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From Direct Sensing to Combustion Chemistry: Field-Driven Methodology Evolution in Heavy-Duty Diesel Emissions Diagnostics, 2015–2026

A Decade Account of How Field Discipline, Sensor Economics, and Operational Engineering Shaped a Diagnostic Methodology

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Abstract

Heavy-duty diesel emissions diagnostics is often presented as a settled discipline — a matter of reading sensors and comparing readings to thresholds. The reality of field deployment is more interesting. Over the period 2015–2026, an emissions-based maintenance methodology developed for surface mining haul trucks and adjacent applications underwent a series of structural changes that none of its founding documents anticipated. This paper is a retrospective account of those changes.

We describe four inflection points: (1) the 2015 fleet-scale operational validation that demonstrated sustained per-engine fuel reductions before any sensor-development work; (2) the 2018 field trials in Central Asia that established three-way ground-truth validation (CO_2-derived, fill-to-fill volumetric, ECM-reported) alongside a parallel, USTAR-funded Strategic Partnership Project that sponsored evaluation of solid-state CO and HC exhaust gas sensors for field deployability with a national laboratory (a separate sensor-deployability effort, not a validation of the carbon-balance methodology); (3) the methodology shift from direct CO_2 measurement at scheduled diagnostic events to continuous O_2-based monitoring driven by sensor economics; and (4) the platform consolidation that scaled the methodology from per-engine specialist analysis into a multi-tenant diagnostic substrate spanning multiple OEMs and EPA engine tiers.

The paper is intended for engineering and operations audiences in heavy-duty diesel applications, with secondary relevance for measurement-and-verification practitioners. It is structured chronologically because the methodology evolution was driven by field findings, not by theoretical advance — the story is the chronology.

Keywords: *diesel emissions diagnostics; carbon balance method; field validation; fleet telematics; methodology evolution; mining haul trucks; sensor economics.*

1. Setting the Stage

1.1 The state of practice circa 2015

In the mid-2010s, fleet operators of heavy-duty diesel assets — particularly in surface mining — had two practical tools for understanding per-engine fuel consumption and emissions: (a) Engine Control Module data via the SAE J1939 CAN bus, principally SPN 183 (“Engine Fuel Rate”), and (b) fill-to-fill volumetric measurement, which is accurate but operationally cumbersome and rarely conducted at per-engine granularity outside of OEM-supervised field tests.

Both tools have limitations that were well-understood within engine engineering communities but poorly communicated to fleet operators. ECM fuel rate measures fuel-to-injector, not fuel-burned, which is a different question in any modern return-flow diesel fuel system. Fill-to-fill measurement, while accurate, captures only an aggregate over the measurement window — it provides no insight into which engine event consumed the excess fuel or why.

A third tool — exhaust emission profiling — had been the regulatory gold standard for engine certification for decades. ISO 8178 (international), 40 CFR Part 1065 (U.S. EPA), and SAE J1003 codify the carbon balance method as the certification-grade approach to determining fuel consumption from exhaust gas composition. But this tool had not crossed the boundary from certification laboratories into field-level fleet diagnostics. The exhaust analyzers were expensive; the data processing was specialist work; and the connection between an emission profile and a specific maintenance action was nowhere documented.

1.2 The field problem that motivated the work

The diagnostic methodology that became the subject of this paper originated in an operational frustration. Mining haul trucks were burning more fuel than their rated specifications predicted, and conventional diagnostic tools — OEM service indicators, ECM fault codes, fleet telematics dashboards — were silent. Engines that ECMs reported as “healthy” were sometimes the largest fuel offenders. Engines that ECMs reported with fault codes were sometimes performing within tolerance and consuming fuel appropriately. The fault-code-to-fuel-consumption signal was weak.

Steve Forbush, drawing on more than 40 years in heavy-duty diesel engineering and field service, formulated a hypothesis: the engine’s exhaust chemistry contains a more direct signal of combustion state than its ECM data does. The chemistry doesn’t lie. If an engine is burning more fuel than its rated baseline, its exhaust CO_2 concentration will reflect that fact, regardless of what the ECM reports.

