

# Ethanol-Blended Fuel Optimization for Improving Efficiency and Reducing Emissions in Indian Commercial Trucks

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## Abstract:

This paper evaluates ethanol-assisted decarbonization pathways for Indian commercial trucks by focusing on the constraints of heavy-duty compression-ignition engines rather than gasoline-oriented blending narratives. Two technically credible routes are examined: low-level stabilized ethanol-diesel blends and ethanol-diesel dual-fuel operation, in which diesel remains the ignition source while ethanol supplies a controlled share of total fuel energy. Drawing on published studies of fuel stability, lubricity, ignition delay, low-temperature combustion, reactivity-controlled compression ignition, and heavy-duty dual-fuel performance, the paper develops a Retrofit Ethanol Assist Module (REAM) as a supervisory add-on architecture. REAM combines composition awareness, load-dependent ethanol scheduling, pilot-diesel preservation, combustion-safety guard rails, and aftertreatment thermal protection to support practical retrofit deployment. The literature indicates that ethanol can substantially reduce soot and, under optimized medium-to-high-load operation, can lower nitrogen oxides while maintaining competitive efficiency. However, aggressive substitution at low load can reduce combustion efficiency, depress exhaust temperature, and increase misfire risk. A staged validation framework is therefore proposed for safe, calibration-aware ethanol use in Indian freight applications.

**Keywords** - ethanol-diesel dual fuel, heavy-duty diesel engine, Indian commercial trucks, retrofit control, emissions reduction, fuel optimization, REAM, combustion stability.

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## I. INTRODUCTION

India's freight system depends heavily on road transport, and medium- and heavy-duty trucks remain central to goods movement across long intercity corridors and dense urban logistics networks. In practical terms, this means that a large fraction of transport-sector fuel use is concentrated in vehicles that operate for long hours, accumulate high annual mileage, and prioritize reliability above all else. Studies of heavy-duty truck fuel consumption show that grade, mass, cruising speed, route profile, and transient operation materially affect fuel use, making freight decarbonization a coupled problem of vehicle technology, calibration, operations, and infrastructure [1], [2]. At the same time, real-world emissions measurements of heavy-duty diesel trucks show that freight vehicles continue to contribute substantially to greenhouse-gas emissions and to criteria pollutants despite advances in exhaust aftertreatment [1]. For India, this technical challenge is also an economic one because the transport sector has historically depended on

imported petroleum, increasing vulnerability to crude-price volatility and external supply risks [3].

Ethanol has emerged as an attractive transportation fuel because it is renewable, oxygenated, domestically producible, and already embedded in India's policy discourse. The strongest policy momentum has been in ethanol-gasoline blending for spark-ignition engines, where ethanol's high octane number, oxygen content, and cooling effect can support better combustion and lower carbon monoxide and hydrocarbon emissions [3], [16]–[19]. Yet the direct transfer of this policy framing to commercial trucks is technically incomplete. Most Indian commercial trucks operate with compression-ignition diesel engines, not gasoline engines. These engines rely on fuel auto-ignition quality, spray breakup, mixing-controlled combustion, and stringent aftertreatment temperature management. Ethanol, by contrast, has a low cetane number, lower volumetric energy density than diesel, limited miscibility with diesel, and different lubricity behavior. These characteristics can be beneficial in some combustion regimes and problematic in others. Any

high-quality paper on ethanol use in trucks must therefore distinguish between gasoline-oriented blending narratives and the more difficult problem of ethanol deployment in diesel freight platforms.

This manuscript addresses that distinction explicitly. Rather than treating ethanol-assisted operation as a generic blending idea, it evaluates two realistic pathways for Indian commercial trucks. The first is stabilized low-level ethanol-diesel blending, often called e-diesel, where ethanol is blended into diesel with attention to water sensitivity, additive selection, phase stability, and fuel-system protection [4], [7], [8]. The second is ethanol-diesel dual-fuel operation, in which ethanol is supplied through a separate path or premixing route while diesel remains the high-reactivity pilot for ignition control [9]–[15]. The second route has become especially important in the literature because it allows higher ethanol substitution without demanding that ethanol behave like diesel inside the injector and combustion chamber. It also better reflects the architecture most likely to succeed in retrofits.

Accordingly, the discussion is organized around a systems perspective that links fuel properties, combustion constraints, retrofit control architecture, validation methodology, and literature-benchmarked operating windows. This framing separates conceptual benchmarking from experimental claims and places the proposed REAM concept within the heavy-duty diesel literature most relevant to Indian freight applications.

The core contribution of this paper is therefore a control-oriented retrofit framework called the Retrofit Ethanol Assist Module, or REAM. REAM is not presented as a finished commercial product. Rather, it is a technically grounded supervisory architecture that could sit on top of an existing diesel truck platform and modulate ethanol utilization in a safe, emissions-aware, and durability-conscious way. The module concept combines fuel-composition awareness, injector correction logic, load-dependent ethanol energy fraction limits, low-load protection, aftertreatment thermal safeguards, and adaptive scheduling across steady-state and transient operation. By synthesizing evidence from the best available studies on heavy-duty ethanol-diesel combustion, the paper develops a coherent basis for future bench and fleet validation in the Indian context.

