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Effectiveness of On-Engine Test Calibration on Vibration, Exhaust Opacity, and Injector Balancing of Common-Rail Injectors in a Chevrolet Captiva FL Diesel Engine

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Abstract. *Progressive deterioration of common-rail injectors can compromise fuel atomization, intensify cylinder-to-cylinder combustion imbalance, and increase visible exhaust smoke. This field study evaluated an on-engine injector calibration procedure on a Chevrolet Captiva FL C140 diesel engine using a one-group pretest-posttest design. Vibration velocity at four injector-related positions and exhaust opacity were measured in triplicate. Mean vibration decreased from 5.54 to 1.35 mm/s (75.64%), while mean opacity decreased from 55.43% to 28.90% (47.87%). All post-calibration vibration means were below the study reference of 2 mm/s, and all post-calibration opacity readings were below the applicable 40% HSU limit. The injector-level paired vibration comparison did not reach α=.05, t(3)=2.68, p=0.075, whereas the opacity comparison was significant, t(2)=4.82, p=0.040. Mean absolute injector-balancing deviation additionally decreased from 63.25 to 3.75 units, with all four values moving into the −50 to +50 normal range. The procedure shows promising field-maintenance value, but broader claims require testing across multiple vehicles and comparison with test-bench calibration.*
Keywords: *common-rail injector; on-engine test calibration; engine vibration; exhaust opacity; injector balancing; field maintenance*

Abstrak. Penurunan kondisi injektor common-rail secara bertahap dapat mengganggu atomisasi bahan bakar, memperparah ketidakseimbangan pembakaran antar-silinder, dan meningkatkan asap knalpot yang terlihat. Studi lapangan ini mengevaluasi prosedur kalibrasi injektor langsung pada mesin (on-engine) pada mesin diesel Chevrolet Captiva FL C140 menggunakan desain pretest-posttest satu kelompok. Kecepatan getaran pada empat posisi terkait injektor dan opasitas gas buang diukur sebanyak tiga kali pengulangan. Rata-rata getaran menurun dari 5,54 menjadi 1,35 mm/detik (75,64%), sedangkan rata-rata opasitas menurun dari 55,43% menjadi 28,90% (47,87%). Seluruh nilai rata-rata getaran pasca-kalibrasi berada di bawah acuan studi sebesar 2 mm/detik, dan seluruh pembacaan opasitas pasca-kalibrasi berada di bawah batas HSU 40% yang berlaku. Perbandingan getaran berpasangan pada tingkat injektor tidak mencapai signifikansi statistik (α=0,05; t(3)=2,68; p=0,075), sedangkan perbandingan opasitas menunjukkan hasil yang signifikan (t(2)=4,82; p=0,040). Selain itu, rata-rata deviasi absolut penyeimbangan injektor menurun dari 63,25 menjadi 3,75 unit, dengan keempat nilai tersebut masuk ke dalam rentang normal -50 hingga +50. Prosedur ini menunjukkan potensi nilai yang menjanjikan untuk pemeliharaan lapangan, namun klaim yang lebih luas memerlukan pengujian pada berbagai kendaraan serta perbandingan dengan kalibrasi menggunakan test-bench.
Kata kunci: injektor common-rail; kalibrasi uji pada mesin; getaran mesin; opasitas gas buang; penyeimbangan injektor; pemeliharaan lapangan

1. INTRODUCTION

Common-rail direct-injection systems separate pressure generation from electronically controlled injection, enabling precise regulation of injection timing, duration, and quantity. Injector-nozzle deposits, wear, or abnormal return flow can disrupt

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spray formation, create unequal cylinder contributions, and promote soot formation (Reitz, 2015; Dębowski & Karczewski, 2025). Dedicated test benches provide controlled injector assessment but are not equally accessible to general workshops.

