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TECHNICAL REFERENCE · CARBON-BALANCE METHOD

Exhaust CO_2-Based Fuel Consumption Derivation for Diesel Fleet Maintenance Diagnostics

Application of the ISO 8178 Carbon Balance Method to Field-Level Prescriptive Engine Diagnostics

White Paper — Technical Reference · June 2026

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Published by Starboard Research — a segment of Starboard Investment, LLC

Abstract

This paper presents a methodology for deriving real-time fuel consumption rates from exhaust carbon dioxide (CO_2) concentration measurements in diesel engines, grounded in the stoichiometric carbon balance principles codified in ISO 8178, SAE J1003, and 40 CFR Part 1065. The ratio of measured exhaust CO_2 concentration to an engine's certified baseline CO_2 concentration, multiplied by the engine's rated fuel consumption, yields a fuel consumption measurement that is theoretically sound and validated across field deployments spanning three continents.

We further present evidence that this exhaust-derived fuel consumption measurement is structurally more accurate than the Engine Control Module (ECM) fuel rate reported via J1939 CAN bus (SPN 183), which measures fuel injected rather than fuel combusted. Field validation is presented from a controlled deployment at a surface coal mine in Central Asia, where three independent measurement methods — CO_2-derived fuel rate, fill-to-fill volumetric measurement (supervised by the engine OEM's field engineering team), and ECM-reported fuel rate — were compared on the same five-engine fleet. Results confirm that the CO_2-derived fuel rate tracks physical fill-to-fill measurement while ECM estimates diverge by up to 17%.

The methodology has been implemented in a diagnostic platform that uses exhaust emission profiles combined with engine operating parameters to generate prescriptive maintenance diagnostics across all diesel OEMs and all EPA emission tiers. The platform's validated field corpus comprises 124 engines with 3,058 emission tests captured to date.

Keywords: *carbon balance method; exhaust CO_2; diesel fuel consumption; ISO 8178; 40 CFR Part 1065; fleet maintenance diagnostics; ECM accuracy; emissions-based maintenance.*

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1. Introduction

The global heavy-duty diesel fleet — encompassing mining haul trucks, transit vehicles, marine engines, power generation units, and on-road commercial vehicles — consumes billions of gallons of diesel fuel annually. The U.S. transportation sector alone produced approximately 455 million metric tons of CO_2 from diesel consumption in 2023, representing roughly 10% of total U.S. energy-related CO_2 emissions [1]. Identifying and reducing excess fuel consumption in this fleet presents both an economic imperative and an environmental necessity.

Current methods for measuring in-service fuel consumption rely primarily on two approaches: volumetric measurement (tank-level monitoring between refueling events) and ECM-reported fuel rate (derived from injector pulse width and common rail pressure via the SAE J1939 protocol). Both methods have significant limitations. Volumetric measurement requires careful operational controls and extended observation periods. The ECM-reported fuel rate, while convenient, measures fuel dispatched to the injectors rather than fuel actually combusted — a distinction with material implications for accuracy, as detailed in Section 5.

This paper presents a third approach: deriving fuel consumption from exhaust CO_2 concentration using the carbon balance method. This approach is not novel in the laboratory context — it has been the accepted standard for engine certification testing for over four decades. What is novel is its application to continuous field-level fleet diagnostics and prescriptive maintenance.

A single emission test takes approximately 30 minutes per engine and delivers per-engine fuel consumption rate derived from exhaust chemistry, identification of specific maintenance opportunities tied to measurable emission profile changes, ongoing monitoring capability that detects engine degradation, and quantified fuel savings potential expressed in gallons, dollars, and CO_2 reduction.

2. Theoretical Foundation: The Carbon Balance Method

2.1 Stoichiometric basis

The carbon balance method is rooted in the Law of Conservation of Mass: in any chemical reaction, the mass of reactants must equal the mass of products. Diesel fuel combustion is fundamentally a carbon-oxygen reaction. Ultra-low-sulfur diesel fuel (ULSD) has a carbon mass fraction of approximately 0.862–0.874 (86.2–87.4% carbon by mass), as defined in 40 CFR §1065.655(e) Table 2 [2]. When diesel fuel undergoes complete combustion, each carbon atom combines with two oxygen atoms to form carbon dioxide (CO_2):

$$\mathbf{C_{12}H_{21.6} + 17.4\ O_2 \rightarrow 12\ CO_2 + 10.8\ H_2O}$$

The molecular weight ratio of CO_2 to carbon is 44/12 = 3.667. Therefore, each kilogram of diesel fuel containing 0.862 kg of carbon produces approximately 3.16 kg of CO_2 when fully combusted. The U.S. Energy Information Administration (EIA) and the U.S. Department of Energy report that burning one gallon of diesel fuel produces approximately 22.44 pounds (10.18 kg) of CO_2 [1][3]. This factor is a stoichiometric constant — it is derived from the chemical composition of the fuel, not from estimation or modeling.