The hypothesis is, in retrospect, obvious. It is the central insight underlying ISO 8178 and 40 CFR Part 1065. The question was whether it could be operationalized for field deployment at the per-engine level on operating fleets, in contrast to laboratory test cells under controlled conditions.

2. 2015: Fleet-Scale Operational Validation

2.1 The first sustained-reduction demonstration

The methodology’s first fleet-scale operational validation was conducted in early 2015 as an early multi-truck deployment at a surface coal mine in the Western U.S., on large-displacement V16 Tier-2-class haul-truck engines. The deployment captured baseline fuel consumption over a several-month baseline period, then applied the emission-profile-directed maintenance interventions (ECM calibration adjustments, injector service, air filtration), then captured post-intervention fuel consumption over the subsequent months.

The deployment demonstrated a sustained, double-digit-percent reduction in gallons-per-hour fuel consumption across the fleet, measured against the prior multi-month baseline. The reduction was not a one-time event — it persisted across the post-intervention observation window, and longer-tail observation at the same deployment confirmed durability over continued operation.

This is the earliest data point in the methodology’s history. It predates any sensor-development work, any laboratory collaboration, and any platform-development work. It establishes that the underlying physics — exhaust chemistry as a signal of combustion state, with carbon balance providing the path from emission profile to fuel consumption — was operationally tractable on real operating fleets in 2015, with portable instrumentation and trained engineering judgment as the only required infrastructure.

The methodology evolution described in subsequent sections did not invent the capability. It scaled, automated, and made continuous a capability that was first operationally demonstrated on a single Western U.S. surface coal mine in early 2015.

2.2 What the early deployment also exposed

Validation events are also, often, problem-identification events. The 2015 work confirmed that the methodology produced sustained fuel reductions — but it also exposed the deployment economics. Each emission test required portable gas analyzers, trained technicians, on-engine sampling, and roughly 30 minutes per engine. This was tractable for the diagnostic-event use case (a fleet operator wants to characterize a fleet, identify maintenance opportunities, and quantify the savings). It was not tractable for continuous monitoring at fleet-wide scale, where the data flow needs to be passive and ongoing rather than active and scheduled.

The constraint was specifically a sensor-economics constraint. Portable NDIR-based CO_2 analyzers suitable for in-exhaust sampling cost thousands of dollars per unit and require periodic calibration and maintenance. They are inappropriate for permanent installation on every engine in a fleet of hundreds or thousands of vehicles. To move the methodology from the 30-minute-per-engine diagnostic to a continuous-monitoring substrate, a different sensor approach was needed. This is the problem that motivated the work described in Section 3.

3. 2018: Sensor Field Trials and Ground-Truth Validation

3.1 The Central Asia three-way comparison

In May 2018, parallel to other technical work described in this section, the methodology team conducted a controlled field deployment at an open-pit commodity mine operation in Central Asia. The fleet consisted of five 240-ton-class haul trucks powered by 60-liter, V16, Tier 1 diesel engines rated at 2,300–2,500 HP at 1,900 RPM. These were Tier 1 engines with no exhaust aftertreatment — ideal subjects for emission profiling because the post-turbocharger exhaust composition reflected combustion directly, without diesel oxidation catalyst, DPF, or SCR chemistry to filter the signal.

The deployment's scientific significance was the inclusion of direct fill-to-fill fuel measurement alongside exhaust emission testing. The engine OEM's field engineering team supervised the fuel measurement program. This provided a controlled three-way comparison: CO_2-derived fuel rate, supervised fill-to-fill volumetric measurement, and ECM-reported fuel rate via SPN 183 — on the same five engines, in the same operating conditions, on the same routes. The companion paper Section 7.2 reports the three-way comparison numerically; we summarize the structural finding here.

- CO_2-derived fuel rates tracked fill-to-fill measurement within the expected range for engines that received maintenance interventions.
- ECM-reported fuel rates systematically overstated actual fuel consumption — by up to 17%, with one engine (D-3) at 20.5% — as observed in this deployment and varying with engine condition rather than asserted as a fixed property of any OEM ECM.
- The CO_2-based diagnostic identified per-engine maintenance opportunities (ECM calibration, timing solenoid replacement, air filter and intake repair) that ECMs did not flag and that conventional fleet management did not detect.