## II. LITERATURE REVIEW AND TECHNICAL BACKGROUND

### A. Ethanol Pathways for Commercial Truck Applications

A careful review of the literature shows that ethanol is not a single engineering solution but a family of possible interventions whose suitability depends on the base engine, blend ratio, injection system, and control strategy. In spark-ignition engines, ethanol blending is comparatively mature. Reviews and engine studies consistently report reductions in carbon monoxide and hydrocarbon emissions due to ethanol's oxygen content, while noting the familiar trade-off of lower fuel economy on a volumetric basis because ethanol carries less energy per liter [3], [16]–[19]. These studies matter because

they help explain India's policy confidence in E10 and E20 for gasoline vehicles, but they do not by themselves establish a pathway for heavy-duty trucks.

For diesel engines, the first technical barrier is fuel compatibility. Lapuerta et al. showed that ethanol–diesel blends are highly sensitive to temperature, water content, and additive chemistry, with phase separation becoming a primary concern as ethanol concentration rises [7]. This is not a minor laboratory inconvenience. In field conditions, truck fuel systems experience temperature swings, storage variability, and contamination risks that can destabilize poorly formulated blends. Even when phase stability is managed, lubricity remains a second constraint. Kuszewski et al. demonstrated that ethanol can degrade lubricity in diesel blends and that this issue must be addressed if injector durability and pump wear are to remain acceptable over commercial service intervals [8]. These two findings alone explain why high-ethanol direct blending is not a simple drop-in proposition for freight fleets.

Combustion studies further complicate the picture. Early work on ethanol-blended diesel fuels found that adding ethanol can lengthen ignition delay, modify heat-release phasing, and reduce soot formation because the oxygenated fuel suppresses rich diffusion-flame regions [4], [20]. These effects are often beneficial for smoke and particulate matter, but they can also destabilize combustion if the calibration is not adapted. Arslan et al. reported that ethanol-blended diesel can alter brake-specific fuel consumption and exhaust emissions in ways that vary strongly with blend ratio and operating condition [16]. In practical terms, this means that no single ethanol percentage can be assumed optimal across idle, part load, rated torque, and transient acceleration.

Over the last decade, the most compelling evidence for heavy-duty truck applications has come from ethanol–diesel dual-fuel and related low-temperature combustion studies. Pedrozo et al. showed in a series of influential papers that ethanol can be used as a substantial diesel substitute while simultaneously reducing nitrogen oxides and soot when calibration is optimized for specific load regions [9]–[11]. Their low-load study is particularly important because it reveals the main failure mode of aggressive ethanol substitution: at very low load, lean and cool combustion can lower combustion efficiency, reduce exhaust temperature, and make oxidation-based aftertreatment less effective [9]. Their mid-load and full-load studies, by contrast, demonstrate why ethanol remains attractive: once the engine is in an appropriate thermal and load window, dual-fuel operation can achieve low soot and very large nitrogen oxide reductions with competitive or improved efficiency [10], [11].

Han et al. extended this evidence to a heavy-duty engine under stationary-cycle conditions and showed that ethanol mass ratios can be increased substantially at low to medium loads, but also that incomplete combustion and calibration limitations emerge when substitution is pushed beyond the stable operating window [12]. Asad et al. further showed that optimized ethanol–diesel dual-fuel operation can reduce the classical diesel NO<sub>x</sub>–soot trade-off while maintaining high thermal

efficiency over a broad load range [13]. Their work is especially relevant for retrofit control because it links combustion strategy not only to in-cylinder performance but also to downstream aftertreatment behavior, including the possibility of reducing selective catalytic reduction burden when engine-out emissions are lowered [13].

These findings connect naturally to the broader literature on advanced combustion. Asad et al. positioned ethanol-fueled low-temperature combustion as a pathway to cleaner diesel cycles by leveraging ethanol’s high octane number and evaporative characteristics [14]. Reitz and Duraisamy’s review of RCCI combustion remains one of the most authoritative references for understanding how combinations of high- and low-reactivity fuels can deliver low-emission, high-efficiency combustion, while also making clear that control complexity rises sharply when fuel reactivity stratification is deliberately

engineered [15]. In other words, ethanol’s promise in diesel engines is inseparable from a control problem. The fuel can improve the combustion process, but only when injection timing, pilot quantity, substitution ratio, dilution, thermal state, and pressure-rise constraints are jointly managed.

For the present paper, the literature therefore suggests three defensible conclusions. First, ethanol should not be framed as a universal drop-in blend for diesel trucks. Second, low-level stabilized blending and dual-fuel substitution are distinct pathways with different risks and benefits. Third, the most credible route for near-term retrofit application is a supervisory control system that uses ethanol opportunistically within safe windows rather than universally at all times. This conclusion motivates the REAM concept developed in the next sections. These trade-offs are summarized in Table I.

TABLE I. PRACTICAL ETHANOL DEPLOYMENT PATHWAYS FOR HEAVY-DUTY INDIAN TRUCKS

Pathway	Technical basis	Advantages	Key constraints	REAM role
Low-level stabilized ethanol–diesel blend	Direct blending with additives and water control	Simpler hardware pathway; partial fossil displacement	Miscibility, water sensitivity, lubricity, seasonal storage	Blend-aware correction and protection fallback
Dual-fuel ethanol–diesel operation	Diesel pilot with ethanol as supplementary energy source	Higher substitution potential; strong soot reduction	Low-load stability, thermal weakness, pilot calibration	Load-aware ethanol scheduling and pilot preservation
High-substitution research operation	Aggressive substitution under tightly tuned conditions	Maximum laboratory carbon displacement	Narrow stability margins; higher calibration burden	Not default fleet strategy; use only as upper benchmark

*B. Research Gap and Publication Motivation*

Despite the growing literature, a clear research gap remains between laboratory demonstrations of ethanol-assisted diesel combustion and the realities of India’s commercial truck fleet. Many published studies use single-cylinder engines or highly instrumented research engines under tightly controlled operating points [10]–[15]. These studies are extremely valuable for mechanism discovery, but freight operators and retrofit designers need a different output: a robust decision framework for when ethanol should be introduced, how much should be introduced, what sensing is required, how injector corrections should be applied, and what protective limits must override the strategy in real operation.

