



Performance Evaluation of Diesel Engines Using Alternative Biodiesel Fuel Blends

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Peer Review Information	Abstract
<i>Submission: 02 Jan 2018</i> <i>Revision: 17 Feb 2018</i> <i>Acceptance: 05 March 2018</i> Keywords <i>Biodiesel, Diesel engine, Brake thermal efficiency, Brake-specific fuel consumption, Exhaust emissions</i>	Biodiesel-diesel blending is a practical route for reducing dependence on petroleum fuel while retaining the basic operating architecture of compression-ignition engines. This methodology paper presents a structured experimental procedure for evaluating engine performance and regulated exhaust emissions when conventional diesel (B0) is replaced progressively by alternative biodiesel blends. The proposed protocol uses B10, B20, B30 and B40 fuels prepared on a volume basis and tested in a four-stroke direct-injection diesel engine at constant speed under incremental loading. Fuel density, kinematic viscosity and lower heating value are characterized before engine testing. Brake power, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), exhaust-gas temperature and emissions of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x) and smoke are then measured. The method includes stabilization, repeated observations, instrument calibration, uncertainty estimation and statistical comparison against the diesel baseline. An illustrative dataset, included only to demonstrate the analysis workflow, shows the commonly reported trade-off: higher biodiesel fraction slightly increases BSFC and may raise NO_x, while CO, HC and smoke decline because of the oxygenated nature of biodiesel. B20 gives the most balanced performance-emission outcome in the example analysis. The procedure is designed to be reproducible for biodiesel derived from waste cooking oil or other vegetable/non-edible oils and is consistent with research trends reported up to 2018.

Introduction

Compression-ignition engines remain important in transportation, agriculture and decentralized power generation because of their high thermal efficiency, durability and high torque output. Their dependence on petroleum diesel, however, creates concerns related to fossil-resource depletion, fuel-price volatility and pollutant emissions. Biodiesel, composed mainly of fatty-acid alkyl esters produced from vegetable oils, animal fats or waste lipids, is attractive because it is renewable, biodegradable and can be blended with mineral diesel for use in existing diesel engines with limited or no hardware

modification. Agarwal [1] identified biodiesel as one of the most technically mature renewable substitutes for compression-ignition engines and emphasized that its oxygen content can improve oxidation of soot precursors and incomplete-combustion products.

The engine response to biodiesel is not governed by blend percentage alone. Density, viscosity, cetane quality, oxygen content, volatility and lower heating value influence spray formation, ignition delay, premixed combustion, diffusion burning and the quantity of fuel required to produce a given brake output. Rakopoulos et al.

[2] showed that low biodiesel blend levels can be evaluated in conventional direct-injection engines without extensive modification, but the measured response depends strongly on fuel origin and operating load. Lapuerta et al. [3] similarly concluded that emission trends are affected by engine technology, biodiesel composition and test conditions, particularly for NO_x.

Previous experimental work has generally reported that biodiesel blends reduce smoke, CO and HC emissions, whereas BSFC tends to rise because biodiesel has a lower heating value than petroleum diesel. Sahoo et al. [4] reported useful performance from several non-edible biodiesels in a tractor engine and observed reductions in smoke. Buyukkaya [5] measured lower smoke and CO with rapeseed-derived biodiesel but higher specific fuel consumption. These findings support systematic testing of several blend ratios rather than evaluating only neat biodiesel or a single blend.

The objective of the present paper is therefore to define a reproducible methodology for evaluating alternative biodiesel-diesel blends under controlled engine conditions. The procedure is intended for laboratory studies in which B0 is used as the baseline and B10-B40 blends are compared at identical speed and load points. The performance metrics are brake power, BSFC and BTE; the principal emission metrics are CO, HC, NO_x and smoke opacity. The methodology also includes fuel-property characterization, repeatability checks and uncertainty analysis so that observed differences can be attributed to fuel effects with reasonable confidence.

Literature Review

Comprehensive reviews provide a consistent baseline for expected biodiesel behavior. Xue, Grift and Hansen [6] synthesized engine studies and found that biodiesel commonly causes a small loss in power, an increase in fuel consumption and reductions in particulate matter, HC and CO, while NO_x frequently increases. They also noted that low blend levels can achieve emission benefits with relatively small penalties in engine economy. This pattern is important for designing an experiment that treats performance and emissions as simultaneous response variables.