The 2018 Central Asia deployment is the ground-truth validation event in the methodology's history. It established that the carbon balance approach — deployed at field scale, on operating fleets, supervised by OEM engineering personnel — produced fuel-rate estimates consistent with the regulatory gold standard (fill-to-fill volumetric), and identified maintenance opportunities that conventional methods missed.

3.2 Parallel work: solid-state exhaust gas sensors

Parallel to the Central Asia field deployment, the methodology team conducted exhaust-gas sensor field-trial work across 2017–2018 on a Western U.S. open-pit mining haul truck under a Strategic Partnership Project (SPP) agreement with a U.S. Department of Energy national laboratory. The arrangement was structured as follows: the methodology team received a State of Utah Science Technology and Research (USTAR) Technology Acceleration Grant and applied a portion of those funds to sponsor an SPP agreement with the national laboratory under which laboratory personnel evaluated solid-state electrochemical CO and HC exhaust gas sensors developed at the laboratory.

The work tested whether the laboratory’s solid-state sensor portfolio could operate on the methodology team’s telematics substrate under harsh-environment conditions — vibration, dust, heat — representative of active mining service. Bench testing was completed at the laboratory; field testing was conducted on a 70-ton haul-truck platform instrumented with a post-turbocharger exhaust sampling line and a separately-acquired commercial wideband O_2/NOx sensor that fed the team’s telematics data flow alongside the laboratory’s CO/HC sensors. The agreement formally closed in October 2018.

The SPP work was about sensor deployability, not methodology validation. The stoichiometric framework that subsequently became the basis for the methodology’s continuous-monitoring substrate (described in Section 4) is grounded in combustion-chemistry first principles that long predate the SPP. The SPP’s contribution to the methodology’s evolution was different: it confirmed that real-time exhaust gas analysis was technically tractable on operating heavy-duty diesel equipment under harsh-environment field conditions. That confidence, more than any specific sensor outcome, informed the subsequent decision to standardize on commercial O_2 sensors rather than continue investment in specialty CO/HC sensor development.

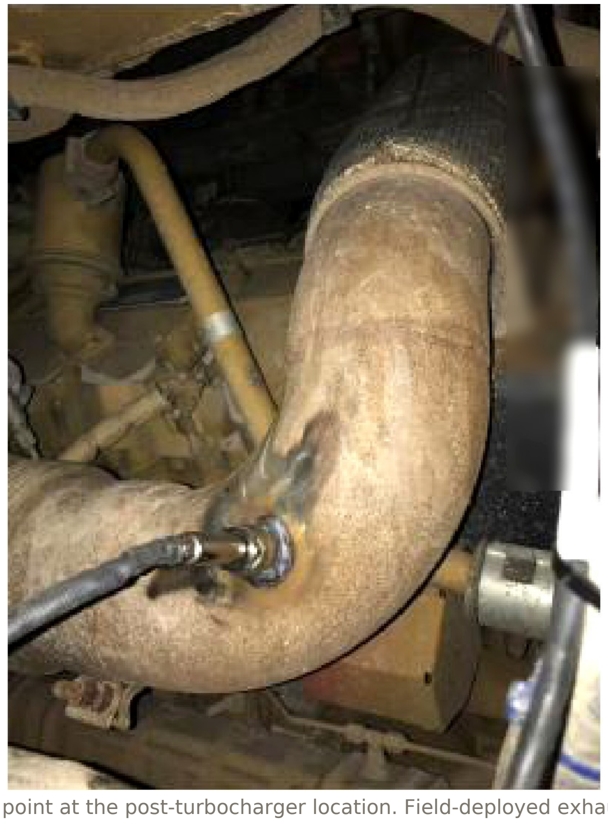

Figure 1: Exhaust gas sampling point at the post-turbocharger location. Field-deployed exhaust sampling at this point captures the direct output of combustion before any aftertreatment chemistry intervenes; on Tier 1 / Tier 2 engines without aftertreatment, it captures unmodified exhaust chemistry. (2018 field deployment context.)