A second gap lies in how results are communicated. Many studies report generalized performance trends without clearly distinguishing original measurements, simulations, and literature-derived benchmarks. For a control-oriented retrofit concept, that distinction is essential. Accordingly, all performance windows and quantitative tendencies discussed in the Results and Discussion section are treated as literature-benchmarked expectations for a REAM-type system, not as newly generated engine-test data. Comparable literature-data approaches have also been used to estimate emission trends across dual-fuel blends, reinforcing the value of benchmark-based calibration before full-scale testing [6].

A third gap concerns system integration. Fuel-property studies focus on stability and lubricity [7], [8]; combustion

papers focus on efficiency and emissions [9]–[15]; heavy-duty fuel-consumption modeling focuses on route and operating factors [1], [2]; and malfunction studies show how emissions and fuel use can change sharply when control and aftertreatment systems deviate from intended operation [5]. Yet few papers combine these domains into a practical retrofit architecture for a diesel truck already in service. This is the specific space that REAM occupies.

Accordingly, the problem addressed in this paper can be stated as follows: how can an existing Indian commercial diesel truck exploit ethanol’s emissions-reduction and carbon-displacement potential without sacrificing combustion stability, fuel-system durability, and aftertreatment effectiveness across the duty cycle? The answer proposed here is not a fixed ethanol percentage. It is a supervisory module that makes ethanol utilization conditional on fuel quality, operating load, thermal state, and calibrated safety thresholds.

**III. RETROFIT DESIGN REQUIREMENTS AND PROPOSED REAM ARCHITECTURE**

*A. Engineering Design Requirements*

From a design perspective, any retrofit concept for commercial trucks must satisfy a stricter requirement set than passenger vehicles. First, the system must be fail-operational. If ethanol sensing is lost, if blend quality becomes uncertain, or if a fault is detected in the supervisory path, the truck must continue operating safely in a diesel-dominant fallback mode.

Second, the control intervention must be torque transparent to the driver. Freight vehicles often operate near schedule constraints, and any retrofit that introduces sluggish response or unpredictable behavior will be rejected by operators regardless of theoretical emissions benefit. Third, the architecture must respect service realities. Sensors, connectors, hoses, and actuators should be selected for contamination tolerance, vibration resistance, and ease of replacement in non-laboratory conditions.

These requirements shape the REAM design choices. The controller should avoid deep dependence on signals that are unavailable on older platforms, and it should use plausibility checks so that single-sensor faults do not trigger harmful commands. Ethanol scheduling should be filtered through ramp-rate limiters to avoid abrupt combustion-state changes during pedal tip-ins, grade changes, or gear shifts. Likewise, pilot-diesel preservation should be treated as a hard constraint, not a tuneable convenience, because reliable ignition remains the foundation of diesel-engine operability under field conditions. Even where the literature demonstrates high ethanol substitution fractions, those values should be treated as ceiling values obtained under specific conditions, not as default fleet settings [10]–[13].

Another design requirement is aftertreatment compatibility. Modern freight engines depend on oxidation catalysts, diesel particulate filters, and selective catalytic reduction systems whose effectiveness depends strongly on exhaust temperature and species composition [1], [5], [13]. A controller that lowers engine-out soot but also depresses exhaust temperature too far may inadvertently weaken downstream emissions control. REAM therefore treats exhaust thermal state as a first-class control variable. During extended idle or low-load conditions, ethanol substitution is reduced not because ethanol is inherently undesirable, but because the total system—including the aftertreatment—must remain inside a viable operating envelope.

Cost and maintainability also matter. A highly instrumented research setup may achieve excellent performance but still fail commercial adoption if it requires expensive sensors, frequent recalibration, or specialist servicing. The retrofit pathway envisioned here therefore favors modularity. A base version of REAM could implement composition sensing, low-level blend correction, and diagnostic fallback. A more advanced version could add dual-fuel scheduling and deeper estimator functionality on trucks whose business case supports it. This modular framing strengthens the practical relevance of the paper because it acknowledges that not every fleet operator will enter at the same technology level.

Finally, the design must be scientifically transparent. A conceptual controller cannot be assumed to have already solved all calibration and durability challenges. REAM is therefore presented as a structured answer to a multi-variable problem rather than as a universal or turnkey solution. Its value lies in making the governing constraints explicit and in translating combustion evidence into a retrofit logic that can be validated systematically.

### *B. Retrofit Ethanol Assist Module (REAM)*

The Retrofit Ethanol Assist Module is conceived as a layered add-on controller rather than a replacement engine control unit. This distinction is important because retrofit solutions succeed only when they minimize intrusion into the base platform. REAM therefore operates as a supervisory architecture with four functional layers: fuel characterization, state estimation, control scheduling, and protection management.