Vibration velocity and exhaust opacity provide complementary indicators of maintenance outcome. Vibration reflects mechanical responses associated with combustion imbalance and has been used for injector-fault diagnosis (Kluczyk & Grządziela, 2017; Taghizadeh-Alisaraei & Mahdavian, 2019). Opacity quantifies light extinction by diesel smoke and responds to incomplete combustion and particulate loading (Giechaskiel et al., 2014). Injector balancing values obtained from engine-management data were added as a third indicator of cylinder-to-cylinder fuel correction. Values outside the workshop reference interval of −50 to +50 were classified as abnormal.

Operationally, injector balancing was defined as the correction value displayed by the scan tool for each injector under the same engine operating condition. The normal interval used by the workshop was −50 to +50. Values approaching zero were interpreted as requiring less electronic correction; however, no physical unit was assigned because the scan-tool parameter name and unit were not documented in the available field record.

Previous studies have generally focused either on vibration-based injector fault detection or on the effects of injection parameters on combustion and emissions under laboratory conditions. Evidence remains limited for a low-equipment, on-engine calibration procedure evaluated simultaneously through mechanical vibration, exhaust opacity, and electronic injector-balancing corrections on the same vehicle. Accordingly, this study aimed to determine: (1) the magnitude of vibration reduction after calibration; (2) the change in exhaust opacity relative to the applicable emission limit; and (3) the degree to which injector-balancing values converged toward the normal diagnostic interval after calibration. The study was designed as initial field evidence rather than as a population-level validation of the method.

2. RESEARCH METHOD

Research Design and Object

A quantitative one-group pretest-posttest design was applied to one Chevrolet Captiva FL C140 equipped with a 1,991 cm^3 inline four-cylinder common-rail diesel engine and solenoid injectors. The engine is the primary experimental unit; repeated readings were treated as technical replications. Testing and injector service were conducted at M-Dos Teknik Workshop with written research permission.

Figure 1. Research object: Chevrolet Captiva FL C140

Item	Specification
Engine	Inline four-cylinder diesel
Displacement	1,991 cm^3
Idle speed	840 ± 20 rpm
Maximum rail pressure	1,600 bar
Fuel	Bio Solar
Injector	Solenoid

Table 1. Research-object specifications

Research Instruments

Vibration was measured with a Lutron VB-8200 vibration meter. The manufacturer gives a velocity range of 0.5–199.9 mm/s, an acceleration range of 0.5–199.9 m/s^2, a frequency range of 10 Hz–1 kHz, and accuracy of ± (5% of reading + 2 digits) at 80 or 160 Hz and 23 ± 5 °C. Opacity was measured with a Heshbon HD-410 diesel smoke opacity meter using a 565 nm green LED and photodiode detection. Published specifications give an opacity range of 0.0–100.0%, 0.1% resolution, and precision within

±1%. Both instruments were calibrated on 14 July 2026. Certificate-specific expanded uncertainty was not available in the supplied information and is therefore not reported.

Instrument	Model	Range/principle	Resolution	Accuracy/uncertainty	Calibration
Vibration meter	Lutron VB-8200	0.5–199.9 mm/s; 10 Hz–1 kHz	Not documented	±(5% reading + 2 digits); certificate uncertainty not supplied	14 July 2026
Smoke opacity meter	Heshbon HD-410	0.0–100.0%; LED 565 nm / photodiode	0.1%	Within ±1%; certificate uncertainty not supplied	14 July 2026

Table 2. Instrument and metrological information

On-Engine Test Calibration and Measurement Procedure

The treatment comprised injector cleaning, inverted installation outside the combustion chamber, rail-pressure activation above 200 bar, visual inspection of the eight-branch spray pattern and mist quality, return-flow inspection, and reinstallation. The same procedure was applied to all four injectors.

