



**22nd – 23rd
October 2026**



**Hotel Taj Vivanta,
Dwarka, New Delhi**

ECT-2026

17th International Conference



CONFERENCE BULLETIN
Technical Articles
CONFERENCE THEME

ENGINEERING CLEAN MOBILITY ADVANCEMENT for BS-VII

ECMA's Sisters Associations

DISCLAIMER

The technical articles, views, opinions, interpretations, data, information and other content published in this Conference Bulletin contributed by individual authors are published for information and knowledge-sharing purposes only. They do not necessarily reflect the views or position of ECMA, its members or the editorial team.

While reasonable care has been taken in presenting the content, ECMA does not assume responsibility for the accuracy, completeness or applicability of the information provided. Publication of any article, technology, process, product or reference does not constitute an endorsement, recommendation or certification by ECMA.

The authors and ECMA shall not be held responsible for any loss, damage, liability or consequences arising from the use of, or reliance upon, the information contained in the published articles.



TECHNICAL ARTICLES



#	Title of the Article	Author	Organisation
1	Evidence-Based Recommendations for Bharat Stage 7 Emission Standards	Dr Ameya Joshi	Mobility Notes, USA
2	AECC Position Paper – Driving a Competitive, Clean, and Technology-Neutra Automotive Transition	---	AECC, Belgium
3	Ammonia as a Future Fuel: Opportunities and challenges	Dr Sukrut Thipse	ARAI
4	From Waste Oils to Clean Fuels: HEFA Pathways for Aviation, Road, Off-Road and Power Applications	Dr Sarmishta Nandy	Energy Transition & Industrial Decarbonization; India, UAE
5	Cleaner vehicles beyond EVs	Sanjeev Chugh	Gen Lotus
6	How much an ICE can pull?	Neelkanth Marathe	ECMA
7	Petrol with 20% Ethanol (E20): The debate	K K Gandhi	Consultant
8	Ensuring AdBlue Quality from production to vehicle tank for reliable SCR performance	German Orduy Rey	Yara International ASA
9	Optimized R-SiC DPF design for LD applications under evolving emission regulations in India	Naoki Kawamura Sri Harsha S	IBIDEN CO. LTD.
10	AECC Fact Sheet – Heavy-Duty vehicles: a robust Euro 7 for a clean and competitive industry	---	AECC, Belgium
11	AECC Fact Sheet – Light-Duty vehicles: debunking myths on VEEFs	---	AECC, Belgium
12	Advancing Emission Measurement and Control through IRLAM Technology	—	HORIBA
13	Integrated Design of an E20-Optimized SI Engine: Combustion, Fuel System, Thermal Management and Control	Dr Sarmishta Nandy	Energy Transition & Industrial Decarbonization; India, UAE
14	India's EV Journey: Progress, challenges and the road ahead	Sanjeev Chugh	Gen Lotus
15	Strategy for controlling Aldehyde emissions in Brazil: Limits and measurement methods	Gabriel M Branco	EnvironMentality, Brazil
16	In-use diesel Generator emissions: reading the NOx-PM signature of legacy engines	Ankit Trivedi	ICAT
17	Accelerating Engine efficiency through integrated technology solutions	Thalavai Venkatesan	Tenneco
18	E20 compatibility and emission-control risks in pre-2023 in-use vehicles	Dr Sarmishta Nandy	Energy Transition & Industrial Decarbonization; India, UAE
19	Engineering Clean Mobility Advancements for BS-VII: (Conference theme of ECT 2026 conference)	Neelkanth Marathe	ECMA

Evidence-Based Recommendations for Bharat Stage 7 Emission Standards

Dr Ameya Joshi
Mobility Notes, USA

1. Introduction

1.1 Background and objectives

Road transport is a major source of urban air pollution in India, contributing to carbon monoxide (CO), nitrogen oxides (NO_x) and ultrafine particulates (PM_{2.5}, particles below 2.5 microns). The impact of pollution on human health is especially acute in densely populated cities such as the National Capital Region (NCR) of Delhi. Successive tightening of emission norms from Bharat Stage (BS) I through BS-VI has brought advanced emission-control technologies to new cars and trucks; however, pollution levels in major cities continue to increase. A common point of contention is the extent of contribution to these pollution levels from transport vs. other sources. Regardless of the exact contribution, it should be obvious that all sectors must do their part in reducing pollution.

As India considers the next stage of emission standards, BS VII, the overarching objective of this study is to provide guidance to policymakers on regulatory and technology pathways for maximising the real-world benefits of tighter standards, in Indian driving and ambient conditions. We used bottom-up emission inventory modelling, using laboratory and on-road emission factors to quantify the contribution of tailpipe and evaporative emissions from various vehicle types, as a function of their age and certification level. Our recommendations for a strong BS VII are based on this study and knowledge of best available control technologies from other advanced markets.

1.2 Study areas

The first study area, the National Capital Region centred on Delhi (hereafter Delhi NCR), is defined as the Union Territory of Delhi and the adjoining NCR cities of Gurugram, Faridabad, Ghaziabad and Noida; the second is the territory of India (all States and Union Territories). In both cases emissions are attributed to vehicular activity occurring within the defined region, irrespective of vehicle registration origin.

The Delhi NCR road network is represented by two functional classes — urban roads (expressways, arterial, sub-arterial, collector and local streets: mixed traffic, frequent stop-go and lower average speeds) and highways (national and state highways and major regional corridors: higher-speed inter-city links with fewer interruptions) — with separate speed and activity profiles. Nationally, activity is represented by four operating classes — urban peak, urban off-peak, rural (major district roads, village roads and non-urban connecting roads) and highway — the peak/off-peak separation being particularly important for representing the strong influence of congestion and speed variation on emissions.

1.3 Temporal scope and baseline year

Both inventories use a common baseline year of 2025; vehicle population data are based on the registered stock available up to August 2025 (when the study was initiated), used with vehicle survival functions to estimate the in-use fleet for 2025. Annual emissions are calculated as described in next section, which combines fleet stock with annual vehicle kilometres travelled (VKT) and speed profiles through pollutant- and technology-specific emission equations; both inventories report annual totals, with sub-annual variation embedded in the VKT and speed assumptions; no explicit seasonal, hourly or weekday/weekend resolution is modelled.

2. Methodology

2.1 COPERT-based bottom-up approach

Road transport emissions in India and Delhi were estimated using the COPERT software [2], a widely recognised tool developed by EMISIA for calculating road transport GHG and air-pollutant emission inventories [3]. Its methodology follows the EMEP/EEA air pollutant emission inventory guidebook [4] and is consistent with the 2006 IPCC Guidelines for GHG calculations, and although developed for official inventories in EEA member countries it has also been applied in non-European contexts (e.g., Australia [5]).

COPERT uses European vehicle classifications, differentiating vehicles by category (cars, vans, heavy-duty trucks, buses and L-category vehicles), powertrain, segment and emission standard (Euro 1–6). Indian vehicles were mapped to their European counterparts, using judgment where direct correspondence was unavailable — feasible because Bharat Stage standards are closely aligned with European standards and similar vehicle types exist in both regions — except for CNG three-wheelers, added as a custom vehicle in the stock sheet. COPERT’s default emission factors (EFs), expressed in g/km for NO_x, CO, HC, PM₁₀, PM_{2.5} (tailpipe and non-tailpipe) and CO₂ as functions of speed, trip distribution and ambient temperature, were used as a starting point and where India-specific values were unavailable.

2.2 Scenario design

Multiple scenarios were developed in which vehicle population, VKT, road-type activity distribution and operating speeds were kept identical and only the emission-factor datasets varied, so that differences are attributable solely to the source and measurement basis of the factors. Three scenarios were analysed for Delhi NCR; for the national inventory only two — baseline and real-world — were implemented.

Scenario 1 (Baseline), used for both inventories, takes emission factors from a recent peer-reviewed national road transport emission inventory study [6] whose scope and intent are closely aligned with the present work. For BS-VI vehicles, where India-specific factors are limited, default COPERT factors for Euro VI-equivalent technologies are applied, India having broadly followed European norms with generally similar control technologies; Scenario 1 is thus the reference case for both study areas.

Scenario 2 (Real-world remote sensing) combines literature-based factors for older standards with factors derived from real-world remote-sensing measurements for BS-IV and BS-VI vehicles, from studies by the International Council on Clean Transportation (ICCT) [7]. Remote-sensing measurements capture emissions under real driving conditions — congestion, driving behaviour, vehicle ageing, maintenance practices and real-world after-treatment efficiency — so Scenario 2, implemented for both inventories, provides a sensitivity on EFs and a possible representation of in-use emissions. We say “possible” because a remote-sensing study has inherent limitations and a limited sample size, offering only a glimpse of emissions under a limited range of conditions, though such data are invaluable in showing the extent of deviation from laboratory values, themselves limited in their veracity to a narrow range of prescribed test conditions. Where remote-sensing data are unavailable, Scenario 1 factors are retained to ensure complete fleet coverage; this patchwork of EFs is meant as a sensitivity on lab-based estimates and a basis for recommending further on-road measurements.

Scenario 3 (Laboratory test data), implemented only for Delhi NCR, combines literature-based factors for older standards with factors derived from laboratory testing under Indian regulatory conditions for BS-IV and BS-VI vehicles.

2.3 Data inputs and sources

Five primary COPERT inputs were required — vehicle population by category, age and fuel type; VKT by vehicle category; speed distributions by road type; emission factors by scenario; and meteorological correction factors (minimum/maximum temperature, humidity) — all reflecting conditions as of the August 2025 baseline.

2.3.1 Vehicle population and in-use fleet

Vehicle population data by category, age and fuel type were compiled for Delhi NCR and India from the MoRTH VAHAN portal [8], which reports registered counts by year of registration, vehicle category, BS standard and fuel or powertrain type. Since VAHAN represents the registered stock rather than the fleet actually circulating, the registered counts were converted into in-use vehicle stock using survival functions. Survival functions from Guttikunda et al. [9] were applied with the low-survival-rate parameter set for Delhi NCR — a dense urban region with relatively high vehicle turnover — and the high-survival-rate set for the national inventory, reflecting the wider variation in vehicle lifetimes across India, including longer retention in smaller towns and rural areas.

2.3.2 Vehicle kilometres travelled and road-type allocation

For Delhi NCR, annual VKT by vehicle category was derived from research papers, MoRTH traffic surveys (2024–2025), ARAI vehicle-usage studies and regional transportation planning documents [10–19]. The split between urban roads and highways used the on-road speed-distribution data of Goel et al. [20] (share of time in speed bins for buses, three-wheelers, two-wheelers and cars), the bus distribution serving as a proxy for heavy-duty trucks and the car distribution for light commercial vehicles in the absence of direct measurements. Speeds up to 15 km/h were classified as peak urban driving, 15–30 km/h as off-peak urban and above 30 km/h as highway driving, and the time share in each range was mapped to the VKT share for each category.

For the national inventory, annual VKT by category was compiled from Singh et al. [6] and mapped to COPERT vehicle classes, fuel types and emission standards, with activity distributed across the four traffic conditions given the much broader range of operating environments. The allocation used the reported intracity and intercity travel shares: intracity movement was split into urban off-peak and peak conditions, and intercity movement between highway and rural operation.

2.3.3 Average operating speeds by road type

Average operating speed is a key COPERT input because emission factors depend, non-linearly, on speed and traffic conditions.