The first layer is fuel characterization. In the simplest implementation, REAM estimates ethanol concentration using an in-line composition sensor and cross-checks it with temperature information. The point of this measurement is not merely to label the tank contents. Ethanol fraction changes the lower heating value of the fuel package, the target fuel mass for a given torque request, the expected ignition delay, and the margin to phase-instability or poor lubricity if direct blending is used. For a dual-fuel implementation, the composition estimate also informs how much diesel pilot energy must be retained to preserve ignition robustness. Recent sensing research shows that composition measurement becomes more reliable when it is designed to be tolerant of water contamination and property variation, reinforcing the need to avoid simplistic single-parameter assumptions in field retrofits.

The second layer is state estimation. REAM infers the current engine regime from signals that are already common in production powertrains or can be added with limited cost: engine speed, requested torque, rail pressure, intake manifold pressure, exhaust temperature, accelerator demand, coolant temperature, and, where available, mass air flow and NO<sub>x</sub> sensor data. A lightweight estimator then classifies the operating point into regimes such as cold start, idle, low load, medium load, high load, and transient tip-in or tip-out. This classification is essential because the literature makes clear that ethanol's optimal use is strongly regime dependent. A fixed global substitution ratio would be suboptimal and sometimes unsafe.

The third layer is control scheduling. Here the module determines one or more of the following depending on architecture: ethanol energy fraction, diesel pilot quantity, injector pulse-width correction, diesel injection timing offset, and blend-specific torque request shaping. For low-level stabilized ethanol–diesel blends, the controller's role is mainly corrective: it compensates for changed fuel energy content and combustion timing so that driveability and emissions remain acceptable. For dual-fuel architectures, the controller plays a broader role by scheduling the ethanol substitution ratio. At low load, the literature suggests using conservative substitution limits because overly lean premixed combustion can depress combustion efficiency and exhaust temperature [9], [12]. At medium load, ethanol fraction can be increased more aggressively because this region tends to offer the best combination of stability, soot suppression, and efficiency [10], [11]. At high load, the scheduler must balance substitution against pressure-rise-rate limits, turbocharger matching, thermal loading, and emission compliance [11], [13].

The fourth layer is protection management. A credible retrofit concept must make failure modes explicit. REAM therefore includes guard rails that cap ethanol contribution when one or more hazards are detected: unstable combustion, low exhaust temperature, cold start, suspected phase instability, implausible sensor readings, rail-pressure deviations, or sustained high pressure-rise indicators. The protection logic also addresses durability. If a formulation suggests compromised lubricity or excessive uncertainty in blend quality, the module falls back toward diesel-dominant operation. Likewise, if exhaust temperature falls below a threshold needed to sustain oxidation or downstream aftertreatment performance, ethanol substitution is reduced until thermal viability is restored.

This layered structure gives REAM three practical advantages. First, it is compatible with staged adoption, beginning with low-blend correction and later extending to dual-fuel capability. Second, it converts literature findings into calibration logic that engineers can test, critique, and refine. Third, it avoids unrealistic claims that one hardware change alone can solve a multi-variable combustion problem. In this sense, REAM is less a single device than a disciplined architecture for supervising ethanol use in trucks that were originally designed for diesel. The regime-wise supervisory logic used by REAM is summarized in Table II.

TABLE II. ILLUSTRATIVE REAM SUPERVISORY SCHEDULING LOGIC BY OPERATING REGIME

Operating regime	Preferred ethanol use	Primary control objective	Dominant risk	Fallback action
Cold start	Minimal or none	Reliable ignition and rapid warm-up	Misfire, low oxidation temperature	Diesel-dominant mode
Idle / very low load	Low and tightly bounded	Stable combustion and exhaust enthalpy	High CO/HC, poor catalyst light-off	Reduce ethanol fraction
Medium load	Moderate to high within calibrated window	Low soot with competitive efficiency	Incorrect phasing if poorly tuned	Adaptive pilot + rate limiter
High load	Moderate and pressure-limited	Emissions benefit without excessive pressure rise	Thermal stress, PRR limits	Cap substitution and preserve diesel pilot
Transient operation	Ramp-limited	Torque transparency and drivability	Oscillation and air-path mismatch	Command filtering and plausibility checks

#### IV. METHODOLOGY AND VALIDATION FRAMEWORK

Because the present study does not claim unpublished engine-test data, the methodology is framed as both a validation protocol for a future REAM implementation and a structured synthesis of the existing literature. The methodology has five components: baseline vehicle definition, fuel-pathway definition, control-map formulation, validation metrics, and benchmarking procedure.

First, the baseline vehicle class is a conventional Indian commercial truck powered by a turbocharged common-rail diesel engine meeting late-generation emissions requirements. The exact displacement and power rating will vary across manufacturers, but the concept assumes a representative freight engine with electronically controlled fuel injection and exhaust aftertreatment. This level of abstraction preserves engineering relevance without fabricating hardware details that have not yet been experimentally validated.

Second, two fuel pathways are defined. Pathway A is low-level stabilized ethanol–diesel blending. This pathway is limited to blend levels that remain within validated miscibility and lubricity constraints after additives and storage conditions are considered [7], [8]. Pathway B is ethanol–diesel dual-fuel operation in which ethanol supplies a variable fraction of the total chemical energy and diesel provides pilot ignition [9]–[14]. The present manuscript focuses more strongly on Pathway

B because the best heavy-duty evidence available today supports dual-fuel operation as the more scalable high-substitution route.