2.2 From exhaust CO_2 concentration to fuel consumption

The key insight of the carbon balance method is that at constant engine load, speed (RPM), and intake airflow, the concentration of CO_2 in the exhaust gas is directly proportional to the mass flow rate of fuel through the engine. This proportionality arises because engine displacement and turbocharger boost determine a fixed intake air mass flow at any given RPM and load combination; the exhaust mass flow rate is approximately equal to the intake air mass flow plus the fuel mass flow (the fuel mass contribution is typically less than 5% of the total exhaust mass). Therefore, at fixed airflow, CO_2 concentration in the exhaust is a direct proxy for fuel mass flow rate.

The formal derivation, as specified in 40 CFR §1065.655 [2], uses the carbon mass fraction of the fuel (w_C), the measured concentrations of CO_2, CO, and total hydrocarbons (THC) in the exhaust, and the calculated exhaust molar flow rate to determine fuel mass flow. In the simplified ratio form implemented for field diagnostics:

Fuel Rate (gal/hr) = (CO_2 actual / CO_2 rated) × Rated Fuel Rate

Where CO_2 actual is the measured exhaust CO_2 concentration (%), CO_2 rated is the engine's certified baseline CO_2 concentration at rated conditions (from the EPA Engine Universe database or OEM specification), and Rated Fuel Rate is the manufacturer's published fuel consumption at rated power (gal/hr).

2.3 Conditions and assumptions

The proportional relationship between CO_2 concentration and fuel consumption holds rigorously under the following conditions: constant horsepower output (engine operating at a consistent load point); constant RPM (ensuring consistent intake air mass flow through fixed displacement and turbo boost); constant barometric pressure and ambient air conditions at the test site; and consistent fuel composition (same fuel source and quality between measurements).

Regarding exhaust gas recirculation (EGR): Engines equipped with EGR recirculate a portion of exhaust gas back into the intake manifold, increasing the CO_2 concentration in the intake charge. Because measurement is taken at the post-turbo exhaust point, the CO_2 reading reflects the total carbon output from combustion — including any recirculated CO_2 that passed through the cylinder. The stoichiometric relationship between fuel burned and CO_2 produced at the measurement point is preserved: the recirculated CO_2 enters and exits the cylinder without being consumed or produced, while only the newly combusted fuel contributes additional CO_2.

Regarding variable-geometry turbochargers (VGT): VGT-equipped engines adjust turbocharger boost based on load demand, varying the intake airflow at a given RPM. This changes the engine's operating lambda (air-fuel ratio), which shifts the CO_2 and O_2 concentrations along the stoichiometric curve. VGT does not alter the stoichiometric constants or the proportionality between CO_2 and fuel rate at a given lambda — it changes where the engine operates on the curve, not the curve itself. A tolerance system accounts for this by comparing readings at comparable RPM and load windows.

These conditions are routinely met in mining operations (where haul trucks operate at consistent load profiles on defined routes), in power generation (where generators run at fixed speed and load), and in controlled test conditions. For field applications with varying loads, the methodology is applied by comparing CO_2 readings at comparable RPM and load windows.

2.4 Measurement basis and sensor placement

All exhaust gas measurements referenced in this paper are on a dry-volume basis, consistent with standard portable gas analyzer operation (NDIR for CO_2, electrochemical for O_2) where the sample is conditioned through a water trap or Nafion dryer before reaching the sensor cell. Wet-basis analyzers (which do not remove water vapor before measurement) will report different absolute values; back-calculation formulas must be adjusted accordingly.