For Delhi NCR, speeds were established from Goel et al. [20] as time-weighted averages accounting for congestion, signal timings and mixed-traffic interactions, and enter COPERT through non-linear speed-correction curves. For all vehicle categories, urban peak, urban off-peak and highway speeds of 10 km/h, 23 km/h and 45 km/h were used, consistent with the VKT allocation criteria (≤ 15 km/h peak urban, 15–30 km/h off-peak urban, > 30 km/h highway).

For the national inventory, urban off-peak and peak speeds of 25 km/h and 15 km/h were adopted from Akbar et al. [21], which describes mobility behaviour across Indian cities, and applied uniformly across vehicle categories; a representative rural speed of 35 km/h was obtained by averaging the terrain-specific (plain, rolling, mountainous and hilly) speeds derived using the methodology of Kadiyali [22]; and highway speeds, differentiated by vehicle category to reflect differences in vehicle performance, regulation and operating behaviour, were taken from Ahmad and Rathore [23]: 45 km/h for HCV, 46 km/h for LCV and buses, 57 km/h for 4W, 40 km/h for 2W and 35 km/h for 3W.

2.3.4 Meteorological inputs

COPERT requires monthly minimum and maximum temperatures and average relative humidity for its temperature-dependent (cold-start and evaporative) corrections. Region-specific monthly data were used for Delhi NCR, where the strong winter–summer contrast can substantially influence cold-start behaviour, combustion conditions and evaporative losses, and all-India monthly averages for the national inventory. Both were sourced from the India Meteorological Department [24]; the Delhi NCR values are long-term averages for 2020–2025, representative of the baseline year while smoothing out inter-annual variability.

2.3.5 Emission factors by scenario

Emission factors for CO, NO_x and PM_{2.5} (total and exhaust) were implemented for the three scenarios of Section 2.2 as the core variable input, all other parameters being held constant. In Scenario 1, factors were primarily derived from Singh et al. [6] and cover vehicles up to BS-IV; for BS-VI vehicles, COPERT's inbuilt factors calibrated for Euro VI-equivalent technology were applied in the absence of India-specific BS-VI data in the primary source, and for three-wheelers, where direct data were unavailable, factors from comparable categories (e.g., light petrol motorcycles) were applied with adjustment factors. In Scenario 2, factors for BS-III and below were kept as in the baseline, while BS-IV and BS-VI factors were taken from real-world remote sensing device (RSD) measurements by Narla et al. [7] — a combination reflecting the Delhi NCR fleet, where 90% of registered vehicles are BS-IV and above; bus and truck factors were carried forward from Scenario 1 in the absence of bus-specific remote-sensing data. In Scenario 3, factors for BS-III and earlier were again kept as in the baseline, while BS-IV and BS-VI factors were derived from laboratory measurements under Indian regulatory test conditions; truck factors were carried forward from Scenario 1 in the absence of truck-specific laboratory data.

2.4 Evaporative emission model and inputs

Evaporative emissions — the release of VOCs from a vehicle's fuel system through evaporation rather than combustion — were estimated with a proprietary fuel-system model. The model accounts for all principal evaporative pathways from petrol vehicles rather than diurnal breathing alone: diurnal ("breathing") losses driven by daily temperature cycling, running-loss and hot-soak losses associated with vehicle operation and engine-off cool-down, and refuelling losses displaced from the tank when fuel is dispensed. It is driven by fuel properties, fuel-system hardware and the rate of adoption of evaporative-control canisters: fuel volatility, the most influential fuel input, is represented through Reid Vapour Pressure (RVP) and ethanol content (E20 petrol, RVP 70 kPa); canister adoption is 100% for cars under both BS-IV and BS-VI and 75% (BS-IV) to 100% (BS-VI) for two-wheelers; and fuel-tank volume (50–75 L) and canister working capacity (0.5–3.0 L, rising with the emission standard) are specified by vehicle category and emission standard, since both determine the headspace available for vapour generation and the capacity to capture and store it between trips.

For each vehicle category the model combines these inputs with a representative diurnal temperature profile to produce a per-vehicle daily emission rate; for Delhi a diurnal range of approximately 25–40 °C was applied, with temperature inputs from VisualCrossing. The national estimate extends the same model and inputs, unchanged, to the 20 most-populated Indian cities, the only new inputs being city-specific temperature profiles from the same source over the past ten years.

3. Results

3.1 CO emissions

Fig. 1a shows CO emissions for Delhi NCR under the baseline scenario: total emissions were 58,959 t/year, with two-wheelers (2W) the dominant contributor (note the separate scale) at 29,013 t/year, or ~49% of the total. Between Scenario 1 (Baseline) and Scenario 2 (Remote Sensing), total emissions rose from 58,959 t/year to 215,563 t/year — approximately a 3.7-fold increase — reflecting the higher real-world emission factors captured in the remote-sensing dataset.

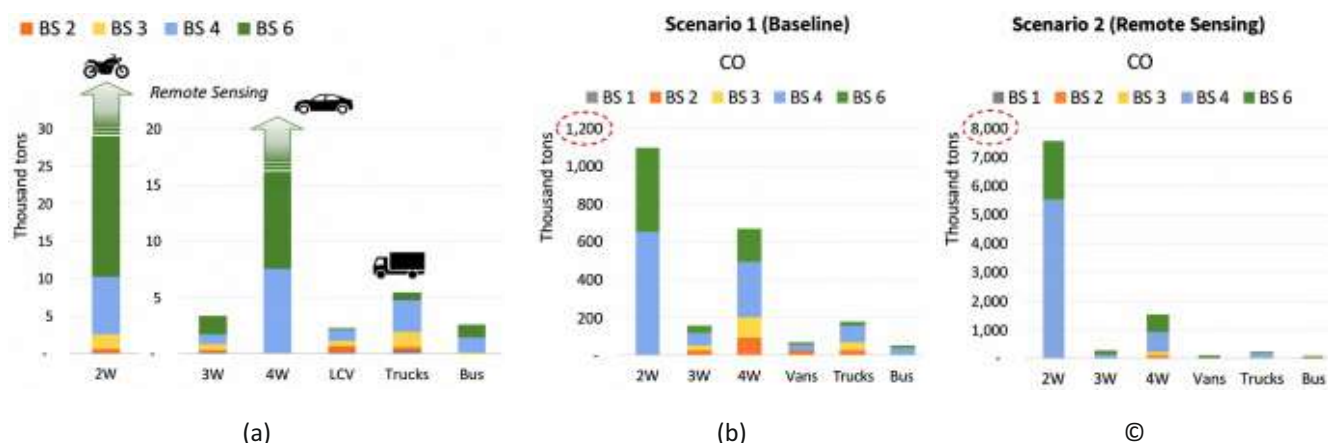


Fig. 1: Comparison of CO emissions under the baseline and Scenario 2 conditions for (a) Delhi NCR and, nationally, under (b) the baseline and (c) Scenario 2. Note that the y-axes of the two national plots have a different range.

At the national level (Fig. 1b, 1c), CO emissions rose from 2.2 Mt/year in Scenario 1 to 9.6 Mt/year in Scenario 2, an approximate 4.5-fold increase. Two-wheelers were the dominant source in both scenarios, at ~50% of the total in Scenario 1 and ~79% in Scenario 2, indicating the strong influence of real-world factors on the largest vehicle category in the fleet.

3.2 NOx emissions

NOx emissions in Delhi increased from ~30 kt/year in Scenario 1 to 41.7 kt/year in Scenario 2, approximately 35–40% higher than the baseline (Fig. 2a,b). Trucks and 2W dominated in all scenarios: in Scenario 1 trucks contributed the largest share (approximately 11.5 kt/year), followed by 2W (~7.4 kt/year); under Scenario 2, 2W rose sharply to nearly 12 kt/year, comparable to trucks. By emission norm, BS-IV vehicles were the largest contributors across all scenarios, accounting for roughly 16–18 kt/year, followed by BS-VI vehicles, whose emissions nearly doubled from ~8.5 kt/year in Scenario 1 to ~17.5 kt/year in Scenario 2; BS-I to BS-III contributed comparatively smaller share, mostly due to the fleet having been turned over to BS IV & VI compliant.

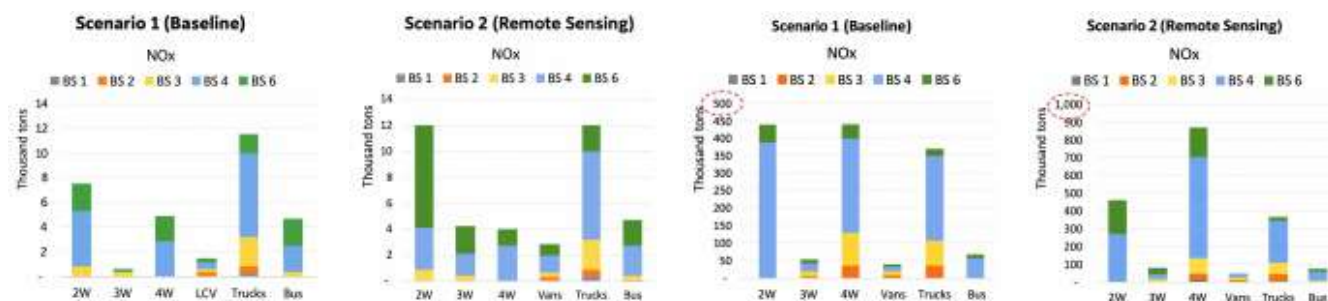


Fig. 2: Comparison of NOx emissions under (a) the baseline and (b) Scenario 2 conditions for Delhi NCR, and under (c) the baseline and (d) Scenario 2 conditions nationally.

Nationally (Fig. 2c,d), NO_x emissions increased from 1.4 Mt/year in Scenario 1 to 1.9 Mt/year in Scenario 2, an approximate 30% increase. Two-wheelers were the largest contributor in Scenario 1 at approximately 438 kt/year, increasing slightly to ~460 kt/year in Scenario 2; four-wheelers were comparable in Scenario 1 at approximately 438 kt/year, followed by trucks at approximately 365 kt/year. The most significant change was in four-wheelers, whose emissions roughly doubled from approximately 438 kt/year to around 870 kt/year, making 4W the dominant contributor in Scenario 2.

3.3 Particulate matter emissions

PM_{2.5} emissions in Delhi are shown in figure 3. Emissions were driven primarily by 2W, 4W and trucks, although their relative importance shifted considerably: in the baseline, four-wheelers were dominant at approximately 460 tons, closely followed by 2W (~430 tons) and trucks (~400 tons); under Scenario 2, overall emissions declined, 2W dropping to approximately 300 tons and 4W falling sharply to around 130 tons, leaving trucks as the largest contributor at approximately 400 tons.

