injector activation duration from 1 to 60 s. The integration of electronically controlled injector triggering and RPM monitoring enabled the developed system to simulate variable operating conditions during injector testing while maintaining repeatable testing sequences.

2.4 Experimental Validation Procedures

Experimental validation was conducted using a Denso Hino RN285 common-rail injector equipped with a six-hole nozzle and an opening pressure of approximately 362 bar (36.2 MPa). The validation procedure focused on pressure generation, fuel delivery measurement, and spray pattern analysis. Tests were conducted under laboratory ambient conditions using automotive diesel fuel. The reported values are expressed as mean ± standard deviation from three repeated measurements (n = 3). The uncertainty discussion considers the pressure-gauge reading, the 100 mL graduated cylinder resolution (±1 mL), and spray-image measurement repeatability.

The pressure generation capability was evaluated at three target operating stages: low, medium, and high pump speed. The actual stabilized rotational speeds recorded during pressure testing were 538, 826, and 1,472 rpm. The pressure values are reported primarily in bar because this is the unit used on the installed gauge and in common workshop diagnostics; MPa conversions are provided where helpful, using 1 bar = 0.1 MPa. Stable pressure generation was considered a critical parameter because pressure fluctuation significantly influences injection consistency and spray characteristics [6].

Fuel delivery measurements were performed by collecting injected fuel over a fixed 20 s test window. The collected fuel volume was measured using a 100 mL graduated glass cylinder with an accuracy of ±1 mL. The fuel-delivery tests were conducted separately from the pressure-only test; therefore, the actual stabilized rpm values differed slightly because of hydraulic loading and speed stabilization. The actual rpm values were 565, 877, and 1,472 rpm. Because these values did not exactly match the Hino reference points of 500, 1,000, and 1,500 rpm, the manufacturer's reference volume was linearly interpolated using the proportional relation Vtarget = 0.03 x rpm, derived from 15 mL/20 s at 500 rpm, 30 mL/20 s at 1,000 rpm, and 45 mL/20 s at 1,500 rpm.

Spray pattern evaluation was conducted through visual observation and quantitative spray-angle analysis at three operating stages. Spray images were captured perpendicular to the spray plane, with a fixed camera position and a reference scale placed in the field of view. The images were analyzed using a tangent-based method: the nozzle outlet was defined as the origin, two boundary tangents were drawn along the visible spray envelope, and the angle between them was recorded as the spray angle. Each image was analyzed three times, and the mean value was compared with the manufacturer's specification range of 15° to 30 °.

To prevent excessive thermal loading of the injector solenoid during repeated operation, the maximum collection window used in the validation test was limited to 20 s. The measured injection volume was then expressed as mL/20 s and compared with the manufacturer's reference data after rpm interpolation. The validation basis was limited to manufacturer tolerance values and repeated laboratory measurements; benchmarking against a calibrated commercial injector test bench was not performed and is acknowledged as a limitation of the present study.

3. Result and Discussion

3.1 Pressure Generation and Hydraulic Stability

The operational performance of the developed test bench is primarily defined by its ability to generate and maintain hydraulic pressure sufficient for common rail injector actuation. The pressure test showed that the bench generated 360 ± 5.8 bar (36.0 ± 0.58 MPa) at 538 rpm, 650 ± 7.6 bar (65.0 ± 0.76 MPa) at 826 rpm, and 850 ± 10.0 bar (85.0 ± 1.00 MPa) at 1,472 rpm. The lowest measured value was slightly below the nominal Hino RN285 opening pressure of 362 bar; therefore, this point should be interpreted as being near the opening threshold rather than exceeding it. The injector operated consistently at the medium and high operating stages, where rail pressure was clearly above the opening threshold.

Table 1. Comparison of experimental and Hino standard fuel delivery volumes

No	Operating stage	Actual motor speed (rpm)	Rail pressure (bar)
1	Low	538	360 ± 5.8
2	Medium	826	650 ± 7.6
3	High	1,472	850 ± 10.0