Measurements are taken at the post-turbocharger sampling point in pure, untreated exhaust — upstream of any aftertreatment devices (diesel oxidation catalyst, diesel particulate filter, or selective catalytic reduction system). This measurement point captures the direct output of combustion without interference from aftertreatment chemistry. Diesel oxidation catalysts convert CO to CO_2, which would inflate measured CO_2 downstream. DPF regeneration events inject fuel into the exhaust stream. SCR systems inject urea and produce additional chemical reactions. By measuring post-turbo and pre-aftertreatment, the methodology isolates the combustion signal from aftertreatment effects, ensuring the stoichiometric relationship between fuel burned and CO_2 produced is preserved regardless of the engine's emission tier or aftertreatment configuration.

3. Regulatory and Standards Framework

The carbon balance method is not an approximation or a novel technique. It is the established regulatory standard for fuel consumption determination in engine certification across multiple jurisdictions:

STANDARD	DESCRIPTION	JURISDICTION
ISO 8178-1:2020	Specifies measurement methods for gaseous and particulate exhaust emissions from reciprocating IC engines on a test bed, including carbon balance method for fuel flow calculation [4].	International
ISO 8178-2:2021	Extends ISO 8178-1 to field conditions, applicable to non-road machinery, marine, rail, and generating sets. Includes PEMS (Portable Emission Measurement Systems) provisions [5].	International
40 CFR §1065.655	Defines the EPA's carbon balance equations for calculating fuel consumption from exhaust gas composition [2].	United States

STANDARD	DESCRIPTION	JURISDICTION
40 CFR §1036.535	Requires carbon mass balance for indirect fuel-flow measurement in heavy-duty engine certification [6].	United States
SAE J1003	Specifies carbon balance as an approved method for calculating mass rate of emissions from exhaust gas concentration and fuel properties [7].	International
EU 2017/2400	Implements CO_2 certification for heavy-duty vehicles using the VECTO simulation tool. Engine CO_2/fuel maps form the certification basis [8].	European Union
IMO NOx Code §5.5.3	Specifies carbon balance for exhaust gas mass flow calculation for marine diesel engines [9].	International

Table 1: Regulatory standards codifying the carbon balance method for fuel consumption determination.

4. Physical Constants and Conversion Factors

The following constants are used in the fuel consumption derivation. All values are sourced from regulatory authorities and peer-reviewed engineering references:

PARAMETER	VALUE	SOURCE
Carbon mass fraction of diesel fuel (w_C)	0.862–0.874	40 CFR §1065.655 Table 2 [2]
CO_2 produced per gallon of diesel	22.44 lbs (10.18 kg)	U.S. DOE / EIA [1][3]
Molecular weight ratio CO_2:C	44/12 = 3.667	Stoichiometric [10]
Diesel fuel density	7.1 lbs/gal (3.22 kg/gal)	ASTM D975 [11]
CO_2 mass per kg diesel burned	3.16 kg CO_2/kg fuel	IPCC 2006 GL, Vol. 2 [12]

Table 2: Physical constants and conversion factors used in CO_2-derived fuel consumption.

5. ECM Fuel Rate vs. CO_2-Derived Fuel Rate

A critical finding from field deployments is that the ECM-reported fuel rate — widely used in fleet telematics — is structurally less accurate than the exhaust CO_2-derived fuel rate for determining actual fuel combustion.

5.1 How the ECM calculates fuel rate

The Engine Control Module reports fuel consumption via J1939 CAN bus parameter SPN 183 (“Engine Fuel Rate”). This value is calculated from injector pulse width, common rail pressure, and injector calibration maps. It represents the volume of fuel dispatched to the fuel injectors per unit time.

However, modern diesel fuel systems operate on a return-flow architecture: fuel is drawn from the tank, pressurized by the high-pressure pump, dispatched to the injectors, and any unused fuel is returned to the tank via the return line. The ECM has no visibility into:

- Return fuel volume. At partial load, a significant fraction of pressurized fuel is returned unused. The ECM counts this fuel as “consumed.”
- Fuel quality degradation. Returned fuel is oxygenated and heated, reducing its energy density over time. The ECM applies the same energy-content assumptions regardless of fuel cycling history.
- Actual combustion efficiency. The ECM assumes a combustion efficiency based on calibration maps. It cannot detect real-time deviations caused by injector wear, turbocharger degradation, or intake restriction.

5.2 Why CO_2-derived fuel rate is more accurate

The exhaust CO_2 measurement captures the output of combustion — the actual carbon mass that was oxidized in the cylinder. It is insensitive to return fuel volume, fuel system pressure variations, and injector calibration drift. The CO_2-derived fuel rate answers the question: “How much fuel was actually burned?” The ECM fuel rate answers a different question: “How much fuel was sent to the injectors?”