Because the diagnostic samples at the post-turbocharger, pre-aftertreatment point, the framework applies to Tier 4 / Stage V engines on the same basis as Tier 1 and Tier 2: aftertreatment is downstream of the measurement and does not alter the captured combustion signal. Engine-specific differences are absorbed by comparison to each engine's certified baseline.

Figure 2: Field-deployed telematics instrumentation in a protected equipment compartment. Continuous capture of engine-control parameters at engine-cycle cadence supports the diagnostic substrate; the same physical install supports both the diagnostic-event use case and the continuous-monitoring use case described in Section 4. (2018 field deployment context.)

4. The Sensor Economics Pivot

4.1 The economic constraint

As of the early 2020s, the per-unit cost picture for the relevant exhaust sensors looked roughly as follows:

SENSOR TYPE	PER-UNIT COST	MAINTENANCE / CALIBRATION	FIELD-DEPLOYMENT SUITABILITY
NDIR CO_2 (laboratory-grade)	\$5,000–\$20,000+	Periodic calibration; specialist support	Diagnostic events only; not continuous
Portable NDIR CO_2 (handheld)	\$1,500–\$5,000	Periodic calibration; trained operator	Diagnostic events only; not continuous
Wideband O_2 / lambda (automotive grade)	\$50–\$200	Self-calibrating; long service life	Suitable for continuous in-engine deployment
Industrial O_2 cell	\$100–\$400	Periodic replacement (annual)	Suitable for continuous; some hardening needed

Table 1: Approximate sensor economics circa early 2020s. Costs vary by manufacturer, application context, and integration requirements. The structural picture — O_2 sensors substantially cheaper than CO_2 sensors at specifications suitable for continuous in-exhaust deployment — has been stable for the relevant time period.

The pricing gap is not narrow and not closing. CO_2 NDIR cells require optical components and reference-cell isolation; O_2 sensors are essentially small electrochemical or zirconia-based devices manufactured at automotive volumes. Continuous monitoring economics tilt decisively in favor of O_2 sensing as long as the carbon balance methodology can be made compatible with O_2-derived data.

4.2 The methodology pivot

The pivot was to retain the carbon balance methodology while moving continuous-monitoring deployments from direct CO_2 sensing to commodity O_2 sensing for reasons of sensor economics. The derivation by which an O_2 reading is resolved to the carbon-balance CO_2 value used in the fuel-rate ratio is the subject of pending patent applications and is not described here; the downstream fuel-rate computation of Section 2 is unchanged.

The pivot preserves the methodology's structural integrity: the ratio of measured (or back-calculated) CO_2 to certified rated CO_2, multiplied by the engine's rated fuel rate, yields a per-engine fuel consumption estimate that is grounded in the regulatory carbon balance method. What changes is the sensor at the engine.

Diagnostic deployments (the 30-minute-per-engine emission test, on demand) continue to use direct CO_2 sensing with portable NDIR analyzers. The accuracy of direct sensing is preferable when sensor cost is not the binding constraint and a trained technician is on-site.

Continuous monitoring deployments use commodity O_2 sensors integrated with telematic data flows, with stoichiometric back-calculation to CO_2 happening server-side. This makes fleet-wide continuous monitoring economically tractable in a way that direct CO_2 sensing is not.

4.3 The 2024–2026 field validation period

The methodology pivot required field validation under operating conditions — not just to confirm the stoichiometric relationship holds (it does), but to characterize the operational considerations: sensor placement, sample conditioning, response time, sensor drift over service life, and integration with the engine's telematic data flow.

The 2024–2026 validation period focused on these operational questions. Field deployments captured paired O_2 and CO_2 readings across operating conditions, enabling characterization of the relationship under field-realistic variability (fuel composition variation, ambient condition variation, engine state variation). Detailed validation statistics, calibration parameters, and engine-tier coefficient sets that operationalize the relationship across diverse fleet conditions are maintained as proprietary methodology.