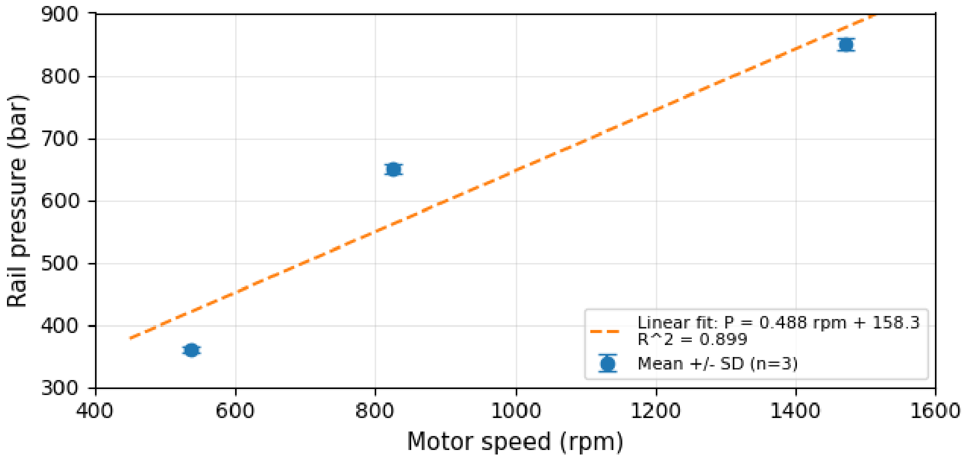

Figure 3. Relationship between rail pressure and motor speed

The pressure response increased with motor speed, as illustrated in **Fig. 3**. A simple linear fit to the three mean values produced P = 0.488 rpm + 158.30 with $R^2 = 0.899$, indicating a positive trend but not a definitive linear pressure model. Because only three operating stages were evaluated, the relationship should be interpreted as preliminary monotonic behavior rather than as a fully validated calibration curve. The pressure repeatability results are summarized in **Table 1**.

3.2 Fuel Delivery Analysis and Volumetric Efficiency

The volumetric validation focused on fuel delivery volume across three actual stabilized speed stages. The experimental results showed delivery volumes of 18.0 ± 0.6 mL at 565 rpm, 27.0 ± 1.0 mL at 877 rpm, and 39.0 ± 1.5 mL at 1,472 rpm over the 20 s collection window. Because the measured rpm values did not exactly match the manufacturer's reference speeds, the comparison was performed using the interpolation equation described in Section 2.4. The resulting comparison is shown in **Table 2**.

Table 2. Comparison of experimental and Hino standard fuel delivery volumes

No	Manufacturer reference		Result		
	Standard point	Specified volume	Actual rpm	Measured volume	Target
1	500 rpm	15 mL/20 s (±2-4 mL)	565	18.0 ± 0.6 mL	16.95 mL
2	1,000 rpm	30 mL/20 s (±2-4 mL)	877	27.0 ± 1.0 mL	26.31 mL
3	1,500 rpm	45 mL/20 s (±2-4 mL)	1,472	39.0 ± 1.5 mL	44.16 mL

At 565 rpm, the interpolated target volume was 16.95 mL/20 s, while the measured value was 18.0 ± 0.6 mL/20 s. At 877 rpm, the interpolated target was 26.31 mL/20 s, while the measured value was 27.0 ± 1.0 mL/20 s. Both points remained within the manufacturer's tolerance range. At 1,472 rpm, the interpolated target was 44.16 mL/20 s. At the same time, the measured value was 39.0 ± 1.5 mL/20 s, indicating a measurable high-speed delivery deficit. This result may reflect hydraulic loss, internal injector leakage, or actuation limitations. However, the exact cause cannot be confirmed without additional return-flow measurement, injector current tracing, or needle-lift diagnostics. Therefore, the interpretation has been limited to identifying a performance deviation rather than assigning a specific failure mechanism.

3.3 Spray Atomization and Geometric Characteristics

The atomization quality was evaluated by measuring the spray angle, which is a critical indicator of fuel-air mixing potential and injector hydraulic condition. The Hino RN285 injector is specified to maintain a spray angle of 15-30 degrees. Image-based spray analysis produced mean angles of 15.38 ± 0.18 degrees at 657 rpm and 470 bar, 18.79 ± 0.21 degrees at 798 rpm and 650 bar, and 20.44 ± 0.24 degrees at 1,472 rpm and 850 bar. All measured spray angles remained within the manufacturer's specification range, as summarized in **Table 3**.