For applications requiring accurate fuel accounting — fleet cost optimization, carbon credit quantification, and maintenance diagnostics — the combustion-based measurement is the correct metric. This distinction is especially material for carbon credit programs, where credits must be calculated based on actual CO_2 emissions reduced, not estimated fuel consumed.

6. Field Implementation

6.1 Platform architecture

The diagnostic platform implements the carbon balance fuel derivation within a comprehensive diagnostic framework. The platform ingests exhaust emission profiles — captured via direct measurement probes or OEM telematics connectors — and combines them with engine operating parameters (RPM, load, boost pressure) and certified engine baseline configurations.

The system maintains a database of 24,079 EPA-certified engine configurations, each with rated emission baselines, rated fuel consumption, rated power, and rated speed. When a telematic reading is ingested, the platform automatically matches the vehicle’s engine to its certified baseline and applies the carbon balance ratio to derive estimated fuel consumption.

6.2 Calculation workflow

For each emission reading, the system executes the following:

- Retrieve the vehicle’s engine configuration, including rated CO_2 baseline (%) and rated fuel consumption (gal/hr), from the EPA Engine Universe.

- Capture the measured exhaust CO_2 concentration (%) from the telematic or probe reading.
- Apply the carbon balance ratio: Estimated Fuel Rate = (CO_2 measured / CO_2 rated) × Rated Fuel Rate.
- Compare the estimated fuel rate against the expected range for the engine at the observed RPM and load to identify excess fuel consumption.
- Generate prescriptive maintenance recommendations based on emission profile deviations from baseline, using a multi-phase tolerance system.

6.3 Worked example: 50-liter V16 diesel (Site B, northern Africa)

Using representative engine data from an open-pit commodity mine operation deployment on a 50-liter, V16, Tier 2 diesel engine powering a class 190-ton haul truck:

PARAMETER	VALUE
Engine configuration	50-liter, V16, Tier 2 diesel (representative 50-liter V16 class)
Rated power	1,860 kW (2,494 HP)
ISO rated fuel consumption (BSFC)	0.340 lbs/HP-hr → 119.4 gal/hr
Rated CO_2 baseline (from EPA certification)	7.5%
Pre-service CO_2 (measured)	11.4%
Post-service CO_2 (measured)	8.1%

Table 3: Worked-example engine configuration. Engine class is representative of the 50-liter V16 platform; specific operator and OEM identifications are anonymized.

Before service: Fuel Rate = (11.4 / 7.5) × 119.4 = 181.5 gal/hr

After service: Fuel Rate = (8.1 / 7.5) × 119.4 = 128.9 gal/hr

Fuel savings per unit: 52.6 gal/hr (29% reduction)

This result — a 29% fuel reduction corresponding to a 29% CO_2 reduction at constant load — demonstrates the direct proportionality predicted by the carbon balance theory. The fuel savings percentage equals the CO_2 percentage reduction, confirming the stoichiometric relationship. The pre-service CO_2 of 11.4% represents an extreme case (lambda ≈ 1.35, indicating severe air restriction or turbo deficiency); this was one of the most degraded engines in the fleet and is presented to illustrate the upper bound of savings potential rather than a typical result.

6.4 Continuous-monitoring deployment (method withheld)

For continuous fleet monitoring, the methodology can operate from commodity in-exhaust O_2 (lambda) sensors — widely available at $50–$200 per unit — in place of higher-cost continuous CO_2 instrumentation. The derivation by which an O_2 signal is resolved to the carbon-balance fuel-rate estimate of Section 2, together with its calibration constants, is the subject of pending patent applications and is not disclosed in this paper. All field results reported here rest solely on the public-domain carbon-balance relationship of Section 2 (40 CFR Part 1065, ISO 8178, SAE J1003).