The structural finding from the validation period is that the stoichiometric relationship holds with high robustness in field deployments. Deviations from the expected stoichiometric pattern, when they occur, are themselves diagnostically informative: they correspond to identifiable engine states (incomplete combustion; fuel composition anomalies; sensor calibration drift) that warrant separate diagnostic attention. The deviation itself becomes a diagnostic signal.

5. Platform Consolidation: From Methodology to Multi-Tenant Diagnostic Infrastructure

5.1 Why a platform was needed

A diagnostic methodology is not the same as a deployable system. The 2015–2026 evolution included a parallel track of platform development that took the methodology from a per-engine analysis conducted by trained specialists on individual mine sites to a substrate designed to support thousands of engines across multiple fleets, multiple EPA tier levels, and multiple OEMs.

Three platform requirements drove the consolidation work:

- Engine-baseline matching. The methodology requires comparing measured emission profiles to certified rated emission profiles. With tens of thousands of EPA-certified engine families across 200+ manufacturers in the EPA Engine Universe alone (and additional non-U.S.-certified engines in international deployments), a manual lookup process is not scalable. The platform automates the matching from vehicle / engine identifier through to the appropriate certified baseline.
- Cross-OEM and cross-tier normalization. Engine families differ across OEMs and across EPA tier levels in rated baselines and exhaust architecture. The diagnostic substrate abstracts these engine-specific differences from the underlying carbon-balance calculation, so the same measurement pipeline applies across a heterogeneous fleet without forking the methodology per engine type.
- Customer fleet onboarding. Real-world fleet documentation arrives as unstructured spreadsheets, OEM service records, maintenance logs, and operator data feeds. An AI-assisted onboarding pipeline converts this unstructured input into the structured engine-asset records the platform requires for diagnostic operation.

5.2 What the platform supports today

As of 2026, the platform supports:

- Diagnostic events conducted with portable instrumentation at the 30-minute-per-engine scale (the original 2015-era use case, now operationally mature).
- Continuous monitoring via O_2-sensor telematic feeds with stoichiometric back-calculation (the post-pivot use case described in Section 4).
- Retrospective replay of historical telematic data to establish longitudinal baselines and characterize asset-level degradation trends without requiring forward-looking measurement campaigns.
- Cross-fleet aggregate impact reporting of the kind summarized in the companion paper (“Cumulative Fuel and CO_2 Impact of Emissions-Based Maintenance,” June 2026).

The platform itself is the product of a decade of incremental work and is subject to its own intellectual property protection regime. Specific platform architectural decisions and implementation details are outside the scope of this methodology-retrospective paper.

6. What We Learned

6.1 The methodology evolved because the field demanded it

Looking back, none of the inflection points described in this paper were predicted by the methodology’s founding documents. The 2015 fleet-scale work was scoped as a service engagement; it became, in retrospect, the operational validation that justified the entire downstream methodology program. The 2018 Central Asia deployment was scoped as a customer engagement; it became the ground-truth validation against the regulatory gold standard. The parallel 2017–2018 sensor field-trial work was scoped as a deployability test; it became the confidence basis for the eventual sensor-economics pivot. The pivot itself was scoped as a cost-reduction step; it became the foundation for continuous-monitoring as a distinct product category from on-demand diagnostics.

The pattern is consistent: field deployment reveals constraints (operational, economic, regulatory) that the founding methodology did not anticipate, and those constraints drive the methodology's evolution. Laboratory work and theoretical analysis can confirm or refute specific hypotheses, but they cannot, by themselves, generate the right hypotheses to test. The right hypotheses to test come from field discipline — from doing the work, observing what breaks, and identifying which part of the methodology the field considers binding.

6.2 ECM data is structurally less reliable than fleet operators believe

The most operationally consequential finding of the 2018 Central Asia work is that ECM-reported fuel rates systematically overstate actual fuel consumption in the majority of engines, with overstatements reaching up to 17% (one engine at 20.5%) and lower-but-still-material overstatements on most others, as observed in this deployment. This finding is structural — it reflects how modern diesel return-flow fuel systems work and what J1939 SPN 183 actually measures — not an artifact of the test fleet.