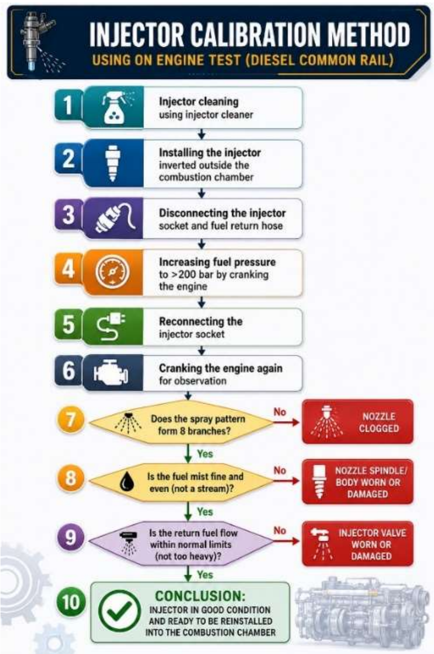

Figure 2. Flowchart of the on-engine test calibration method

The engine was conditioned at 60–70 °C coolant temperature, or within the manufacturer-recommended normal range. Vibration was measured in triplicate at idle. The probe was placed at the same fixed engine-block point in every trial. The exact block coordinate and measurement axis were not documented in the field record and are acknowledged as a reproducibility limitation. Opacity was measured in three free-acceleration trials at 3,000 rpm using the same probe placement and operating protocol.

The 40% HSU opacity criterion follows Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. 8 of 2023 for applicable diesel vehicles in categories M, N, and O with gross vehicle weight below 3.5 tonnes manufactured from 2010 to 2021. The regulation prescribes free-acceleration testing and refers to SNI 7118-2:2018. The vehicle manufacturing year and gross vehicle weight must be stated in the submitted manuscript to demonstrate exact applicability of the 40% criterion.

Data Analysis

Triplicate vibration readings were averaged for each injector-related position before paired analysis across four positions. Opacity trials were paired by test order. Percentage reduction was calculated as [(pre mean − post mean)/pre mean] × 100. Paired-samples t tests were interpreted at $\alpha=.05$. Owing to the small number of independent pairs and the use of one vehicle, inferential results were treated as exploratory. Injector balancing was evaluated descriptively for each of the four injectors. Because positive and negative corrections can cancel in an arithmetic mean, the mean absolute balancing deviation was used to quantify overall imbalance. A paired t test of absolute deviations is reported as exploratory.

3. RESULT AND DISCUSSION

Description of Research Data

Injector	Pre R1	R2	R3	Mean	Post R1	R2	R3	Mean
1	4.1	3.5	3.3	3.63	1.6	1.1	1.7	1.47
2	9.5	9.7	8.6	9.27	0.9	1.3	1.7	1.30
3	7.4	5.7	6.6	6.57	1.3	0.7	1.2	1.07
4	3.0	2.0	3.1	2.70	1.7	1.7	1.3	1.57

Table 3. Vibration velocity before and after calibration (mm/s)

The grand mean decreased from 5.54 to 1.35 mm/s, a 75.64% reduction. Injector-level pre-calibration means ranged from 2.70 to 9.27 mm/s, while post-calibration means ranged from 1.07 to 1.57 mm/s. All post-calibration means were below 2 mm/s. The paired comparison yielded t(3)=2.68, p=0.075; consequently, the large descriptive reduction did not reach the conventional significance threshold.

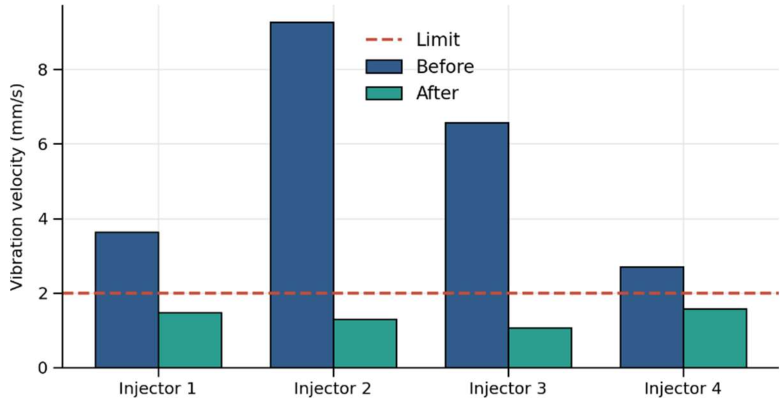

Figure 1. Injector-level mean vibration before and after calibration

Exhaust Opacity Test Results

Test	Before (%)	After (%)	Limit (%)	Before status	After status
1	48.4	31.8	40	Fail	Pass
2	54.5	27.1	40	Fail	Pass
3	63.4	27.8	40	Fail	Pass
Mean	55.43	28.90	40	Fail	Pass