7. Field Validation

7.1 Deployment summary

The methodology has been validated through field deployments across three continents, encompassing 124 engines and 3,058 emission tests. Deployments are anonymized to protect client confidentiality:

SITE	LOCATION / APPLICATION	ENGINES	TESTS (RESTATED)	TRACK	ENGINE CLASS (DESCRIPTOR)
A	Surface coal mine, Western U.S.	64	1,190	manual	78L / 85L V16, Tier 2
B	Open-pit commodity mine operation, northern Africa	14	18	manual	50L / 78L V16
C	Commodity mine, Western U.S. (demo)	5	5	manual	60L V16 — single-day demo
D	Open-pit commodity mine operation, Central Asia	5	17	manual	60L V16, Tier 1
E	Commuter rail, Western U.S.	16	16	manual	locomotive 2-stroke V16
F	Government / defense fleet (demo)	1	1	manual	genset — single-day demo
G	Surface mine, Western U.S.	5	10	manual	75L V16
H	Surface coal mine, Western U.S.	3	81	manual	mixed fleet
I	Surface coal mine, Western U.S.	10	114	manual	60L V16
J	Industrial minerals, Western U.S.	1	1,606	telematic	~52L (telematic stream)
TOTAL	**three continents**	124	3,058		**83 build-artifact rows**

SITE	LOCATION / APPLICATION	ENGINES	TESTS (RESTATED)	TRACK	ENGINE CLASS (DESCRIPTOR)
					excluded

Table 4: Validated field corpus (restated). Sites C and F are single-day demonstrations, excluded from portfolio impact totals; active impact basis is Sites A, B, D, E.

7.2 Site D (Central Asia): ground-truth fuel validation

The Site D deployment is of particular scientific significance because it included direct fill-to-fill fuel measurement alongside exhaust emission testing, supervised by the engine OEM’s field engineering team. This provides a controlled three-way comparison of fuel consumption measurement methods on the same five-engine fleet.

The fleet consisted of five class 240-ton haul trucks powered by 60-liter, V16, Tier 1 diesel engines rated at 2,300–2,500 HP at 1,900 RPM. These Tier 1 engines have no exhaust aftertreatment systems, and measurements were taken at the post-turbocharger exhaust point on each turbo bank (left and right measured independently). Fill-to-fill fuel tracking was conducted during November 2017, with a second supervised measurement period in May 2018 that included both fill-to-fill tracking and DEMS (Dispatch and Equipment Management System) fuel rate recording.

7.2.1 Three-way comparison results

TRUCK	CO_2% (AVG)	CO_2-DERIVED (L/H)	FILL-TO-FILL (L/H)	ECM LONG-TERM (L/H)	DEMS (L/H)	ECM VS FTF ERROR
D-1	7.56	114.7	128.7 / 129.6	146.7	140.3	+12.3%
D-2	7.84	118.9	131.3 / 134.8	142.2	132.8	+7.6%
D-3	8.18	124.1	123.2 / 135.3	148.5	138.1	+17.0%
D-4	7.75	117.5	138.8 / 140.6	139.6	129.4	+0.6%
D-5	8.15	123.6	148.1 / 134.6	148.2	138.4	+0.0%

Table 5: Three-way fuel rate comparison, Site D. Fill-to-Fill shown as November 2017 / May 2018 averages. ECM vs FtF Error is ECM long-term rate vs. Nov 2017 fill-to-fill.