Third, control maps are formulated by load regime. The low-load map prioritizes stability, exhaust temperature, and misfire avoidance; therefore it enforces a conservative ethanol fraction and retains a strong diesel pilot [9], [12]. The medium-load map targets the region where the literature reports the most attractive combination of low soot, lower nitrogen oxides, and high efficiency [10], [11]. The high-load map limits ethanol fraction based on pressure-rise-rate and thermal considerations while preserving emission and durability margins [11], [13]. Cold-start operation remains predominantly diesel until coolant and exhaust states indicate a stable thermal window. Transient operation uses rate limiters so that ethanol scheduling cannot oscillate faster than the air-path and combustion system can accommodate.

Fourth, the validation metrics are grouped into performance, emissions, combustion, and system-level operability. Performance metrics include brake-specific fuel consumption, brake-specific energy consumption, torque tracking error, and fuel-equivalent cost sensitivity. Emissions metrics include carbon monoxide, total hydrocarbons, nitrogen oxides, particulate matter or smoke proxy, and carbon dioxide equivalent. Combustion metrics include ignition delay, combustion duration, coefficient of variation of load-related work, peak pressure, and pressure-rise rate. System-level

metrics include start quality, thermal recovery after idle, sensor plausibility, drivability during step transients, and evidence of adverse impact on aftertreatment temperature windows. This grouping is important because a retrofit that only improves one metric while damaging thermal or durability behavior would not be acceptable in fleet service.

Fifth, the benchmarking procedure maps each REAM design choice to evidence from the literature. For example, if the controller allows higher ethanol fraction at medium load, the justification is drawn from studies that showed optimized mid-load operation with good efficiency and low engine-out emissions [10], [11]. If the low-load map is conservative, the justification is drawn from studies showing poor combustion efficiency and low exhaust temperature under aggressive substitution at light load [9], [12]. If direct blending is bounded by formulation constraints, the justification comes from blend-

stability and lubricity studies [7], [8]. In this way, the methodology does not merely cite prior work; it uses that work to parameterize the control philosophy.

A future experimental campaign based on this framework would proceed in three stages. Stage 1 would validate blend stability, lubricity, and materials compatibility off-engine. Stage 2 would calibrate REAM on an engine dynamometer across steady-state points and transient sweeps. Stage 3 would move to vehicle-level route testing informed by heavy-duty fuel-consumption modeling, with grade, payload, and traffic effects captured explicitly [1], [2]. Stating the methodology this way keeps the present analysis grounded in current evidence while also defining a clear path to experimental extension. Table III consolidates the core validation metrics recommended for a future REAM test campaign.

TABLE III. VALIDATION METRICS RECOMMENDED FOR A FUTURE REAM TEST CAMPAIGN

Metric group	Representative variables	Why it matters	Recommended test context
Performance	BSFC, BSEC, torque tracking	Determines energy and driveability penalty/benefit	Steady-state map + route cycles
Emissions	CO, HC, NOx, PM/smoke, CO2e	Captures environmental value and trade-offs	Engine dynamometer + vehicle route test
Combustion	Ignition delay, combustion duration, PRR	Shows stability and phasing quality	Cylinder-pressure based calibration
System operability	Cold start, idle recovery, fault response	Determines commercial usability	Repeated transients and fault-injection checks

## V. RESULTS AND DISCUSSION

### A. Fuel-Efficiency Implications

The results discussed in this section should be read as a literature-benchmarked expectation for a REAM-governed truck powertrain, not as newly generated engine-test data. This distinction improves scientific transparency while still allowing a rigorous engineering analysis.

From a fuel-efficiency perspective, the literature supports a nuanced conclusion. Ethanol almost always imposes a volumetric fuel-consumption penalty because its lower heating value per unit volume is below that of diesel or gasoline [3], [17]–[19]. However, that penalty can be partly or substantially offset when the combustion process itself becomes cleaner and more thermodynamically favorable. Heavy-duty dual-fuel studies show that, under optimized medium-to-high-load conditions, ethanol substitution can maintain or even improve indicated efficiency relative to conventional diesel combustion [10], [11], [13]. The implication for REAM is that fuel economy should be discussed on both a volumetric basis and an energy basis. A retrofit that uses more liters but less fossil-derived carbon and achieves similar brake-specific energy consumption may still be attractive, especially if ethanol pricing or policy incentives are favorable. Conversely, low-load operation remains a weak region. Both Pedrozo et al. and Han et al. report that excessively cool, lean, low-load combustion reduces combustion efficiency and may raise fuel

consumption if ethanol substitution is not constrained [9], [12]. This directly justifies REAM’s low-load protection logic.

### B. Emissions and Combustion Stability

On emissions, the strongest and most consistent benefit is soot and particulate reduction. Across blend and dual-fuel studies, ethanol’s oxygen content tends to reduce rich local zones that favor soot formation [4], [10]–[14], [16]. For commercial trucks operating in densely populated corridors, this is a major advantage because particulate emissions are closely linked to urban air-quality harms. Carbon monoxide and unburned hydrocarbons show a more conditional pattern. In spark-ignition ethanol blends these species often decrease because combustion is more oxygenated [17]–[19]. In diesel dual-fuel operation, however, carbon monoxide and hydrocarbons can increase at low load when temperature is insufficient to complete oxidation [9], [12]. This again reinforces the principle that ethanol should be used selectively rather than indiscriminately. REAM’s supervisory logic therefore treats CO and HC not as fixed outputs of fuel chemistry but as indicators of whether the present combustion regime is genuinely favorable.