Table 4. Exhaust opacity results

Mean opacity decreased from 55.43% to 28.90%, corresponding to a 47.87% reduction. All pre-calibration trials exceeded 40%, whereas every post-calibration trial complied with the limit. The paired comparison yielded t(2)=4.82, p=0.040.

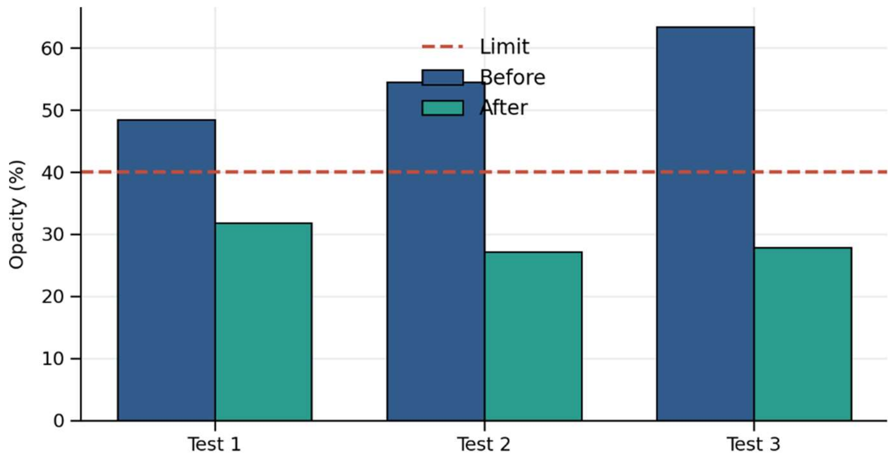

Figure 2. Opacity before and after calibration

Injector Balancing Test Results

Before calibration, all four injector balancing values were outside the normal workshop reference interval of −50 to +50. After calibration, all values fell within the interval and clustered close to zero. The absolute mean deviation decreased from 63.25 to 3.75 units, corresponding to a 94.07% reduction. The maximum absolute deviation decreased from 72.0 to 6.0 units.

Injector	Before	After	Before status	After status	Absolute improvement
Injector 1	-57.0	4.0	Abnormal	Normal	53.0
Injector 2	-71.0	3.0	Abnormal	Normal	68.0
Injector 3	72.0	-2.0	Abnormal	Normal	70.0
Injector 4	53.0	-6.0	Abnormal	Normal	47.0

Table 5. Injector balancing values before and after calibration

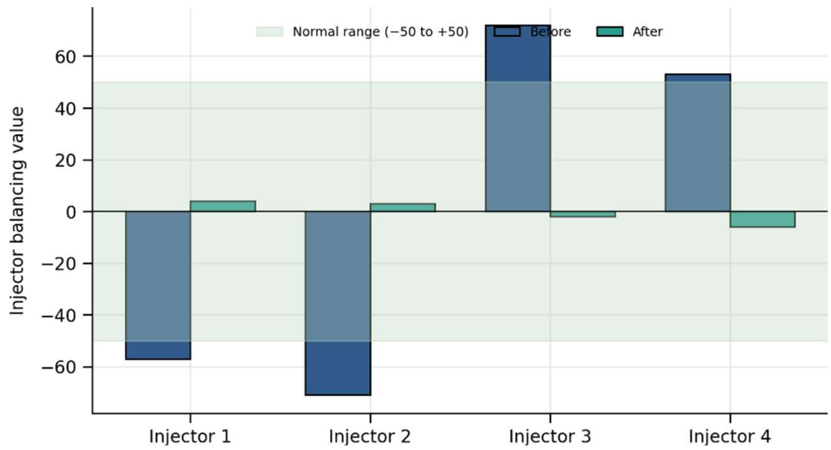

Figure 3. Injector balancing values relative to the normal range

A paired comparison of the absolute balancing deviations yielded $t(3) = 10.56$, $p = 0.002$. This exploratory result indicates a statistically significant reduction in deviation from zero; however, balancing values are simultaneous ECU correction outputs from a single engine and should not be treated as four independent vehicles.