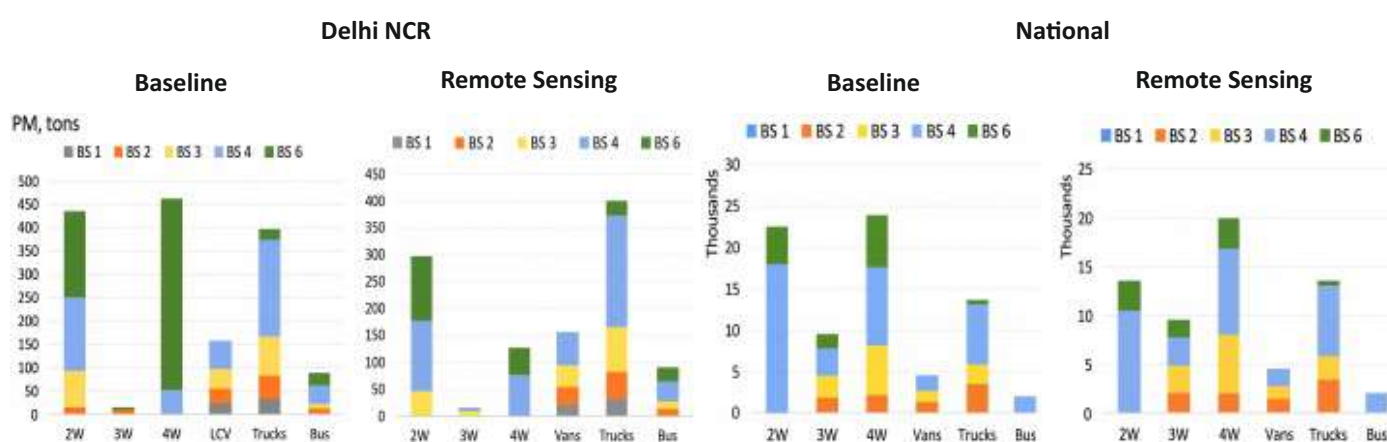


Fig. 3: PM_{2.5} exhaust emissions under (a) baseline, (b) Scenario 2 conditions for Delhi NCR (tons), and under (c) baseline and (d) Scenario 2 conditions nationally (thousands of tons).

Nationally, PM_{2.5} emissions showed a contrasting trend, with a moderate reduction in Scenario 2 relative to the baseline that was also reflected in exhaust emissions (Fig. 3d,e). Two-wheelers and four-wheelers remained the dominant contributors but, unlike in Delhi, both declined under Scenario 2 and drove the overall reduction, two-wheelers showing the most noticeable decline, particularly in exhaust emissions, suggesting a strong sensitivity of this category to real-world emission estimates. Three-wheelers, vans, trucks and buses remained largely unchanged, indicating that national-level differences were primarily influenced by light-duty rather than heavy-duty categories; trucks nonetheless continued to contribute a significant share.

The particulate inventory is estimated in terms of mass, not number count; ultrafine particles are the most dangerous to health, which has led to number-based standards with a counting cut-off of 23 nm under BS-VI, whereas technology now allows counting down to 10 nm (already implemented in Europe); these additional very small particles add little to particulate mass but are extremely harmful, and the additional burden in terms of particle count is beyond the scope of this study.

3.4 VOC emissions: tailpipe

Volatile organic compounds, unlike the species above, are emitted through two pathways: from the tailpipe, associated with incomplete combustion, and through evaporation. Fig. 4 shows the baseline tailpipe VOC emissions for Delhi and nationally by vehicle type: two-wheeler emissions dominate, as for CO and not surprisingly, since both CO and VOC emissions are associated with incomplete combustion. Total emissions are ~6,300 tons in Delhi, of which ~54% are from two-wheelers; the corresponding number is ~260,000 tons for the entire country, of which ~70% is contributed by two-wheelers. The emissions are almost evenly split between BS-IV and BS-VI vehicles — not because BS-VI two-wheelers emit at similar levels as BS-IV, but because a much larger fraction of vehicles in Delhi is certified to BS-VI.

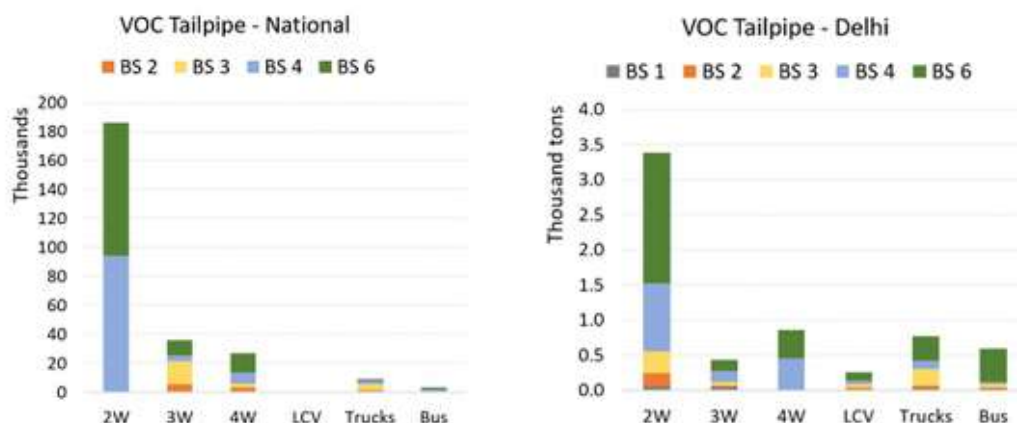


Fig. 4: VOC exhaust emissions (thousands of tons) under baseline conditions for (a) Delhi and (b) national.

3.5 VOC emissions: evaporative

Evaporative emissions are a disproportionately large source of VOC emissions in India relative to most other markets; several VOC species are harmful to health and known carcinogens, and the emissions are simply fuel lost via evaporation, with a direct negative impact on fuel consumption and cost of ownership. The dominant driver is ambient temperature: emissions scale strongly with diurnal temperature swings, and across April 2015–April 2025 major Indian cities recorded a substantially higher share of days above 35 °C than European cities such as Brussels, while Delhi’s daily maximum exceeds 40 °C (even reaching 45 °C) for several months, so that a diurnal range of 25–40 °C is better suited to Indian conditions.

Across the 20 cities, modelled per-vehicle rates span roughly 6.3 to 10.5 g VOC per car per day, driven almost entirely by ambient temperature: highest in hot, continental northern and central cities with large diurnal swings, lowest in milder, humidity-moderated coastal and southern cities. Two representative city profiles (Fig. 5a,b) illustrate the seasonal pattern behind these averages: emissions peak sharply through the pre-monsoon summer and fall back in cooler, wetter months, with the diurnal (“breathing”) component dominating the summer spike. Weighting the 20 city rates by vehicle population gives a single national mean of 8.2 g VOC per petrol car per day, which amounts to ~81 million tonnes VOC/year for the entire fleet of ~27 million cars.

For Delhi, the model estimates average evaporative emissions of 9.5 g VOC per petrol car per day, rising to roughly 50 g VOC per car per day during the summer months (Fig. 5a); applied across Delhi’s petrol-car fleet of approximately 2.2 million vehicles, this corresponds to a total of about 7,628 tons of VOC per year (9.5 g/day × 365 days × 2.2 million cars). The contrast with tailpipe VOCs is the central finding: a Delhi car driving the local average of about 11,000 km per year, emitting hydrocarbons at 75% of the 68 mg/km limit, produces roughly 1.6 g/day of tailpipe HC, so evaporative emissions exceed tailpipe HC by about 6× on an annual-average basis and by about 32× at the summer peak (Fig. 5c).

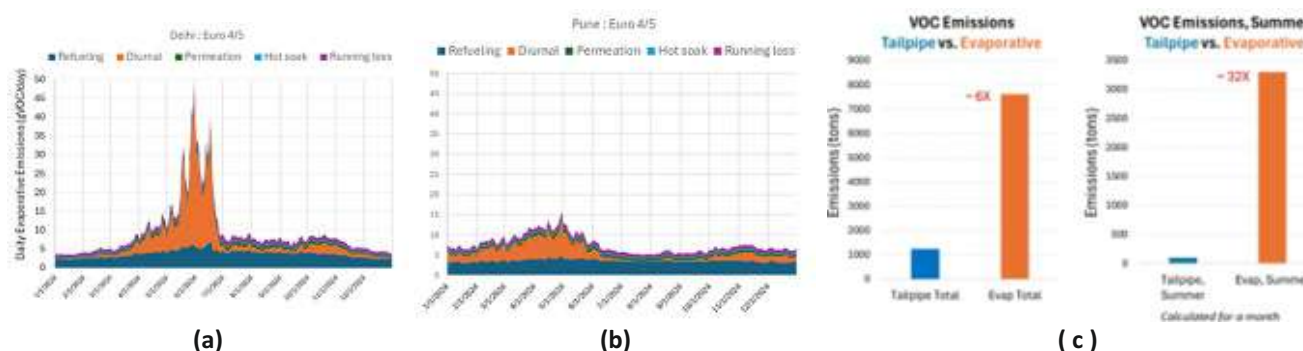


Fig. 5: Daily evaporative emissions by pathway for two example cities, (a) Delhi and (b) Pune, showing the summer-dominated diurnal profile — the Delhi panel is the modelled daily evaporative emissions for a passenger car in Delhi, using a diurnal temperature profile of 25–40 °C, E20 fuel, RVP 70 kPa; (c) average and summer-peak evaporative emissions compared with tailpipe HC emissions for a Delhi passenger car (g/day).

Refuelling losses — emissions from the tank and around the nozzle during refuelling — are also a significant fraction of the total; the two common controls are Stage II vapour recovery at fuel stations and onboard refuelling vapour recovery (ORVR) on vehicles, and while India has implemented Stage II norms, the hardware is typically plagued by inefficiencies and maintenance issues. A limitation is that no similar analysis was made for two-wheelers, owing to the lack of reliable inputs, of a robust model comparable to the four-wheeler one, and of emission factors measured under India-specific diurnal temperatures. Two-wheelers suffer from the same evaporative sources, worsened by exposed fuel tanks and more propensity for refuelling losses; their much smaller tanks mean the diurnal losses per vehicle are expected to be smaller, but the parc is much larger, so overall two-wheelers are expected to be a very important source of evaporative VOC, and a model validated with India-specific data is recommended before a reliable inventory can be calculated for them.

3.6 Sensitivity analyses

The estimates are inherently influenced by uncertainties in key inputs — in a highly heterogeneous country such as India, variations in regional travel behaviour, traffic conditions, fleet composition and driving patterns make it challenging to represent real-world conditions with a single set of assumptions — among which VKT and average vehicle speed were identified as critical determinants. A dedicated sensitivity analysis therefore quantified the responsiveness of the estimates to plausible variations in VKT and speed.

3.6.1 Elevated VKT

A large range of VKT is found in the literature for India, reflecting in part regional and demographic differences (Fig. A8); with improved vehicles, roads and infrastructure and lifestyles involving more travel, VKT is likely to increase in coming years, which will increase emissions for a given fleet. Increased VKT raises emissions, as expected, but the extent depends on the species: vehicles with a particulate filter are not expected to see a significant increase, since their tailpipe emissions are near-zero irrespective of distance driven, and gaseous emissions are mostly a cold-start problem whose increase depends on the extent of advanced catalysts used. Varying VKT within the literature range, CO emissions more than doubled for both two- and four-wheelers, driven especially by BS-IV vehicles; NO_x also showed a two-fold increase, for both light- and heavy-duty vehicles; and PM_{2.5} exhaust emissions increased 2–4× for two-wheelers, cars and trucks (Fig. 7a), mostly from BS-IV and older vehicles owing to their lack of filters and high emission factors. The inventory presented here could therefore be a lower bound, considering the increase in mobility predicted for India, and further data collection is needed to increase the robustness of the calculations.