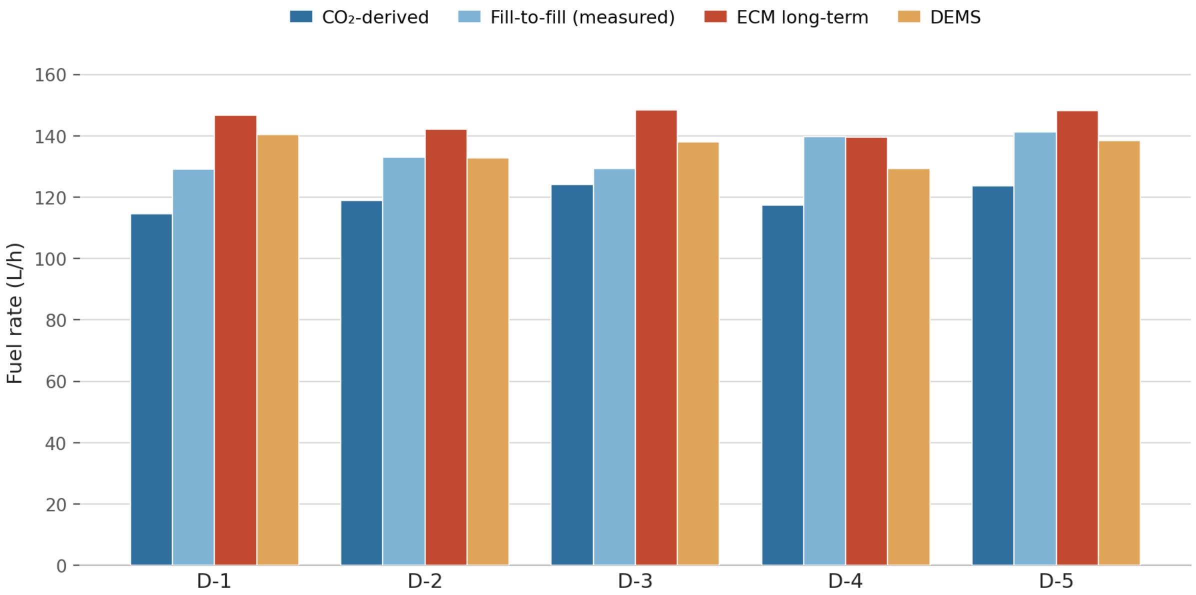

Figure 1: Three-way fuel rate comparison across the Site D five-truck fleet. CO_2-derived rates track fill-to-fill measured rates while ECM long-term and DEMS estimates diverge upward. Fill-to-fill shown as the November 2017 / May 2018 average.

7.2.2 Key findings

ECM over-reports fuel consumption in the majority of tested engines. Across the five-truck fleet, ECM long-term fuel rates exceeded fill-to-fill measured rates by up to 17%. For Truck D-3, the ECM reported 148.5 L/H while actual measured consumption was 123.2 L/H — a 20.5% overstatement. Two trucks (D-4 and D-5) showed ECM rates close to fill-to-fill measurements, suggesting the degree of overstatement varies by engine condition. Fleet managers relying solely on ECM data risk masking significant per-engine performance differences.

CO_2-derived rates track with physical measurement. The CO_2-derived fuel rates fall within the expected range of fill-to-fill measurements, particularly for trucks that received maintenance interventions. The two methods are measuring the same physical quantity — actual fuel burned — through different instrumentation pathways.

The methodology identifies per-engine maintenance opportunities. The emission profile data revealed specific, actionable maintenance items for each engine:

TRUCK	MAINTENANCE ACTIONS IDENTIFIED	CO_2% BEFORE	CO_2% AFTER
D-1	Baseline within tolerances — no intervention required	7.56	7.56
D-2	ECM calibration update, air filter replacement, exhaust leak repair	7.84	7.67
D-3	Timing solenoid replacement, air filter replacement	8.18	7.79

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TRUCK	MAINTENANCE ACTIONS IDENTIFIED	CO_2% BEFORE	CO_2% AFTER
D-4	ECM calibration, timing solenoid, injector adjustment (4-stage process)	7.75	7.75*
D-5	ECM calibration update	8.15	7.83

Table 6: Maintenance actions identified and CO_2 outcomes, Site D. *Truck D-4 initially improved but subsequently degraded post-deployment (see Section 7.2.3).

7.2.3 The monitoring loop: Truck D-4

Truck D-4 provides a compelling demonstration of ongoing-monitoring value. After initial testing and a four-stage intervention process (ECM calibration update, timing solenoid replacement, injector adjustment, and send-off verification), the engine was returned to service at a CO_2 of 8.11%. Subsequent monitoring revealed significant deterioration: CO_2 climbed to 8.59–8.70% at the follow-up check, triggering an out-of-scope alert.

Diagnostic analysis identified air intake system, turbo boost, and air filter issues as probable root causes. The ECM reported no fault codes for this engine during the same period. Without continuous emission-based monitoring, the fleet manager would have had no visibility into the degradation, and the engine would have continued consuming excess fuel until the next scheduled maintenance — potentially months later.

This case demonstrates the core value proposition of the methodology as a continuous monitoring capability — not a one-time diagnostic event, but an ongoing tool that catches problems conventional systems miss.

7.3 Site B (northern Africa): new-engine commissioning discovery

The Site B deployment produced an unexpected finding with significant commercial implications: brand-new engines from a major OEM were found to be significantly out of emission specification from the factory. These were not engines degraded by service life — they were new units that had never achieved their rated efficiency.

Emission testing on 14 vehicles identified substantial annual fuel savings potential across the tested fleet. One truck showed a 29% fuel reduction after a single maintenance intervention directed by the diagnostic. The operator’s full fleet at that mine represents multiples of this impact.