Nitrogen oxides require especially careful interpretation. Simplistic discussions often claim that ethanol either decreases NOx because combustion temperatures fall or increases NOx because oxygen availability rises. The heavy-duty literature shows that both outcomes are possible depending on load,

injection strategy, and dilution [10]-[14], [16]. The most valuable insight is not the sign of the effect in one study; it is the possibility of breaking the conventional diesel NO<sub>x</sub>-soot trade-off when ethanol is used with optimized pilot and dilution strategies [10], [11], [13]. For Indian truck retrofits, that means NO<sub>x</sub> reduction is possible but not automatic. A robust calibration strategy must acknowledge that achieving low NO<sub>x</sub> and low soot simultaneously requires careful control of reactivity stratification, heat-release timing, and, where available, exhaust gas recirculation.

Combustion stability is arguably the decisive criterion for real vehicles. High ethanol fractions can work impressively in research settings, but production-relevant freight operation includes cold starts, idling, stop-and-go congestion, variable payloads, altitude shifts, and imperfect fuel quality. The literature consistently indicates that stability margins shrink first at light load and during thermally weak operation [9], [12]. In those conditions, longer ignition delay and lower in-cylinder temperature can produce cycle-to-cycle variability, poor oxidation, and reduced exhaust enthalpy. A REAM-equipped truck should therefore be expected to rely on diesel-dominant operation during cold start, prolonged idle, depot maneuvering, and some urban crawl conditions. This is not a weakness of the concept; it is an example of engineering discipline. The purpose of a retrofit controller is not to maximize ethanol at all times. It is to maximize useful ethanol under conditions where it remains compatible with efficiency, emissions, and durability.

### *C. Duty-Cycle Feasibility and Deployment Implications*

System-level feasibility also emerges from the literature. Fuel-consumption modeling for heavy-duty trucks shows that route grade, mass, and speed strongly shape energy demand [2]. This matters because the value of ethanol substitution will vary by duty cycle. Long-haul and moderately loaded regional routes with sustained medium-load operation are likely to offer better ethanol utilization windows than ultra-low-speed urban drayage dominated by idle and low-load transients. Similarly, malfunction studies remind us that engine and aftertreatment faults can distort fuel use and emissions sharply [5]. For REAM, this implies that retrofit deployment should begin on well-maintained fleets with predictable routes, where calibration uncertainty is lower and benefits are more reproducible.

A final result of the synthesis is that the best-performing ethanol strategies are not the highest-ethanol strategies. They are the most intelligently scheduled strategies. This finding may appear obvious, but it is central to the paper's contribution. The literature does not support an indiscriminate push toward the highest possible ethanol fraction. Instead, it supports a control problem: identify the operating window where ethanol offers emissions and efficiency gains, and retreat gracefully when the window closes. REAM formalizes that principle into a practical framework that can be tested, criticized, and improved.

## **VI. COMPLIANCE, DURABILITY, AND MEASUREMENT CONSIDERATIONS**

Any credible validation study should also explain how its findings interface with regulatory and measurement practice. In freight applications, it is no longer sufficient to report only steady-state brake-specific metrics. Real-world emissions can diverge from laboratory conditions, and load, route, temperature, and aftertreatment events can materially influence observed results [1]. Accordingly, a future REAM validation campaign should include not only engine-dynamometer mapping but also vehicle-level testing over representative freight cycles and, where feasible, portable emissions measurement or equivalent route-resolved instrumentation. This would allow the system's benefit to be reported in a way that is meaningful for commercial operation rather than only for isolated operating points.

A second compliance consideration concerns durability and deterioration. Fuel-system components in commercial vehicles are expected to survive long service intervals under contaminated and variable fuel conditions. Because ethanol changes solvency, water affinity, and lubricity characteristics, a convincing retrofit paper must eventually move beyond first-day performance and into endurance behavior [7], [8]. Even if that evidence is not yet available, the paper should demonstrate awareness of the issue. For this reason, the present manuscript treats materials compatibility and lubricity assurance as gating requirements, not secondary notes.

A third issue is data integrity. When future experimental results are published, they should report fuel properties, blend preparation protocol, ambient conditions, repeatability, uncertainty treatment, and any change in aftertreatment configuration. The heavy-duty ethanol studies cited in this paper are persuasive precisely because they define their engine conditions and load windows clearly [9]-[13]. A manuscript that follows this discipline will be more technically persuasive than one that offers impressive percentage reductions with incomplete methodological context.

Taken together, these considerations position ethanol retrofit not as a generic clean-fuel idea but as a measurable, calibratable, and compliance-aware engineering system. That framing also clarifies the evidence still needed to move from literature-grounded architecture to full experimental validation.

## **VII. DISCUSSION AND FUTURE RESEARCH DIRECTION**

The main contribution of this work is not the claim of an entirely new combustion mode, but the integration of multiple isolated findings into an implementable architecture for India. This integration matters because the Indian trucking ecosystem differs from the laboratory environments in which most ethanol-diesel studies are performed. Fleet operators value payback time, serviceability, fuel availability, warranty risk, and roadside robustness just as much as raw thermodynamic performance. A viable ethanol strategy must therefore satisfy four conditions simultaneously: it must reduce fossil

dependence, preserve freight productivity, avoid premature injector or pump wear, and remain compatible with emissions compliance hardware. The REAM framework is designed around exactly these conditions.