Fuel preparation and feedstock chemistry are equally important. Hoekman et al. [7] demonstrated that biodiesel properties vary with fatty-acid composition and that viscosity, specific gravity, cetane number and low-temperature

behavior are linked to molecular structure. Consequently, the test methodology should record basic fuel properties rather than assuming that every B20 or B40 blend is chemically equivalent. Ashraful et al. [10] reviewed biodiesels from non-edible oils and reinforced the need to connect feedstock-dependent fuel properties with engine performance and emissions.

Engine-specific experiments support the same need for controlled comparisons. Muralidharan and Vasudevan [8] evaluated waste-cooking-oil methyl ester blends in a variable-compression-ratio engine and showed that compression ratio and blend level influence both combustion and exhaust emissions. Özener et al. [9], using soybean biodiesel blends, measured approximately 2-9% higher BSFC and lower CO/total hydrocarbon emissions relative to diesel, with a moderate NO_x increase. Their work demonstrates why an evaluation should include both energy-efficiency indicators and gaseous emissions instead of selecting a single performance measure.

More recent work available by 2018 confirms that the blend trade-off persists in modern engine systems. How et al. [11] tested Calophyllum inophyllum biodiesel-diesel blends in a multi-cylinder common-rail engine and reported increased BSFC with increasing biodiesel fraction, alongside lower CO, smoke and particulate emissions and higher NO_x. Collectively, the literature suggests that B10-B20 often provides a useful compromise, but the optimum blend cannot be transferred directly between engines or feedstocks. A standardized test matrix, identical operating points and repeated measurements are therefore required for a defensible comparison.

Methodology

The proposed method is an experimental comparative design in which fuel blend is the primary independent variable and engine load is the secondary operating factor. The same engine, injection system, speed, warm-up condition and measurement instruments are maintained throughout the study. A waste-cooking-oil methyl ester (WCOME) is used as the representative alternative biodiesel, although the protocol can be applied to jatropha, karanja, soybean, rapeseed or other ASTM-compatible biodiesels. The blend nomenclature B_x indicates x% biodiesel and (100-x)% petroleum diesel by volume.

Step 1 - Fuel preparation and conditioning. Prepare B0, B10, B20, B30 and B40 in clean

graduated glassware by volume. Mix each fuel for at least 10 min and allow it to stand so that free water or phase instability can be detected. Store samples in sealed, labeled containers away from direct sunlight. Before testing, bring all fuels to the same laboratory temperature.

Step 2 - Fuel-property characterization. Measure density at 15-25 °C, kinematic viscosity at 40 °C and lower heating value. Cetane number, flash point and oxygen content may be included when suitable equipment is available. The properties should fall within accepted diesel/biodiesel blend ranges; abnormal viscosity or water contamination is grounds for rejecting a batch.

Step 3 - Engine and instrumentation. Use a single-cylinder, four-stroke, water-cooled direct-injection diesel engine operated at 1500 rpm and coupled to an eddy-current or electrical dynamometer. A fuel burette or calibrated mass-flow meter measures fuel consumption. CO, HC and NO_x are measured with a calibrated exhaust-gas analyzer; smoke is measured using an opacity or Hartridge-type smoke meter. Thermocouples record exhaust-gas and cooling-water temperatures.

Step 4 - Test matrix. For each fuel, operate the engine at 0%, 25%, 50%, 75% and 100% of rated load at constant speed. To reduce order effects, begin with diesel, then test the biodiesel blends in ascending concentration; after each fuel change, flush the line and operate for sufficient time to remove the previous fuel. Repeat the complete sequence if randomization is desired.

Step 5 - Stabilization and data acquisition. Warm the engine on B0 until cooling-water and lubricating-oil temperatures become stable. At each load point, wait approximately 3-5 min after stabilization before recording measurements. Obtain at least three readings for torque/load, speed, fuel-consumption time, exhaust temperature and emissions. Use the arithmetic mean as the reported value.

Step 6 - Performance calculations. Calculate brake power from measured torque and speed using BP

$= 2\pi NT/60,000$ (kW), where N is rpm and T is torque in N·m. Determine BSFC = m_f/BP (kg/kWh), where m_f is hourly fuel mass flow. Compute BTE = $BP/(m_f \times LHV) \times 100$. These equations normalize the comparison for the different energy content of diesel and biodiesel blends.