3.6.2 Speed sensitivity of urban emissions

Extreme congestion in Delhi NCR, where peak-period vehicle speeds approach walking pace — a 2.1 km busy corridor requires 25 minutes by vehicle (~5 km/h) versus 19 minutes on foot at 12:30 pm on a Monday, post-rush hour, indicating chronic low-speed operation across much of the urban network (Fig. A9) — motivated an analysis of speed–emission relationships. Off-peak, peak and highway speeds were varied from baseline by +10 km/h and +20 km/h for CO, NO_x and PM_{2.5}. COPERT emission factors remain invariant below 10 km/h, preventing direct assessment of Delhi’s most congested regimes, and the study’s custom remote-sensing and laboratory-derived factors for nearly all vehicles are speed-independent by construction, so that speed adjustments would yield no emission response. To overcome both limitations, standard COPERT factors were applied across the fleet while preserving scenario activity and age distributions, and speed–emission curves characterised for ≥10 km/h were extrapolated to 5 km/h. The four-wheeler response curves (Fig. 7b) show emissions predicted to increase by ~20–40% at 5 km/h compared with 30 km/h, confirming speed as a dominant emission lever in congested cities: even modest flow improvements yield disproportionate air-quality gains, underscoring congestion management and public-transport reinforcement as high-leverage interventions beyond fleet renewal. The increase at low loads and speeds is well understood and is associated with lower exhaust temperatures reducing the efficacy of emission-control systems; the US and Europe have implemented low-load, low-speed cycles in their latest heavy-duty regulations (Euro 7 and the EPA HD Clean Trucks Plan).

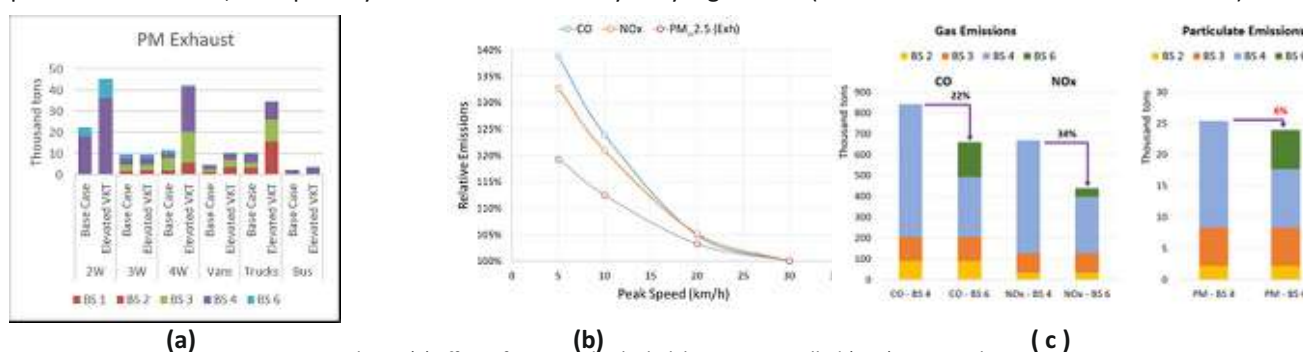


Fig. 7: Sensitivity analyses: (a) effect of increased vehicle-kilometres-travelled (VKT) on PM exhaust emissions; (b) four-wheeler emission sensitivity to speed: mean % change per –10 km/h (CO, NO_x, PM_{2.5}); (c) comparison of CO, NO_x and PM emissions (kt/year) for passenger cars under BS-IV and BS-VI scenarios (see text for a description).

The 68 mg/km Bharat Stage limit, and hence the 1.6 g/day tailpipe figure, is defined on a hydrocarbon (THC/NMHC) basis, whereas the evaporative emissions and inventory totals are expressed as VOC. For petrol the two are close in magnitude but not identical: VOC excludes methane and adds oxygenated organics (e.g., ethanol and aldehydes, which are elevated under E20) that hydrocarbon measurement omits. A VOC/THC speciation factor should be applied for a strictly like-for-like comparison.

3.6.3 Impact of evolving emission standards

To isolate the effect of standard progression, a counterfactual analysis was conducted for the passenger-car (4W) category, comparing a hypothetical BS-IV-only fleet with the current BS-VI-compliant fleet: the same overall car parc was assumed, but the emission factors of all BS-VI-compliant vehicles were replaced with BS-IV ones. As shown in Fig. 7c, the transition to BS-VI reduced passenger-car CO by 22% compared with a scenario in which all modern cars were only BS-IV compliant, and NO_x by a marked 34%, the higher NO_x reduction reflecting the effectiveness of the advanced emission-control technologies introduced under BS-VI (especially for diesels, which are still a significant fraction of the Indian fleet). Instructively, PM emissions are estimated to be reduced by only 6%: BS-VI introduced a particle-number (PN) limit that enforced filters, but only on direct-injected engines (diesels and petrol GDI), and India has a low fraction of GDI vehicles, so the PN limit does not apply to the majority of port-fuel-injected (PFI) vehicles; BS-VI thus enforced little to no additional technology adoption for most of the passenger-car fleet, resulting in similar overall emissions.

4. Recommendations

The findings of this inventory point to a clear agenda for India's next vehicle emission standard, Bharat Stage VII (BS VII). Four principles should anchor it:

- BS VII should be implemented as early as possible: each year of delay locks in higher-emitting vehicles for their full operating life and prolongs the transport sector's contribution to urban air pollution.
- The standard should be technology- and fuel-agnostic, applying the same emission limits across all powertrains and fuels and to all vehicle categories — including two-wheelers, which dominate the Indian fleet yet have historically faced weaker controls.
- Test procedures should measure real-world emissions under India-specific ambient conditions rather than being transposed unchanged from European cycles, since India's temperatures and driving patterns differ materially from those the European tests were designed around.
- The emission standards should protect against high emissions through the realistic lifetime of the vehicles. Accordingly, durability testing and in-use compliance requirements should be modified for all vehicles so that catalyst and evaporative control deterioration should be demonstrated to be commensurate with the lifetime of vehicles.

Following are specific recommendations for particulate, tailpipe gas emissions and evaporative emissions.

4.1 Particulate control

- A single particle-number (PN) limit of 6×10^{11} #/km should apply to every vehicle, with no distinction between gasoline direct-injection (GDI), port-fuel-injection (PFI) and diesel passenger cars, and — critically — extended to two-wheelers.
- The measurement cut-off should be lowered to capture solid particles down to 10 nm (PN₁₀), in line with Euro 7 and a step beyond the 23 nm threshold used under Euro 6; the smallest particles carry the greatest health risk yet are invisible to the current count.
- To maximise the health benefit, test conditions should be revised to span the temperatures experienced across India's major populated regions (0–45 °C) and a wide range of real-world driving representative of Indian traffic and driving patterns, so that certified performance reflects how vehicles actually emit on Indian roads.
- RDE limits in BS VI include a conformity factor (CF) of 1.5 for PN. This provides for an error margin associated with portable emission measurement systems (PEMS) and the challenges of performing measurements on the road compared with controlled lab conditions. The CF has been taken from Euro VI standards. However, there have been significant technology developments with PEMS, and India should consider reducing the CF to 1.0 (that is, the same limits on road as in the lab).

4.2 Gas emission control

4.2.1 Tailpipe emissions

- For heavy-duty trucks, NO_x limits should be lowered and supported by stronger real-world testing, with explicit attention to low-load operation where current procedures under-represent emissions.
- For NO_x, the conformity factor (mentioned above with particulates) should be changed to 1.0, ensuring that the same limits are enforced for RDE tests as in lab conditions.
- Across the fleet, CO, HC and NO_x standards should be tightened by at least 60% considering technological advancements, and real-driving-emissions (RDE) testing improved to include India-specific driving patterns.

- While not included in this study, India should introduce a limit for aldehydes, given the increasing targets for ethanol blending with petrol. Also included should be limits on ammonia, given the increased urea consumption anticipated with tighter NO_x limits, and N₂O, considering its role as a potent greenhouse gas.
- In-use compliance should be enforced so that on-road performance does not drift from type-approval values over a vehicle's life.

4.2.2 Evaporative VOC emissions (petrol and blended vehicles)

- The diurnal test window should be shifted from 20–35 °C today to 25–40 °C to reflect Indian ambient conditions. Testing should be done using SHEDs, and the test duration should be increased to 48 hours.
- The test procedure and emission limit should be tightened to align with those implemented in other major markets and to enforce best available technology. This includes implementing a 48-hour test procedure and a limit of 0.5 g/test. The latter has already been implemented in Brazil, another market with high ethanol content, that India is targeting to emulate.
- India should adopt a refuelling emission standard: onboard refuelling vapour recovery (ORVR) captures the vapour displaced when a tank is filled — a significant and otherwise uncontrolled VOC source — and proven test procedures already exist in other major markets such as the U.S., Brazil and China that India can draw on.
- The same limits and test procedures should be implemented for two-wheelers, considering their dominant share in the Indian market, and especially considering their high evaporative emissions due to exposed fuel tanks. The diurnal temperature range should be adjusted to 25–40 °C, similar to what is recommended for cars. The current test duration in India is a one-hour test, as compared with 24 hours in China and 72 hours in California; India should adopt a 48-hour test, similar to that for cars.
- Durability tests should be appropriately designed to ensure that vehicles meet the regulations over their lifetime. We recommend more data be collected on Indian two-wheelers to quantify the impact of higher diurnal temperatures (25–40 °C) on increasing evaporative emissions. Finally, we also recommend a refuelling emission standard for two-wheelers.

4.3 Priority actions by vehicle type

The table below consolidates the differentiated recommendations by vehicle type: the limits and test principles are common to all categories — consistent with a technology- and fuel-agnostic standard — while the entries note each category's binding gap and largest opportunity for improvement.

Vehicle Emissions: Recommended Measures

Comparison across vehicle categories

Measure	Light-Duty Vehicles	Two-wheelers	Heavy-duty Vehicles
 Particle number (PN) limit	6×10 ¹¹ #/km for Diesel, GDI, PFI, CNG, dual-fuel etc.; remove the GDI-only carve-out	Extend the same PN limit to 2W — currently no PN standard at all	Fuel/tech neutral PN limit
 PN measurement cut-off	Lower to 10 nm (PN10) from 23 nm	10 nm (PN10) from first application	10 nm (PN10) from 23 nm
 NO_x tailpipe	Tighten with BS-VI-class after-treatment across all fuels	Tighten; 2W are a large fleet-aggregate NO _x source	Deepest cuts (~60–90%, per US/EU); low-load/low-speed test cycles (or improved RDE)
 Real-world driving emissions (RDE)	Reduce PN & NO _x CF from 1.5 to 1.0	Apply RDE with CF 1.0	Reduce CF to 1.0; PEMS over low-load duty
 Evaporative / VOC	Diurnal 25–40 °C, 48-h SHED, tighten limit to 0.5 g/test. Implement refuelling limit	Same as cars; replace 1-h test with 48-h; ORVR; improved durability test	n/a (diesel)

Note: 'n/a (diesel)' indicates that evaporative VOC control is not material for the diesel-dominated heavy-duty segment.

Taken together, these measures keep BS VII uniform in its limits while directing the heaviest near-term effort to where the evidence points: closing the particle-number gap for the entire fleet, bringing two-wheelers fully into the standard for the first time, and tightening heavy-duty NO_x for real-world low-load operation.