The Indian relevance of REAM is strongest in two scenarios. The first is a transitional decarbonization pathway for fleets that cannot rapidly replace vehicles but can adopt selective retrofit solutions. In this scenario, REAM offers a pathway for partial carbon displacement without demanding a full shift to new powertrain architectures. The second is as a bridge technology that supports domestic biofuel utilization while the heavy-duty sector gradually diversifies across electrification, hydrogen, natural gas, and advanced biofuels. In both cases, ethanol should be viewed as one lever among many, not as the sole destination of freight decarbonization.

A practical deployment roadmap follows naturally from the literature. Phase 1 should focus on data gathering and materials validation: seasonal fuel stability, water tolerance, lubricity correction, and compatibility of seals and hoses [7], [8]. Phase 2 should address engine-dynamometer calibration, with explicit emphasis on low-load stability and medium-load efficiency windows [9]-[13]. Phase 3 should move to limited fleet pilots on routes where payload, speed profile, and refueling control are well understood. Only after these phases should larger-scale rollout be considered. This staged pathway is worth making explicit because it links concept development to progressively stronger engineering evidence.

The control implications are equally important. REAM suggests that future freight biofuel systems should become more state-aware and less fuel-centric. In traditional discussions, engineers ask what ethanol percentage should be used. In a supervisory-control framing, the better question is when ethanol should be used, for how long, and with what guard rails. This shift from static blending to dynamic scheduling is the manuscript's main conceptual advancement. It aligns the paper with the broader trend toward software-defined powertrain optimization in which sensors, estimators, and adaptive calibration are as important as the base fuel itself.

The paper also clarifies a recurring confusion in policy and technical writing. Ethanol's policy success in gasoline does not imply equal simplicity in diesel freight. Spark-ignition engines exploit ethanol primarily through octane benefits and oxygenation. Diesel engines must instead contend with cetane deficiency, ignition-delay shifts, and fuel-path compatibility. The freight application is therefore not a simple extension of passenger-car blending; it is a separate engineering problem that happens to use the same molecule.

There are, however, clear limitations. The present paper does not report new engine-test measurements, and it does not claim that every truck architecture will respond identically. The control maps are literature-grounded but not yet fleet-calibrated. The economic analysis is directional rather than exhaustive because fuel-price dynamics, tax treatment, and retrofit costs can vary by state and by time. Finally, emissions compliance in commercial operation depends on regulatory detail, measurement protocol, and deterioration behavior that

extend beyond the scope of the present conceptual study. These limitations define the next steps toward full experimental validation.

Future research should therefore prioritize three threads. The first is bench validation of REAM scheduling limits across a representative heavy-duty engine map, including cold-start and transient response. The second is fuel-path engineering for real-world Indian conditions, especially seasonal storage stability, lubricity assurance, and service-interval durability. The third is route-coupled fleet analysis that combines control calibration with freight-demand modeling so that ethanol benefit can be expressed per route, payload, and duty cycle rather than as a single fleet-wide average. These steps would move the concept from literature-grounded systems framing to deployable engineering evidence.

## VIII. CONCLUSION

This paper argues that ethanol can contribute meaningfully to cleaner and less fossil-intensive operation of Indian commercial trucks, but only when the problem is framed correctly. For heavy-duty diesel fleets, ethanol is not simply a blend percentage to be mandated. It is a combustion and control challenge that must be managed through fuel-quality awareness, regime-dependent scheduling, and explicit protection of stability, durability, and aftertreatment function. The literature consistently supports this view. Low-level stabilized blends remain constrained by miscibility and lubricity, while dual-fuel strategies offer the strongest pathway to significant soot and nitrogen-oxide benefits when calibration is optimized. The same literature also warns that low-load operation, cold thermal states, and uncontrolled substitution can erode efficiency and emissions performance.

The proposed Retrofit Ethanol Assist Module responds to these realities by turning ethanol utilization into a supervised operating strategy rather than a fixed fuel property. Its value lies in the integration of composition sensing, state estimation, load-aware scheduling, and safety fallback logic into one coherent architecture. Although the paper does not claim new bench data, it establishes a stronger technical basis by aligning the concept with authoritative diesel-combustion literature and by removing ambiguous performance claims.

For India, the most practical implication is that ethanol in trucks should begin with controlled, route-aware, and calibration-aware deployment rather than universal substitution. That approach preserves engineering credibility and defines a realistic path to future experimental validation and fleet demonstration.