Step 7 - Emission comparison. Report CO as volume percent, HC and NO_x as ppm (or convert to g/kWh where exhaust-flow data are available), and smoke as opacity percent or Hartridge smoke units. Calculate percentage change relative to B0 at each load: $\Delta X = (X_{blend} - X_{B0})/X_{B0} \times 100$. A negative change is desirable for CO, HC and smoke; NO_x is assessed separately because it often shows the opposite trend.

Step 8 - Repeatability, uncertainty and statistics. Calibrate instruments before the test series and document analyzer ranges and stated accuracies. Estimate combined uncertainty for derived parameters from measurement uncertainties using root-sum-square propagation. For a formal study, apply two-way ANOVA with blend and load as factors at $\alpha = 0.05$, followed by a post-hoc comparison if significant differences are found. An optimum blend can be selected using a normalized desirability score that rewards high BTE and low BSFC, CO, HC and smoke while penalizing NO_x increase.

Before calculation, screen the repeated readings for transcription errors and obvious instrument faults. For each operating point, report the mean and standard deviation. A coefficient of variation below about 3% for fuel-consumption and torque readings is a practical repeatability target for a teaching/research laboratory; larger scatter should trigger an additional run. Ambient temperature and pressure should also be recorded because air density and analyzer response can vary during long test sessions. All comparisons must use the same load definition and the same fuel-basis convention (mass or volume) throughout the analysis.

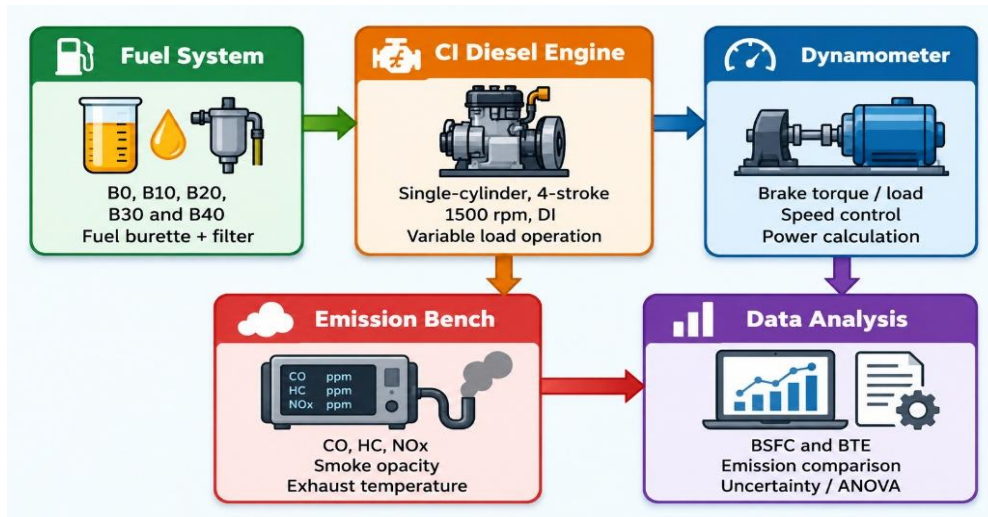
Table 1. Recommended engine and measurement specifications for the proposed test

Parameter	Recommended specification
Engine type	4-stroke, single-cylinder, water-cooled, direct injection
Rated speed	1500 rpm (constant-speed testing)
Compression ratio	Approximately 17.5:1-18.5:1
Loading device	Eddy-current/electrical dynamometer
Fuel measurement	Burette or mass-flow meter; $\pm 1\%$ or better
Gaseous emissions	CO, HC, NO _x exhaust-gas analyzer

Smoke	Opacity meter or Hartridge smoke meter
Test fuels	B0, B10, B20, B30 and B40 by volume
Load points	0%, 25%, 50%, 75% and 100% rated load
Replicates	Minimum three stabilized readings per point

Table 2. Experimental variable matrix and response variables

Role	Variable	Levels / outputs
Independent variable	Fuel blend	B0, B10, B20, B30, B40
Operating factor	Engine load	0, 25, 50, 75, 100%
Controlled factor	Engine speed	1500 rpm
Performance responses	Efficiency/economy	Brake power, BTE, BSFC
Emission responses	Exhaust pollutants	CO, HC, NO _x , smoke
Supporting responses	Thermal condition	Exhaust-gas temperature

**Figure 1.** Schematic of the proposed diesel-engine test rig and measurement/data-analysis flow.

Results

Because this paper defines a methodology rather than reporting a newly completed laboratory campaign, the numerical values in Table 3 are an illustrative dataset constructed to demonstrate the calculation and interpretation procedure.