5. Concluding remarks

This study set out to quantify the emissions from the current vehicular fleet in India, allocate the contribution to the various types and certification levels of vehicles, and test whether laboratory-derived emission factors adequately describe the on-road emissions burden, for a highly populated, urban and polluted city (Delhi NCR) and for the entire country, using COPERT with emission factors measured in the laboratory and on the road by remote sensing. Our study shows that India should take bold measures to reduce pollution from all vehicles. India is not Europe: while Bharat Stage norms have traditionally followed Europe, it is time to adjust the testing boundary conditions that significantly affect emissions — notably ambient temperature and driving patterns — since India's much warmer temperatures result in very high evaporative VOCs, and its slower-speed, start-stop driving leads to higher particulates from cars and NO_x emissions from trucks. One of the key takeaways is that India must extend the stringency of emission standards to two-wheelers, given their high contribution to the inventory for almost all pollutants and the absence of any particle-number standard for these vehicles, which have been found to emit at levels similar to cars. NO_x remains a heavy-duty and two-wheeler problem; BS-IV and BS-VI vehicles account for the bulk of fleet emissions because of their volume in the active stock rather than poor per-vehicle performance, and the counterfactual case study shows that the latest standards must have had a significant impact on reducing CO and NO_x, pointing to the need for faster fleet turnover. As expected, on-road emissions were found to be much higher than those measured in the laboratory, which points to the need for further real-world measurements and an emphasis on RDE testing. The next emission standard (BS VII) must be implemented as soon as possible, should be technology- and fuel-agnostic, and should require testing under India-specific boundary conditions; the impact of higher renewable-fuel blends on criteria pollutants, and non-tailpipe emissions from brakes and tyres, should be evaluated in future studies.

Acknowledgments

We are grateful to the Emission Control Manufacturers' Association (ECMA) for the opportunity to contribute to this work; to Namita Singh of the International Council on Clean Transportation (ICCT) for her valuable inputs and support, and for her earlier work, which provided an important foundation and reference point for this study; to Dr. Shantanu Roy, Director of IIT Delhi Abu Dhabi, for facilitating the study through the provision of intern support, and to Bilal Rasheed and Ankit Kumar for their contributions to its development and execution; to EMISIA, with special appreciation to Traianos Karageorgiou and Charis Kouridis, for their collaboration, guidance and extensive support; to the Ministry of Road Transport and Highways, Government of India, for initiating the request for this work and providing invaluable intermediate checkpoints; to Dr. Virinder Sharma and his staff at the Commission for Air Quality Management (CAQM) for guidance on making the study relevant for Delhi NCR; and to the Automotive Research Association of India (ARAI) and the International Centre for Automotive Technology (ICAT) for expert technical discussions and for helping align the study with potential future regulatory directions.

References

- [1] MoEFCC. (2024). India: Fourth Biennial Update Report to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India.
- [2] EMISIA. COPERT. <https://copert.emisia.com/> (2026).
- [3] Ntziachristos, L., Gkatzoflias, D., Kouridis, C. & Samaras, Z. COPERT: A European Road Transport Emission Inventory Model. in 491--504 (2009). doi:10.1007/978-3-540-88351-7_37.
- [4] EMEP & EEA. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023 : Technical Guidance to Prepare National Emission Inventories. (Publications Office of the European Union, 2023).
- [5] EMISIA. COPERT Australia. <https://copert.emisia.com/copert-australia/>.
- [6] Singh, N., Mishra, T. & Banerjee, R. Emission inventory for road transport in India in 2020: framework and post facto policy impact assessment. *Environmental Science and Pollution Research* 29, 20844--20863 (2022).
- [7] Narla, A., Bernard, Y., Dallmann, T. & Bhatt, A. Real-World Motor Vehicle Exhaust Emissions in Delhi and Gurugram Using Remote Sensing. (2024).
- [8] Ministry of Road Transport and Highways, G. of I. Vehicle population data. <https://analytics.parivahan.gov.in/> <https://analytics.parivahan.gov.in/>.
- [9] Guttikunda, S. K. Vehicle Stock Numbers and Survival Functions for On-Road Exhaust Emissions Analysis in India: 1993--2018. *Sustainability* (Switzerland) 16, (2024).

- [10] Planning Department, Govt. of N. D. Economic Survey of Delhi. (2024).
- [11] Ministry of Earth Sciences, Govt. of I. SAFAR-High Resolution emission inventory of mega city Delhi - 2018. (2018).
- [12] Sabarish Elango Dharshan Siddarth Mohan Himani Jain Hemant Mallya Virendra Ade, A. What Drives Vehicle Ownership Costs in India? (2025).
- [13] Gopalaswami, R. An Integrated Vehicular Emission Control Programme for the City of Delhi Using Retrofitted Emission Control Technologies. *Journal of Atmospheric Pollution* 4, 1--14 (2016).
- [14] Goel, R. & Guttikunda, S. K. Evolution of on-road vehicle exhaust emissions in Delhi. *Atmos. Environ.* 105, 78--90 (2015).
- [15] Prakash, J., Vats, P., Sharma, A. K., Ganguly, D. & Habib, G. New emission inventory of carbonaceous aerosols from the on-road transport sector in India and its implications for direct radiative forcing over the region. *Aerosol Air Qual. Res.* 20, 741--761 (2020).
- [16] Pandey, A. & Venkataraman, C. Estimating emissions from the Indian transport sector with on-road fleet composition and traffic volume. *Atmos. Environ.* 98, 123--133 (2014).
- [17] Goel, R., Mohan, D., Guttikunda, S. K. & Tiwari, G. Assessment of motor vehicle use characteristics in three Indian cities. *Transp. Res. D Transp. Environ.* 44, 254--265 (2016).
- [18] Baidya, S. & Borken-Kleefeld, J. Atmospheric emissions from road transportation in India. *Energy Policy* 37, 3812--3822 (2009).
- [19] Bansal, P., Kockelman, K. M., Schievelbein, W. & Schauer-West, S. Indian vehicle ownership and travel behavior: A case study of Bengaluru, Delhi and Kolkata. *Research in Transportation Economics* 71, 2--8 (2018).
- [20] Goel, R., Guttikunda, S. K., Mohan, D. & Tiwari, G. Benchmarking vehicle and passenger travel characteristics in Delhi for on-road emissions analysis. *Travel Behav. Soc.* 2, 88--101 (2015).
- [21] Akbar, P. A., Couture, V., Duranton, G., Ghani, E. & Storeygard, A. Mobility and Congestion in Urban India. <http://faculty.haas.berkeley.edu/couture/index.html>. (2018).
- [22] L. R. Kadiyali. CHOICE OF LOW COST STANDARDS AND SPECIFICATIONS FOR RURAL ROADS. Ministry of Shipping and Transport (Roads Wings), New Delhi <https://pmgsy.nic.in/choice-low-cost-standards-and-specifications-rural-roads#:~:text=The%20paper%20evaluates%20the%20current,forth%20suggestions%20on%20several%20aspects.>
- [23] Raees Ahmad, R. & Rathore, R. A Study of Traffic Stream Characteristics on National Highway Under Heterogeneous Traffic Conditions. *International Journal of Innovative Research in Engineering & Management* <https://doi.org/10.55524/ijirem.2022.9.6.17> (2022) doi:10.55524/ijirem.2022.9.6.17.
- [24] India Meteorological Department. Master Data: Year- and Month-wise Minimum, Maximum and Mean Actual Temperatures recorded in India (from 1901) . Preprint at <https://dataful.in/datasets/18471/>.
- [25] Google Map. Travel time comparison for 2.1 km Chawri Bazar--Khari Baoli: motor vehicle vs pedestrian. <https://www.google.com/maps> (2026)



ALKEGEN ADVANCED + TRUSTED AUTOMOTIVE SOLUTIONS



Emission Control

Portfolio of support mats
for exhaust systems



PC-Max

VC-Max

CC-Max

Ecoflex

Insulfrax LTX

QSP XPE

100+ Years of
Proven Products

Sealing Gaskets

Engineered with a composite material
+ electromeric rubber band



Interface
Performance Materials
By ALKEGEN

SelectASeal

EnCore™ MBG
Mechanically-Bonded Graphite
Nonasbestos Gasket Material

alkegen.com
INMobility@alkegen.com

Driving a Competitive, Clean, and Technology-Neutral Automotive Transition

AECC Position Paper

5 October 2026

As negotiations continue on the Automotive Package, policymakers have an opportunity to establish a genuinely technology-neutral road transport decarbonisation framework that supports industrial competitiveness, climate neutrality, and clean air. Discussions in the European Parliament and Council demonstrate growing recognition that a successful transition must underpin climate ambition with technology-neutrality, ensuring that policy objectives reflect real-world economic and technological realities.

The Commission's proposal represents a welcome shift towards greater technology-neutrality. The introduction of fuel and steel credits represents an important acknowledgement that vehicle life-cycle emissions must be addressed within the regulatory framework. However, the restrictions on timing (beyond 2035) and contribution

(3-7% cap) significantly hinder their impact and risk limiting innovation. Therefore, important modifications are needed to ensure that all credible low- and zero-emission technologies can contribute on a level playing field to achieving the EU's climate objectives.

At the same time, proposed changes to Euro 7 in the Automotive Omnibus risk weakening the EU's air quality objectives at precisely the moment policymakers are moving toward a more flexible long-term approach to vehicle decarbonisation. In this context, it is essential to support ambitious pollutant emission standards to safeguard air quality and public health, as well as to enable complementary technologies.

AECC therefore calls on policymakers to ensure that the final package delivers both technology-neutral climate ambition and clean air with the following key priorities:

1. Establish a genuinely technology-neutral framework for road transport decarbonisation based on life cycle assessment considerations, providing long-term regulatory certainty for investment across all technology pathways
2. Remove the arbitrary caps on fuel and steel credits and allow these credits to apply immediately, and extend the scope of the credits to other vehicle-life-cycle emission topics
3. Establish a Vehicle category running Exclusively on Eligible Fuels (VEEF)
4. Prevent any further weakening of current Euro 7 standards in the Omnibus and consider the need for a Euro 7 reassessment within the evolving regulatory landscape

Technology-Neutrality based on Life Cycle Assessment

The Commission's proposal to introduce limited flexibilities is an acknowledgement that alternative decarbonisation pathways are credible and an initial move toward addressing vehicle life-cycle greenhouse gas (GHG) emissions, the real issue to tackle. However, the restrictions on timing and contribution hinder innovation and do not fully address technology-neutrality and required decarbonisation flexibility.

The long-term approach should be based on Life Cycle Assessment (LCA) considerations in line with the upcoming UNECE/EU methodology. This would allow all viable solutions to contribute across the value chain as best fits market needs, while advancing decarbonisation.

AECC studies¹⁻³ have already demonstrated that the Internal Combustion Engine (ICE) is not the problem. The real issue is the use of fossil fuels. All powertrains result in similarly low life cycle GHG emissions when operated on sustainable renewable fuels, renewable electricity, or renewable hydrogen. The LCA data shows that combustion becomes net-zero when sustainable renewable fuels (e-fuels or biofuels) are used. It is therefore clear that complementary technologies including efficient ICEs, PHEVs, and REEVs are credible contributors to decarbonisation when using renewable fuels. The Tour d'Europe project⁴ showed that sustainable renewable fuels today already enable a significant CO₂ reduction of -77% on a Well-to-Wheel basis.