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## REFERENCES

- [1] C. Keramydas, L. Ntziachristos, C. Tziourtzioumis, G. Papadopoulos, T.-S. Lo, K.-L. Ng, H.-L. A. Wong, and C. K.-L. Wong, "Characterization of Real-World Pollutant Emissions and Fuel Consumption of Heavy-Duty Diesel Trucks with Latest Emissions Control," *Atmosphere*, vol. 10, no. 9, p. 535, 2019, doi: 10.3390/atmos10090535.
- [2] J. Wang and H. A. Rakha, "Fuel consumption model for heavy duty diesel trucks: Model development and testing," *Transportation Research Part D: Transport and Environment*, vol. 55, pp. 127–141, 2017, doi: 10.1016/j.trd.2017.06.011.
- [3] P. Sakthivel, K. A. Subramanian, and R. Mathai, "Indian scenario of ethanol fuel and its utilization in automotive transportation sector," *Resources, Conservation and Recycling*, vol. 132, pp. 102–120, 2018, doi: 10.1016/j.resconrec.2018.01.012.
- [4] B.-Q. He, J.-X. Wang, X.-G. Yan, X. Tian, and H. Chen, "Study on Combustion and Emission Characteristics of Diesel Engines Using Ethanol Blended Diesel Fuels," *SAE Technical Paper*, 2003, doi: 10.4271/2003-01-0762.
- [5] Y. Huang et al., "Impact of potential engine malfunctions on fuel consumption and gaseous emissions of a Euro VI diesel truck," *Energy Conversion and Management*, vol. 184, pp. 521–529, 2019, doi: 10.1016/j.enconman.2019.01.076.
- [6] A. Saleem, I. A. Karimi, and S. Farooq, "Estimating NOx emissions of useful two-fuel blends from literature data," *Fuel*, vol. 316, p. 123213, 2022, doi: 10.1016/j.fuel.2022.123213.
- [7] M. Lapuerta, O. Armas, and R. García-Contreras, "Stability of diesel–bioethanol blends for use in diesel engines," *Fuel*, vol. 86, no. 10–11, pp. 1351–1357, 2007, doi: 10.1016/j.fuel.2006.11.042.
- [8] H. Kuszewski, Ł. Jaworski, M. Ustrzycki, and A. Balawender, "Lubricity of ethanol–diesel blends – Study with the HFRR method," *Fuel*, vol. 208, pp. 491–498, 2017, doi: 10.1016/j.fuel.2017.07.046.
- [9] V. B. Pedrozo, I. May, V. D. G. D. Lanzanova, H. Zhao, and A. L. N. De Souza, "Experimental analysis of ethanol dual-fuel combustion in a heavy-duty diesel engine: An optimisation at low load," *Applied Energy*, vol. 165, pp. 166–182, 2016, doi: 10.1016/j.apenergy.2015.12.052.
- [10] V. B. Pedrozo, I. May, and H. Zhao, "Exploring the mid-load potential of ethanol-diesel dual-fuel combustion with and without EGR," *Applied Energy*, vol. 193, pp. 263–275, 2017, doi: 10.1016/j.apenergy.2017.02.043.
- [11] V. B. Pedrozo, I. May, W. Guan, and H. Zhao, "High efficiency ethanol-diesel dual-fuel combustion: A comparison against conventional diesel combustion from low to full engine load," *Fuel*, vol. 230, pp. 440–451, 2018, doi: 10.1016/j.fuel.2018.05.034.
- [12] J. Han, N. M. Somers, M. T. Cracknell, K. J. Werner, and R. D. Matthews, "Experimental investigation of ethanol/diesel dual-fuel combustion in a heavy-duty diesel engine," *Fuel*, vol. 275, p. 117867, 2020, doi: 10.1016/j.fuel.2020.117867.
- [13] U. Asad, P. S. Divekar, and M. Zheng, "High efficiency ethanol–diesel dual-fuel combustion: Analyses of performance, emissions and thermal efficiency over the engine load range," *Fuel*, vol. 318, p. 122397, 2022, doi: 10.1016/j.fuel.2021.122397.
- [14] U. Asad, M. Zheng, P. M. Yousif, and J. C. J. Yang, "Ethanol-fueled low temperature combustion: A pathway to clean and efficient diesel engine cycles," *Applied Energy*, vol. 141, pp. 1–8, 2015, doi: 10.1016/j.apenergy.2015.01.057.
- [15] R. D. Reitz and G. Duraisamy, "Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines," *Progress in Energy and Combustion Science*, vol. 46, pp. 12–71, 2015, doi: 10.1016/j.peccs.2014.05.003.
- [16] H. E. Arslan, D. Güneş, E. Şenveli, and B. Doğru, "Experimental Investigation of the Effect of Using Ethanol-Blended Diesel Fuels on Engine Performance and Exhaust Emissions," *Petroleum Science and Technology*, vol. 30, no. 1, pp. 100–113, 2012, doi: 10.1080/10916460902967759.
- [17] D. Kulkarni, H. A. Malekar, R. Thonge, and S. Kanchan, "Effect of E20 Fuel on Vehicle Performance Parameters of 694CC Gasoline Engine for Commercial Vehicle Application," *SAE Technical Paper*, 2026, doi: 10.4271/2026-26-0565.
- [18] Y. Sahu, S. P. M. Sithanathan, and M. Maheshwari, "Experimental Study on Performance and Emissions of BS VI Complaint EFI Motorbike with Oxygenated Fuel Blends (E0, E10, E20 & M15)," *SAE Technical Paper*, 2024, doi: 10.4271/2024-01-2372.
- [19] L. Wang, Z. Huang, L. Ren, B. Tao, and J. Pan, "Experimental Investigation of Combustion and Emission Characteristics of Ethanol–Gasoline Blends across Varying Operating Parameters," *ACS Omega*, vol. 10, no. 16, pp. 16079–16089, 2025, doi: 10.1021/acsomega.4c09398.
- [20] J. Zhu, P. Li, Y. Xie, and X. Geng, "Combustion and Emission Characteristics of Dual Fuel Engine for Different Parameters," *International Journal of Vehicle Structures and Systems*, vol. 13, no. 4, 2021, doi: 10.4273/ijvss.13.4.03.