They are intentionally consistent with the direction and approximate magnitude of trends documented in prior experimental studies [5], [6], [9], [11], but they must not be cited as new measured results. In an actual study, this table should be replaced by the researcher's calibrated measurements and uncertainty intervals.

Table 3. Illustrative full-load performance and emission comparison (method demonstration only)

Fuel	BTE (%)	BSFC (kg/kWh)	EGT (°C)	CO (%)	HC (ppm)	NO _x (ppm)	Smoke (HSU)
B0	31.8	0.265	450	0.24	54	1030	64
B10	31.5	0.271	454	0.20	48	1060	59
B20	31.2	0.279	459	0.17	43	1090	54
B30	30.7	0.289	465	0.15	39	1125	50
B40	30.1	0.301	472	0.13	36	1160	47

The illustrative data show a gradual reduction in BTE as biodiesel concentration increases, while BSFC rises from 0.265 kg/kWh for B0 to 0.301 kg/kWh for B40. This behavior follows from the lower heating value and slightly higher density/viscosity typically associated with biodiesel. Similar increases in fuel consumption have been reported for rapeseed and soybean biodiesel blends [5], [9]. The comparatively small BTE difference at B10-B20 indicates why low-to-medium blend levels are often preferred when no engine recalibration is performed.

The emission response is more favorable for products of incomplete combustion. Relative to B0, the example B20 case reduces CO by about 29%, HC by about 20% and smoke by about 16%. Oxygen chemically bound within biodiesel can support more complete local oxidation during diffusion combustion, although atomization quality and combustion temperature still depend on viscosity, injection characteristics and engine load [3], [6]. At B40, the reductions become larger, but the performance penalty also becomes more noticeable.

NOx increases moderately across the illustrative blend series, reaching roughly 13% above diesel for B40. The direction agrees with many experimental studies, although NOx is not universally higher and can change with ignition timing, feedstock, injection strategy and combustion temperature [3], [11]. For this reason, the methodology treats NOx separately from CO/HC/smoke and does not assume that the blend with the lowest smoke is automatically the optimum fuel. In the example, B20 provides the best compromise between a small efficiency penalty and meaningful reductions in incomplete-combustion emissions.

Conclusion and Discussion

This paper establishes a step-by-step methodology for evaluating diesel-engine operation with alternative biodiesel fuel blends. The key strength of the approach is that all fuels are tested on the same engine at the same speed, load points, stabilization conditions and measurement procedure. This minimizes confounding effects and permits direct comparison of BTE, BSFC, exhaust temperature, CO, HC, NOx and smoke. Fuel-property characterization is included because biodiesel composition and feedstock influence viscosity, density, cetane behavior and energy content [7], [10]. Repeated readings, calibration and uncertainty analysis are also necessary because the expected changes between B0 and low biodiesel blends may be only a few percent. The

literature available through 2018 indicates a consistent engineering trade-off. Biodiesel can substantially reduce smoke, CO, HC and particulate emissions, yet it commonly causes slightly higher fuel consumption and can increase NOx [3], [6], [11]. Experimental investigations using non-edible oils, waste cooking oil, rapeseed and soybean biodiesel demonstrate that these effects are sensitive to blend level and engine condition [4], [5], [8], [9]. Therefore, the most useful outcome is not simply identification of the “cleanest” fuel, but selection of a blend that provides an acceptable balance between efficiency, fuel consumption and regulated emissions. For a typical unmodified diesel engine, B10-B20 is a defensible starting range for optimization because it preserves diesel-like performance while providing measurable emission benefits. Nevertheless, the final optimum should be obtained from actual test data for the selected feedstock and engine. Future extensions may include combustion-pressure analysis, heat-release rate, particulate-number measurement, long-duration durability tests, life-cycle greenhouse-gas assessment and optimization of injection timing or exhaust-gas recirculation to control the NOx increase. The methodology presented here provides the experimental foundation for those advanced investigations.

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