Establish a VEEF Category as ZEV

The Automotive Package recognises for the first time that sustainable renewable fuels can make a meaningful contribution to road transport decarbonisation. However, the restriction on the introduced credits is blocking an increase in renewable fuel volumes, as eligible fuels on the market already fully exhaust the cap despite it only applying as of 2035. The caps should therefore be removed, and the credits should apply immediately.

Policymakers should furthermore build on the momentum by establishing a dedicated Vehicle category running Exclusively on Eligible Fuels (VEEF) as ZEV (Zero Emission Vehicle) to provide regulatory certainty and ensure consistent treatment of all credible decarbonisation technologies. This would:

- Support technology-neutrality across the transport policy framework
- Ensure regulatory consistency between vehicle, fuels, and fleet legislation
- Recognise the contribution of sustainable renewable fuels to life cycle GHG reductions, accelerating emissions reductions with complementary technology pathways
- Provide a pathway for continued innovation in highly efficient combustion technologies operating on renewable fuels; an area in which Europe has a competitive edge over global competitors

A VEEF category should also be recognised under related initiatives, including the Clean Corporate Vehicles proposal, to ensure consistency and a level-playing field for all net-zero technologies. The Working Group on Monitoring Methodologies has already developed a workable definition of eligible fuels⁵, which can serve as the basis for implementation in line with the Renewable Energy Directive (RED).

The upcoming RED revision should set out a progressive, realistic and economically sustainable evolution of fuel GHG saving thresholds, ensuring a predictable investment framework and allowing for continuity of existing production assets and long-term investment planning.

Safeguard Ambitious Euro 7 Standards

While seeking to simplify testing procedures, the proposed Automotive Omnibus would further weaken Euro 7 vehicle emission standards, which already fail to meet the level of ambition our industry can deliver. If adopted as proposed, the Omnibus would undermine progress on air quality and negatively impact the health of everyday Europeans.

While AECC supports simplification efforts, it is essential that the level of ambition for vehicle emission standards is not further reduced. To do so would only delay already available technologies, disrupt investments already committed, and lock high-emitting vehicles into the European fleet for years.

Ambitious vehicle pollutant emission standards are essential to enabling flexibility and technology-neutrality in CO₂ standards without compromising air quality and public health. Advanced emissions control systems can ensure real-world road transport pollutant reductions alongside decarbonisation. This will support a balanced regulatory framework that aligns flexibility with climate objectives and air quality.

AECC urges policymakers to reject any further weakening of Euro 7 standards under the Automotive Omnibus and to assess the need for a future reassessment of standards considering the evolving regulatory landscape, where the road transport decarbonisation framework is moving toward greater flexibility and technology-neutrality. Amendments in the European Parliament provide a pathway for such reassessment, ensuring that developments in the CO₂ regulatory framework do not undermine the EU's air quality and public health objectives. Pollutant emission standards should remain effective, proportionate, and fit for purpose.

As global leaders in advanced emission control technologies, European companies have already developed solutions in anticipation of a more ambitious Euro 7 than was ultimately adopted. The solutions exist and we are ready to deliver.

About AECC

The Association for Emissions Control and Climate (AECC) is the international, Brussels-based association of European companies operating worldwide in the research, development, testing and manufacture of key sustainable technologies for mobile and stationary applications. Our membership includes Emitec Technologies, Johnson Matthey, NGK Europe, Umicore, Albonair, BASF ECMS and W.L. GORE.

We have a strong and focused European footprint across our members – employing around 22 500 skilled people in Europe across 47 production sites and 20 research and development (R&D) technical sites. We are present in

11 European countries and we are proud to be an integral part of Europe's automotive ecosystem, advancing innovation in a vital industrial sector.

AECC members' emission control technologies are integrated into the exhaust systems of cars, commercial vehicles, buses, motorcycles, construction equipment and industrial installations in Europe. We work with OEMs and other industry stakeholders, providing innovative technological solutions to the pollution problem that we see today. AECC supports the European Commission's long-term ambition for zero pollution and increased greenhouse gas emission reductions. Clean air and greenhouse gas reduction are priorities for all of us.

AECC is registered in the EU Transparency Register under n° 78711786419-61.

Should you need more information, you can contact AECC at info@aecc.eu.

References

- 1 J. Demuyne, et al., Zero-Impact Emissions from a Gasoline Car with Advanced Emission Controls and E-Fuels, 43rd International Vienna Motor Symposium, 27-29 April 2022.
- 2 D. Bosteels, et al., Combination of advanced emission control technologies and sustainable renewable fuels on a long-haul demonstrator truck, SIA Powertrain & Energy, 15-16 June 2022.
- 3 J. Demuyne, G. Jungmeier and D. Bosteels, Life Cycle Assessment (LCA) of Light- and Heavy-duty Vehicles - Focus on GHG Emissions and Primary Energy, SIA Powertrain Conference, 12 June 2025.
- 4 Tour d'Europe, Driving Decarbonisation with Renewable Fuels, 2025.
- 5 Working Group on Monitoring Methodologies of CO₂-neutral fuels, A Pathway to Climate Neutrality for Road transport, founded in 2024.



Ammonia as a Future Fuel: Opportunities and Challenges

Dr Sukrut Thipse

Automotive Research Association of India (ARAI)

Introduction

The transportation industry in the world faces a new challenge where all its impacts on the environment should be completely removed since it accounts for approximately 24% of direct emissions of CO₂ produced through the burning of fossil fuels. Although battery electric vehicles represent a solution to reduce the impact on the environment for passenger light vehicles, there are serious limitations which make it not possible to completely rely on electrification.

Hydrogen fuel is usually regarded as one of the cleanest alternatives; however, it has low energy density and complicated infrastructure since it can only be used when compressed at 700 bar or cooled to -253°C.

In contrast, ammonia (NH₃) represents a solution to the storage problems due to its function as a carrier of hydrogen which can easily get liquid in normal pressure or even at -33.3°C. It does not contain any carbon; therefore, it does not produce carbon dioxide during combustion. Moreover, ammonia has high octane rating from 110 to 130, which enables to use it with high compression ratio without knocking.

Chemical & Physical Identity: Why Ammonia?

NH₃ (ammonia) is a polar, trigonal pyramidal molecule that weighs 17.03 g/mol, and its gas density is 0.73 kg/m³. Contrary to hydrogen, requiring the cryogenic cooling of -253°C or pressurization of 700 bar, ammonia becomes the high-density liquid substance at a relatively moderate pressure of 8-12 bar or a manageable temperature of -33.3°C. This peculiarity makes ammonia an outstanding hydrogen carrier, offering a volumetric energy density (11.5-12.69 MJ/L) being 1.5-2.3 times higher than that of the liquid and compressed hydrogen.

Ammonia demonstrates excellent properties related to internal combustion engines thanks to its extraordinary Research Octane Number (RON >130). Such an extraordinary ability to resist the knocking provides the possibility to significantly advance the spark timing, manage highly pressurized intake charge and increase the dynamic compression ratio without the engine knocking.

However, molecular stability results in enormous thermodynamic drawbacks. Ammonia demonstrates the high autoignition temperature (~651°C), astronomically high minimum ignition energy (0.25 to 680 mJ) and a low burning velocity (~7 cm/s). Moreover, the narrow flammability range (15%-28%) also limits its operability.

Furthermore, ammonia demonstrates the extremely high latent heat of vaporization (~1370 kJ/kg), which is 1.5 times larger than one of traditional fuels. Upon injection, it acts as the heat sinks and cools down the cylinder. Although such temperature drop poses the danger of uncomplete combustion and misfires, the effect can be applied strategically through forced induction to cool down the combustion peak and block NO_x creation.

On-Board Storage & Material Behavior Being liquefied at 8-12 bar or -33.3°C, ammonia allows very efficient storage. Keeping 30-50 kg gives the 400-600 km range. High corrosive nature of the substance, however, demands the exclusion of all copper and brass from the material of the tank. The only possible materials are the 316L stainless steel and PTFE/Viton seals to avoid severe stress-corrosion cracking.

The Spectrum of Production Pathways

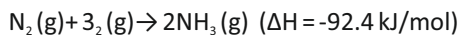
Ammonia production is currently shifting from a heavy industrial chemical sector to a highly diversified clean energy landscape. Historically manufactured via fixing calcium carbide, modern industrial global output exceeds 176 million metric tons annually, predominantly for fertilizers. However, to serve as a sustainable automotive fuel, production methods must evolve beyond carbon-intensive pathways to unlock true net-zero mobility.

Property	Ammonia (NH ₃)	Gasoline	Diesel	Hydrogen (H ₂)
Molecular weight (g/mol)	17.03	~114	~170	2.016
Lower Heating Value (MJ/kg)	18.6	44	42.5	120
Volumetric Energy Density (MJ/L)	11.5	~32	~35	2.9
Boiling Point (°C)	-33.3	~27	180-360	-253
Critical Temperature (°C)	132.4	~220	~300	-240
Critical Pressure (bar)	113	~30	~40	13
Specific Heat Capacity (kJ/kg·K)	4.7	~2.0	~2.2	14.3
Thermal Conductivity (W/m·K)	0.024	~0.12	~0.15	0.18

Table 1 : Properties of ammonia as compared with other fuels

1. Gray Ammonia (Conventional Haber-Bosch)

The foundational industrial method synthesizes ammonia from nitrogen extracted from liquefied atmospheric air and hydrogen produced via Steam Methane Reforming (SMR) of natural gas or coal gasification. The standard reaction operates under harsh conditions of 400–500°C and 150–250 atm over an iron-based catalyst:



This process is incredibly energy-intensive, releasing 1.6 to 2.0 kg of CO₂ per kilogram of ammonia produced, leaving a substantial lifecycle environmental burden.

2. Blue Ammonia

Blue ammonia acts as an immediate mid-term scaling solution. It maintains the conventional Haber-Bosch footprint but integrates Carbon Capture, Utilization, and Storage (CCUS) technologies. By capturing and permanently sequestering process emissions underground, blue ammonia cuts the overall fuel carbon footprint by 50% to 90%.

3. Green Ammonia (Sustainable Net-Zero Fuel)

Green ammonia eliminates fossil fuels entirely by pairing the synthesis loop with zero-carbon hydrogen. Water H₂O is electrolytically split via Proton Exchange Membrane (PEM) or Alkaline Water Electrolyzers (AWE) operating at

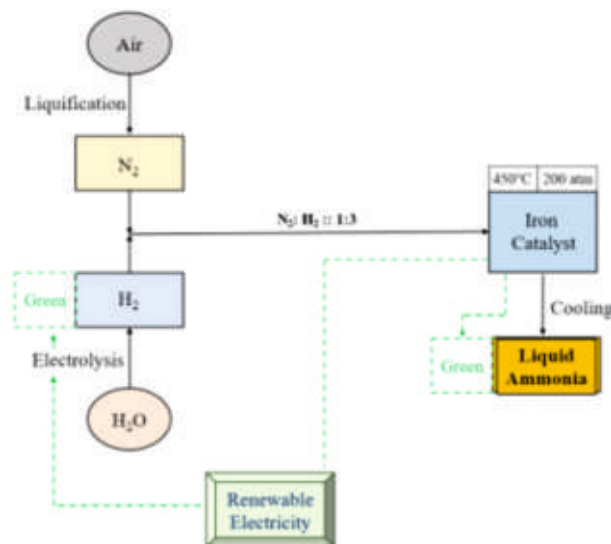


Figure 1: Flow diagram of the Haber-Bosch process to produce liquid Ammonia

low temperatures (30°C–80°C) powered purely by solar, wind, or hydro energy. This path reduces lifecycle emissions to a negligible 0.05 to 0.3 kg CO₂-eq per kilogram.