Table 3. Fuel spray angle measured under each operating parameter

No	Actual speed (rpm)	Fuel pressure (bar)	Spray angle (degrees)
1	657	470	15.38 ± 0.18
2	798	650	18.79 ± 0.21
3	1,472	850	20.44 ± 0.24

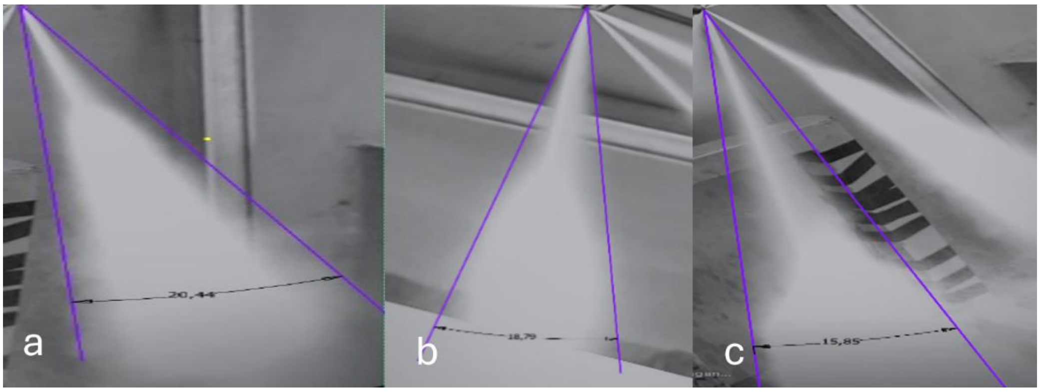

Figure 4. Visual Documentation of Spray Patterns at Various Pressure Stages. (a) 1472 Rpm, (b) 798 Rpm, (c) 657 Rpm

The observed increase in spray angle with higher pressure is consistent with fluid-dynamics principles, in which increased injection pressure enhances fuel-jet momentum and promotes primary and secondary breakup at the nozzle exit (**Fig. 4**). However, the present spray evaluation was limited to macroscopic spray angle; droplet-size distribution, penetration length, and high-speed transient behavior were not measured. Consequently, the results should be interpreted as a preliminary geometric validation of spray formation rather than as a complete characterization of atomization.

3.4 System Functionality and Operational Constraints

During the evaluation phase, the system demonstrated stable basic functionality, although several technical limitations were identified. A critical operational constraint was the thermal load on the injector solenoid. To mitigate the risk of solenoid overheating, the Arduino control system was programmed to limit the validation collection window to 20 s. This limit provided sufficient fuel volume for measurement while reducing the risk of excessive solenoid heating during repeated tests.

Initial testing also revealed minor hydraulic leakage at the high-pressure pipe joints and the pressure gauge interface. This problem was resolved through improved pipe-end machining and the installation of copper crush washers to obtain a reliable metal-to-metal seal. Leakage control was important for maintaining pressure stability, as even small leaks in a common-rail circuit can cause pressure fluctuations and measurement errors.

Compared with commercial test benches, the developed system offers operational transparency because the Arduino-based PWM controller can be modified for educational and research purposes. Nevertheless, the present validation was not a full replacement for calibrated industrial equipment. The bench was evaluated only with one injector type, three operating stages, and a short-duration test window. Long-term endurance testing, automatic return-flow measurement, injector-current monitoring, and benchmarking against a calibrated commercial test bench should be considered for future work.

4. Conclusion

This study engineered and preliminarily validated a low-cost diesel common-rail injector test bench using a Chevrolet Captiva supply pump and an Arduino-based PWM control system. Developed through the ADDIE framework, the system integrates mechanical, hydraulic, electronic, and safety design elements for laboratory-scale simulation of high-pressure diesel injection. The equipment achieved a maximum hydraulic output of 850 bar (85 MPa) at 1,472 rpm, while the lowest operating point of 360 bar (36 MPa) was near the Hino RN285 injector opening threshold. Experimental validation using a Hino RN285 injector confirmed that the bench can measure fuel delivery volume and macroscopic spray angle under controlled operating stages. Fuel delivery at low and medium speeds remained within manufacturer tolerance after interpolation to the actual measured rpm. In contrast, the highest operating stage showed a delivery deficit relative to the interpolated reference value. The recorded spray angles of 15.38 degrees to 20.44 degrees remained within the specified range of 15 degrees to 30 degrees. The developed test bench provides an accessible platform for vocational education, preliminary diagnostics, and laboratory experimentation on the behavior of diesel common rail injectors. However, its diagnostic validity remains limited by the absence of commercial-bench benchmarking, long-term durability testing, return-flow measurement, and high-speed spray imaging. Future refinements should include multi-injector testing, automated spray-pattern recognition, injector-current measurement, return-flow analysis, and calibration against a certified commercial injector test bench.

Conflict of interest

The authors declare no conflict of interest.

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