Discussion

The updated data show coherent improvement in both monitored outcomes. A 75.64% decrease in vibration suggests that injector service improved mechanical uniformity on the tested engine, particularly at Injectors 2 and 3. Nevertheless, the vibration p value of 0.075 prevents a claim of statistical significance at α=.05. The defensible interpretation is therefore a large descriptive effect that requires replication on additional vehicles.

Opacity declined by 47.87% and changed from fail to pass in all trials. Improved atomization can reduce locally fuel-rich zones and soot formation, which is consistent with established links between injection parameters, combustion quality, and smoke opacity (Budiman et al., 2016; Rocha-Hoyos et al., 2019). The opacity result was statistically significant, but only three technical pairs from one engine were available.

The balancing data strengthen the mechanical interpretation. Before calibration, Injectors 1 and 2 required large negative corrections, whereas Injectors 3 and 4 required large positive corrections, with all four values exceeding the stated normal limits. After calibration, the values ranged only from −6.0 to +4.0. This convergence toward zero is consistent with improved uniformity of injector contribution and complements the observed vibration reduction. The exact balancing unit, scan-tool parameter name, and manufacturer diagnostic definition were not supplied, so the manuscript reports the values without assigning an unsupported physical unit.

This study contributes a field-oriented evaluation framework that integrates a mechanical indicator, an emissions indicator, and an electronic correction indicator within a single maintenance intervention. The method may support preliminary diagnosis and maintenance in workshops without a common-rail test bench. It should not be presented as equivalent to certified bench calibration, which can quantify injection delivery, leakage, and return flow at controlled pressure points.

Limitations of the Study

The findings should be interpreted in light of several methodological constraints. The investigation was limited to one vehicle, did not include an untreated control condition or a direct test-bench comparator, and could not estimate between-vehicle variability. The exact vibration-sensor coordinate and measurement axis were not documented. Certificate-specific measurement uncertainty was not supplied. Environmental variables, rail-pressure traces, fuel properties beyond the commercial fuel type, and long-term durability were also not quantified. These limitations restrict causal and population-level claims. In addition, the balancing parameter unit, ECU calculation method, and diagnostic sampling conditions were not documented; consequently, balancing results should be interpreted as vehicle-specific diagnostic corrections.

4. CONCLUSION AND RECOMMENDATION

On the tested engine, on-engine injector calibration reduced mean vibration from 5.54 to 1.35 mm/s (75.64%) and mean opacity from 55.43% to 28.90% (47.87%). All post-calibration vibration means were below 2 mm/s and all opacity trials were below 40% HSU. Vibration improvement was large but not statistically significant at $\alpha=.05$ ($p=0.075$), whereas opacity improvement was significant ($p=0.040$). Mean absolute injector-balancing deviation also decreased from 63.25 to 3.75 units (94.07%), and all four injectors moved from outside to inside the −50 to +50 reference range. Multi-vehicle validation and comparison with standard test-bench calibration are required before broader adoption claims are made.

Recommendations

For workshop application, the on-engine procedure should be used as a structured preliminary inspection and maintenance protocol. Post-service decisions should consider spray quality, return-flow behavior, vibration velocity, opacity, injector-balancing values, and diagnostic trouble codes together. Injectors that remain outside the diagnostic balancing interval, exhibit excessive return flow, produce an abnormal spray pattern, or cause persistent vibration should be referred for calibrated test-bench examination. For research application, subsequent studies should recruit multiple vehicles, document sensor coordinates and axes, report calibration-certificate uncertainty, and compare on-engine servicing directly with standard test-bench calibration.

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