Green vs. Blue Ammonia Production	
Green Ammonia	Blue Ammonia
Hydrogen Source Renewable electricity (solar, wind) powers electrolysis of water to produce Green Hydrogen	Hydrogen Source Steam Methane Reforming (SMR) of natural gas produces Hydrogen
Process Green Hydrogen is combined with Nitrogen in a Haber-Bosch process powered by renewable	Process Conventional Haber-Bosch process, but the CO ₂ byproduct is captured and stored (CCUS)
Carbon Emissions Near-zero, 0.05 - 0.3 kg CO ₂ per kg of ammonia	Carbon Emissions 0.2 - 0.5 kg CO ₂ per kg ammonia (reduces emissions by 50-90%)

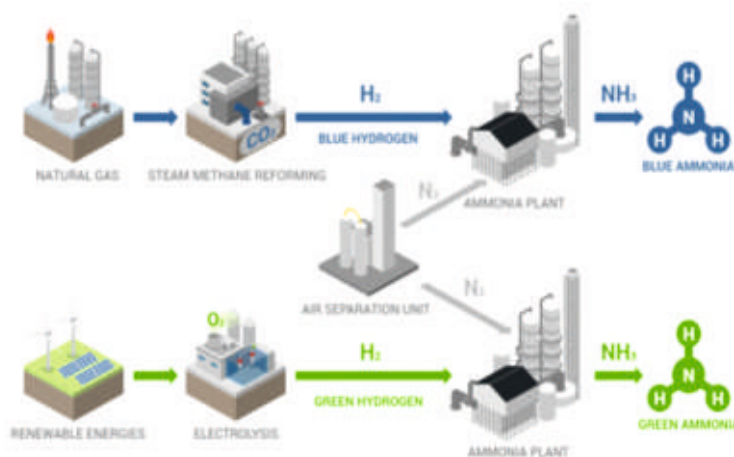


Figure 3: Green v/s blue ammonia

4. Electrochemical Ammonia Synthesis (EAS)

An emerging, alternative paradigm bypasses the rigid Haber-Bosch synthesis loop entirely. EAS utilizes a Nitrogen Reduction Reaction (NRR) to directly generate ammonia from atmospheric nitrogen and water at ambient conditions. While currently held back by lower technological maturity and catalyst degradation, its resistance to variable, intermittent power inputs make it the perfect candidate for decentralized fuel generation.

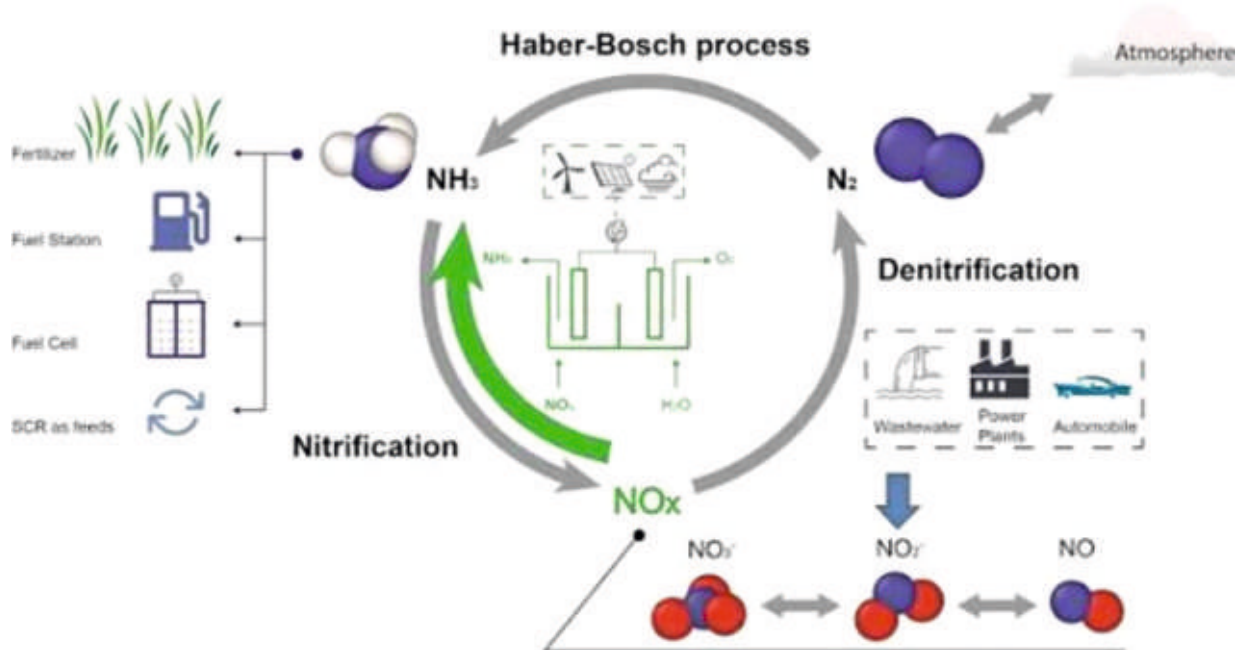


Figure 4: Electrochemical Ammonia Synthesis

Engine Technologies and Modifications

Adapting traditional internal combustion engines (ICE) for pure ammonia combustion requires overcoming fundamental thermodynamic hurdles. Because ammonia possesses a sluggish laminar burning velocity (~ 7 cm/s), high autoignition temperature ($\sim 651^\circ\text{C}$), and narrow flammability window (15%–28%), standard layouts encounter unstable combustion and severe power density penalties. To transform this low-reactivity molecule into a high-performance fuel, automotive engineers are executing sweeping modifications across fuel delivery, ignition, and metallurgy systems.

1. Direct Ammonia Combustion Engines & Fuel System Design: The integration of ammonia into reciprocating internal combustion engines requires a total redesign of both the combustion chamber and the supporting fuel supply infrastructure. Because ammonia possesses low reactivity, low viscosity, high volatility, and severe corrosivity, standard automotive hardware will fail rapidly. To resolve these limitations, developers are deploying specialized hardware adjustments divided into the engine block modifications and fuel delivery safeguards.

- **Combustion Chamber Geometry:** To accommodate ammonia's slow laminar burning velocity ($\sim 5\text{--}7$ cm/s) and ensure stable flame propagation, modified engines utilize large combustion volumes featuring specific arc or wedge-angles. These aggressive geometric shapes optimize fuel-air mixing before the flame front moves through the chamber. Additionally, to counteract low flame temperatures, upgraded and redesigned engine cooling architectures are integrated to maintain steady thermal balance throughout the block.
- **High-Pressure Tank Engineering:** Fuel tanks are engineered as specialized pressure vessels designed to hold liquid ammonia under a moderate pressure of 8–12 bar at ambient temperatures. To handle severe vibration, thermal expansion, and impact structural loads during accidents, these tanks conform to stringent regulatory mandates like DOT 4L and ECE R110. They must feature safety release valves, burst disks, secondary containment structures, and automated emergency venting devices calibrated exactly to ammonia's volatile vapor pressure curve.
- **Cavitation-Resistant Pump Hydraulics:** Liquid ammonia presents a very low viscosity of approximately 0.25 mPa·s, making it exceptionally difficult to pump without triggering vapor lock. Fuel system pumps must be carefully selected to resist cavitation while navigating high operating pressures. Engineers prioritize magnetic drive and diaphragm pump layouts built exclusively from chemically inert materials to preserve consistent flow lines under changing transient engine loads.
- **Vapor Recovery and Leak Mitigation:** Because ammonia is a potent health hazard with an Immediately Dangerous to Life or Health (IDLH) threshold of 300 ppm, the fuel loop must remain completely sealed. Dedicated vapor recovery systems are integrated into the plumbing to capture fugitive emissions and boil-off gas during vehicle operation and station refuelling. This infrastructure is supported by distributed electrochemical or metal-oxide semiconductor leak detection sensors linked to the ECU, which can trigger automatic shut-down sequences within milliseconds of a line failure.
- **Multi-Stage Fuel Conditioning:** To prevent internal fuel contamination and guard expensive downstream exhaust catalysts from poisoning, specific filtration is mandatory. The fuel infrastructure integrates dedicated particulate matter traps and moisture traps. Furthermore, the lines utilize specialized thermal management: inline electrical heaters keep the fuel from

freezing in extreme cold climates (especially below -33°C), while cooling subsystems protect against dangerous thermal runaway events during fast high-pressure refuelling cycles.

2. Injection Strategies: PFI vs. Direct Injection: To achieve uniform mixing and avoid lean misfires, fuel injection architectures must handle ammonia's unique vapor pressure and low viscosity:

- **Port Fuel Injection (PFI):** PFI injectors mist fuel into the intake stream at pressures of 3 to 6 MPa. However, PFI setups frequently suffer from high ammonia slip (unburned fuel escaping into the exhaust manifold) and require auxiliary intake heaters or pre-heated vaporizers.
- **Direct Injection (DI):** Direct cylinder injection gives the engine control system total authority over mixture stratification. DI injectors must operate under significantly higher pressures up to 20 MPa demands advanced sealing materials and specialized engine mapping to manage transient loads.
- **On-Board Catalytic Cracking:** To eliminate unburned ammonia slip, dual-fuel systems route a portion of the fuel through an on-board reformer. Utilizing a nickel-based catalyst heated above 450°C, the unit cracks ammonia into a highly reactive nitrogen-hydrogen mix, boosting peak thermal efficiencies up to 50%.

3. Material Compatibility & Engine Diagnostics: Ammonia is highly corrosive to yellow metals and induces deep stress corrosion cracking in steel. Maintaining a standard engine lifespan requires a total material overhaul:

- **Metallurgical Upgrades:** Components made of copper, brass, and zinc must be eliminated from the fuel lines and valvetrain to avoid rapid degradation. Standard iron and steel elements are upgraded to 316L stainless steel or coated with plasma-sprayed ceramics and nickel plating.
- **Advanced Sealing:** Conventional rubber seals quickly dissolve under exposure. System joints must rely on specialized fluorocarbon-based elastomers, prioritizing PTFE (Teflon) and Viton to prevent fugitive leaks.
- **Model Predictive Control (MPC):** Modern Electronic Control Units (ECUs) must use real-time Model Predictive Control algorithms to instantly adjust fuel metering. Because ammonia's combustion kinetics are slow, the ECU relies on closed-loop feedback from specialized, corrosion-resistant exhaust sensors to balance fuel delivery and suppress unburned slip.

Engineering Parameter	Traditional Gasoline/Diesel Baseline	Ammonia-Compatible Retrofit Specification	Performance Result & Output
Stoichiometric Air - Fuel Ratio	~14.7:1 (Gasoline) / ~14.5:1 (Diesel)	6.05:1 by mass	Accommodates a significantly higher fuel-mass flow rate per combustion cycle.
Engine Compression Ratio	~10:1 (SI)	Up to 15:1 (Exploiting high knock resistance)	Recoups power loss by capitalizing on ultra-high-octane features.
Port Fuel Injection Pressure	~0.3 – 0.5 MPa	3.0 to 6.0 MPa (Requires specialized pumps)	Achieves finer spray atomization but requires intake charge preheating.
Direct Fuel Injection Pressure	~15 – 20 MPa	Up to 20 MPa (Demands advanced sealing)	Provides infinite injection timing authority; minimizes crevice ammonia slip.
On-Board Cracking Profile	Not Applicable	Nickel-catalyst bed operating at >450°C	Supplies hydrogen promoter gas, lifting peak thermal efficiencies toward 50%.