Fleet operators using ECM telematics as the basis for fuel cost analysis, carbon accounting, or per-engine performance benchmarking are operating with a structurally biased input. The bias is correctable, but only with a measurement approach (such as carbon balance) that captures fuel-burned rather than fuel-injected. As fleet decarbonization strategies become more carbon-accounting-sensitive, the materiality of this bias grows.

6.3 The regulatory framework was ready before the field methodology was

ISO 8178 (1996, current edition 2020/2021), 40 CFR Part 1065 (2008, with subsequent updates), and SAE J1003 (multiple revisions since the 1960s) codified the carbon balance method as the regulatory gold standard for engine certification long before field deployment at the per-engine level was operationally tractable. The 2015–2026 evolution did not develop a new methodology — it operationalized an existing one. The regulatory framework was waiting; the field methodology had to catch up.

This pattern is also consistent: the conceptual rigor was in place; the operational engineering was the binding constraint. Continuous deployment economics, telematic integration, cross-OEM compatibility, customer fleet onboarding from unstructured inputs — these were the binding constraints that absorbed most of the development effort. The chemistry was settled in the nineteenth century (the basic stoichiometry of hydrocarbon combustion); the engineering was settled in the 1990s–2000s; the operationalization at fleet scale required the 2015–2026 work.

6.4 The next decade

Several directions are open as of 2026 that we expect to be substantive in the next decade:

- Accumulation of Tier 4 / Stage V field data through pre-aftertreatment telematic capture, and treatment of the post-aftertreatment (tailpipe) measurement case, where DOC/DPF/SCR chemistry alters exhaust composition and the carbon balance requires adjustment relative to the pre-aftertreatment sampling point.
- Expansion beyond off-highway mining into other heavy-duty diesel applications — on-road commercial, marine, rail, stationary power generation — where the underlying physics is identical and the operational context varies.
- Methodology applicability to alternative fuels (renewable diesel, biodiesel blends, hydrogen blends in dual-fuel applications) where the carbon mass fraction and stoichiometric constants differ from #2 ULSD and require fuel-specific calibration.

7. Conclusions

The 2015–2026 evolution of an emissions-based maintenance methodology illustrates the structural pattern that recurs in applied engineering: the conceptual basis is established (often decades earlier); the regulatory framework is in place; the operational engineering is the binding constraint. Progress comes from doing the work — in this case, field deployments at surface mines on three continents, with ground-truth validation supervised by an engine OEM's field engineering team in Central Asia, and parallel exhaust-sensor field-trial work conducted under a USTAR (Utah Science Technology and Research) Technology Acceleration Grant that sponsored a Strategic Partnership Project evaluating CO and HC sensor deployability with a national laboratory.

Four specific findings warrant emphasis:

- The carbon balance method, established as regulatory gold standard for engine certification, is operationally tractable for per-engine field diagnostics and continuous fleet monitoring.
- ECM-based fleet telematics systematically overstate fuel consumption in modern return-flow fuel systems. The overstatement is structural and, in this deployment, reached up to 17% (with one engine at 20.5%).
- Stoichiometric back-calculation from commodity O_2 sensors substitutes effectively for laboratory-grade CO_2 sensing in continuous-monitoring deployments.
- A diagnostic platform abstracting the methodology across multiple OEMs and EPA engine tiers consolidates a decade of methodology evolution into a substrate designed to scale to thousands of engines across diverse fleet applications.

None of these findings represent a discovery of new physics. They represent the slow, durable work of bringing established physics into operational practice at field scale. The companion papers ("Exhaust CO_2-Based Fuel Consumption Derivation," June 2026, and "Cumulative Fuel and CO_2 Impact of Emissions-Based Maintenance," June

2026) document the methodology in technical detail and report the aggregate impact across the deployment portfolio, respectively.

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The authors also acknowledge the customer organizations whose operating fleets served as the field-deployment environments for the methodology over the 2015–2026 period. By agreement, those organizations are not named; the deployment-class anonymization used in this paper and the companion papers reflects that confidentiality.

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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 and Indian Patent 553,370, with additional applications pending. Specific calibration constants, validation statistics, and engine-tier coefficient sets are maintained as proprietary methodology. Correspondence: jforbush@starboardresearch.org.