This discovery demonstrates applications beyond maintenance diagnostics. The methodology can serve as an engine commissioning and acceptance testing tool, enabling fleet operators to verify that new engines meet their rated performance specifications before accepting delivery — a quality assurance step that is currently absent from standard fleet procurement processes.

8. Fuel Savings Calculation Methodology

The fuel savings attributable to maintenance interventions directed by the methodology are calculated using the following relationships. At constant load and RPM:

Fuel Savings (%) = (CO_2 before − CO_2 after) / CO_2 before × 100

This equation follows directly from the proportionality established in Section 2: if fuel consumption is proportional to CO_2 concentration at constant conditions, then the percentage change in CO_2 equals the percentage change in fuel consumption.

The corresponding dollar savings are calculated as:

Annual Savings ($) = Fuel Savings (gal/hr) × Operating Hours/Year × Diesel Price ($/gal)

And the CO_2 reduction:

CO_2 Reduced (lbs) = Fuel Savings (gal) × 22.44 lbs CO_2/gal

9. Limitations and Future Work

The simplified ratio method presented in this paper assumes comparable operating conditions between measurements. The following limitations should be noted:

- Variable load conditions. In applications where engine load varies significantly between measurement periods, the ratio method should be applied within defined load and RPM windows rather than as a gross comparison.
- Altitude and barometric effects. The carbon-balance fuel-rate derivation is independent of barometric pressure because gas analyzers measure mole fraction. However, altitude affects absolute fuel consumption through reduced air density and potential power derate. The fuel rate derivation should account for altitude-adjusted rated fuel consumption if the engine is operating below its sea-level rated power.
- Fuel composition variation. While ULSD composition is tightly controlled, seasonal and regional fuel blends may introduce small variations in carbon mass fraction. For high-precision applications, fuel-specific w_C values should be used.
- Incomplete combustion products. The simplified ratio does not explicitly account for CO and unburned hydrocarbons (THC), which represent carbon that was not fully oxidized to CO_2. In well-maintained engines, these represent less than 1% of total exhaust carbon. In severely degraded engines, this fraction may increase, making the simplified ratio slightly conservative (understating fuel consumption).

Future work will incorporate the full carbon balance equation (including CO and THC terms) from 40 CFR §1065.655, integrate continuous telematics-based measurement for trending analysis, and expand the validation dataset through additional on-road and off-highway pilot programs.

10. Conclusions

This paper demonstrates that exhaust CO_2 concentration provides a scientifically sound, regulatory-endorsed, and field-validated basis for deriving fuel consumption in diesel engines. The methodology is grounded in the same carbon balance principles used by the EPA, ISO, SAE, EU, and IMO for engine certification testing — applied here to the novel context of continuous field-level fleet diagnostics.

Key conclusions:

- The relationship between exhaust CO_2 concentration and fuel consumption at constant load and RPM is stoichiometric — it is chemistry, not estimation. It is codified in ISO 8178, 40 CFR Part 1065, SAE J1003, EU 2017/2400, and the IMO NOx Technical Code.
- The CO_2-derived fuel rate measures actual combustion output, making it structurally more accurate than ECM-reported fuel rates for fleet cost optimization and carbon accounting applications.
- Field validation at Site D (Central Asia) through three-way comparison — CO_2-derived, fill-to-fill measured, and ECM-reported — confirms the methodology. ECM estimates diverged from physical measurement by up to 17%, while CO_2-derived rates tracked actual consumption.
- The platform identifies specific, prescriptive maintenance actions at the per-engine level — a capability that conventional ECM-based fleet management systems cannot provide.
- The methodology enables quantification of fuel savings from maintenance interventions, is applicable to carbon-accounting use cases that quantify emission reductions from measured combustion output, and extends to new-engine commissioning and acceptance testing.
- Continuous telematic monitoring is supported using commercially available O_2 sensors. The derivation by which an O_2 signal is resolved to the carbon-balance fuel-rate estimate, and its calibration values, are proprietary and the subject of pending patent applications.

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> **Disclosure:** The methodology described in this paper is implemented in a proprietary diagnostic platform protected under US Patent 10,718,284 B2 (43 claims) and Indian Patent 553,370 (16 claims), with additional applications pending. The authors are co-inventors of the underlying system. Correspondence: jforbush@starboardresearch.org.