Table 2: Architectural and Operative Parametric Comparison.

Challenges

While ammonia's carbon-free formulation provides an ideal pathway for net-zero transport, transforming this stable molecule into a practical automotive fuel presents severe engineering bottlenecks. Its unique thermodynamic stability, extreme chemical corrosivity, and high toxicity introduce strict hardware trade-offs. Overcoming these friction points requires re-engineering conventional combustion chambers and fluid infrastructure.

- **Sluggish Combustion Kinetics:** Ammonia exhibits a very slow laminar burning velocity (~5–7 cm/s) and long combustion durations. This degrades engine power density and transient responsiveness, making acceleration sluggish compared to conventional hydrocarbon fuels.
- **Cold-Start and Ignition Impediments:** With an exceptionally high autoignition temperature (~651°C) and high minimum ignition energy requirement, ammonia is highly resistant to initial ignition. Overcoming cold starts requires power-hungry auxiliary hardware like intake pre-heaters or secondary pilot fuel setups.
- **Severe Material Corrosivity:** Ammonia aggressively attacks non-polar metals and alloys, causing severe stress corrosion cracking in steels and rapid degradation of copper, brass, and zinc. This requires a total material overhaul using expensive 316L stainless steel and PTFE/Viton seals.
- **Toxic Tailpipe Slip and High Toxicity:** Running an engine on narrow flammability limits risks incomplete combustion, causing unburned ammonia slip. Because ammonia is a potent respiratory hazard with an Immediately Dangerous to Life or Health (IDLH) threshold of 300 ppm, any fugitive slip or cabin leak poses a significant safety threat that demands complex distributed sensor integration.



Figure 5: Challenges for ammonia as a fuel

Assessment and the Future

Evaluating the full lifecycle of ammonia as an automotive fuel reveals a highly competitive, carbon-neutral pathway that stands shoulder-to-shoulder with hydrogen fuel cells and battery electric vehicles. When manufactured as green ammonia via clean water electrolysis, a complete well-to-wheel (WTW) assessment shows an 80% to 90% reduction in lifecycle greenhouse gas emissions compared to conventional petroleum, yielding a near-zero carbon footprint of just 0.05 to 0.3 kg CO₂-eq per kilogram. While direct combustion eliminates carbon monoxide and carbonaceous soot, protecting local air quality remains tightly tethered to the strict deployment of 4-way catalytic after-treatment (SCR/EGR) systems to neutralize tailpipe nitrogen oxides (NO_x) and keep unburned fuel slip firmly below 10 ppm.

Looking toward the horizon, ammonia's market penetration will evolve through a phased adoption pathway. Heavy-haulage logistics fleets and the marine

shipping sector represent the immediate early markets, where ammonia's high volumetric energy density and fast 5-to-8-minute refuelling windows provide clear operational advantages over heavy battery packs. Capturing the mass consumer passenger market by 2040 remains heavily contingent on public-private partnerships driving down station installation costs, which currently sit at \$1 to \$2 million USD per site. Supported by robust international policy frameworks and proactive regional scaling allocations such as India's ₹19,744 crore National Green Hydrogen Mission ammonia is uniquely positioned to transition from an experimental Technology Readiness Level (TRL 5–7) chemical into a cornerstone baseline fuel of the global net-zero mobility mix.

Summary

Ammonia stands at a critical crossroads as the global transport sector races to achieve complete decarbonization. Once viewed strictly as an industrial staple for agriculture, this molecule has rewritten the rules of clean energy logistics, outperforming pure hydrogen in transport efficiency by liquefying under a modest pressure of 8–12 bar or at a manageable temperature of -33.3°C . Capturing its true environmental and economic value will rely heavily on moving away from carbon-heavy Gray production and aggressively expanding sustainable green pathways. Despite real engineering roadblocks from its ultra-slow combustion speed to intense material corrosivity the deployment of on-board catalytic cracking systems, advanced direct injection, and robust 316L stainless steel components prove that ammonia is a highly practical fuel to tame.

As the automotive sector moves past experimental benchmarks toward commercial operations by 2040, success will depend on structural synchronization. Early market entry will naturally favor heavy-haulage logistics networks, marine corridors, and industrial fleets, where its 5-to-8-minute refuelling turnarounds completely eclipse the operational downtime of battery setups. Supported by global policy frameworks and bold regional investments, like India's ₹19,744 crore National Green Hydrogen Mission, the transition from laboratory prototypes to active retail distribution is already gaining momentum. By embracing this scalable vector, the transport industry can bridge the final gaps in electrification, transforming a hazardous industrial chemical into a global cornerstone of net-zero mobility.



From Waste Oils to Clean Fuels: HEFA Pathways for Aviation, Road, Off-Road and Power Applications

Dr Sarmistha Nandy

Consultant- Energy Transition & Industrial Decarbonization; India, UAE

Abstract

Hydro-processed Esters and Fatty Acids (HEFA) is one of the most mature pathways for converting lipid-based feedstocks into renewable hydrocarbon fuels. Although the technology is widely associated with Sustainable Aviation Fuel (SAF), the same hydro-processing platform can produce diesel-range hydrocarbons suitable for renewable diesel or hydrotreated vegetable oil (HVO). This creates an opportunity to extend the role of HEFA beyond aviation to heavy-duty road transport, off-road machinery and stationary power generation.

HEFA processing converts triglycerides and free fatty acids present in used cooking oil, animal fats and other lipid feedstocks through hydrogenation and catalytic deoxygenation. Oxygen is removed through hydrodeoxygenation, decarboxylation and decarbonylation, producing predominantly C_{15} – C_{18} paraffinic hydrocarbons from common C_{16} – C_{18} fatty acids. Subsequent hydro-isomerisation improves low-temperature fuel properties, while controlled hydrocracking and fractionation determine the final distribution between aviation- and diesel-range products.

This article discusses the conversion chemistry and the broader application potential of HEFA-derived fuels. Emphasis is placed on the distinction between HVO and conventional FAME biodiesel, the role of hydrogen in fuel production and lifecycle emissions, and the potential use of renewable diesel in existing compression-ignition engines. The analysis suggests that HEFA should be considered not only as a SAF pathway but as a flexible renewable-hydrocarbon platform for difficult-to-electrify sectors.

Keywords: HEFA; Sustainable Aviation Fuel; SAF; renewable diesel; HVO; used cooking oil; hydrodeoxygenation; hydro isomerisation; heavy-duty transport; off-road engines; generator sets.

1. Introduction

The transition toward low-carbon energy systems is changing the future of transport and power generation; however, not every sector can be electrified at the same pace. Aviation requires fuels with high energy density and strict physical and combustion characteristics. Heavy-duty vehicles and off-road equipment often operate for long periods under high loads, while remote industrial facilities and emergency systems continue to depend on diesel generator sets where uninterrupted operation is essential.

For these applications, renewable liquid fuels can provide an important complementary pathway to electrification.

Hydro-processed Esters and Fatty Acids (HEFA) has emerged as one of the most commercially advanced technologies for producing renewable hydrocarbon fuels from lipid-based feedstocks. Used cooking oil (UCO), animal fats, vegetable oils and other suitable lipid streams can be converted into hydrocarbons through catalytic processing in the presence of hydrogen.

The significance of HEFA lies in the chemistry of the final product. Unlike conventional biodiesel, where oxygen remains within fatty acid methyl ester molecules, HEFA processing removes oxygen from the feedstock. The final product is therefore composed predominantly of paraffinic hydrocarbons, allowing the process to generate aviation- and diesel-range fuel fractions.

The technology has received substantial attention because of its role in Sustainable Aviation Fuel production. However, its potential is broader. A HEFA facility can be configured to produce a combination of aviation-range hydrocarbons and renewable diesel depending on feedstock composition, reaction severity and downstream fractionation. This flexibility is particularly relevant at a time when aviation, heavy-duty transport, agriculture, construction, mining and stationary power are all seeking practical alternatives to fossil diesel and conventional jet fuel.

This article examines HEFA from this broader perspective, focusing on the chemistry that converts waste oils into hydrocarbons and the potential use of the resulting fuels across multiple engine-based applications.

2. From Waste Oils to Renewable Hydrocarbons

Most lipid feedstocks used in HEFA processing consist of triglycerides and free fatty acids. The fatty-acid chains commonly present in vegetable oils and waste cooking oils are mainly within the C₁₆–C₁₈ range. Palmitic acid contains 16 carbon atoms, whereas stearic, oleic and linoleic acids contain 18 carbon atoms.

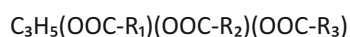
The first technical challenge is feedstock quality.

2.1 Feedstock Chemistry

2.1.1 Triglycerides

Most vegetable oils and animal fats consist predominantly of triglycerides. A triglyceride contains three fatty-acid chains esterified to glycerol.

A simplified triglyceride can be represented as:



where R₁, R₂ and R₃ represent hydrocarbon chains.

Important fatty acids in HEFA feedstocks include:

Fatty acid	Formula	Carbon number	Unsaturation
Palmitic acid	C ₁₆ H ₃₂ O ₂	C16	0
Stearic acid	C ₁₈ H ₃₆ O ₂	C18	0
Oleic acid	C ₁₈ H ₃₄ O ₂	C18	1
Linoleic acid	C ₁₈ H ₃₂ O ₂	C18	2
Linolenic acid	C ₁₈ H ₃₀ O ₂	C18	3

The carbon number and degree of unsaturation influence hydrogen consumption and the final hydrocarbon distribution.

2.1.2 Feedstock Pretreatment

Waste lipid feedstocks can contain water, suspended solids, phospholipids, phosphorus, alkali metals, calcium, magnesium, chlorides and other contaminants.

These components can cause:

- Catalyst poisoning;
- Catalyst deactivation;
- Reactor fouling;
- Corrosion;
- Increased pressure drop;
- Coke formation; and
- Reduced process efficiency.

Pretreatment therefore normally includes some combination of filtration, centrifugation, degumming, drying, adsorption and contaminant removal.



Figure 1. Feedstock pretreatment pathway for waste oils prior to HEFA hydroprocessing.

Waste oils may contain water, suspended solids, phosphorus compounds, metals, chlorides, soaps and oxidation products. If introduced directly into a hydro-processing reactor, these contaminants can reduce catalyst activity, increase fouling and shorten catalyst life. Pretreatment is therefore necessary before catalytic conversion.

Depending on feedstock quality, pretreatment may include filtration, dehydration and removal of phosphorus, metals and other catalyst-deactivating components.

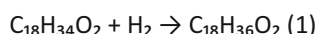
2.2 HEFA Conversion Chemistry

The HEFA process consists of several interconnected reactions. The principal chemistry can be divided into:

1. Hydrogenation;
2. Hydrodeoxygenation;
3. Decarboxylation;
4. Decarbonylation;
5. Hydro-isomerisation; and
6. Hydrocracking.

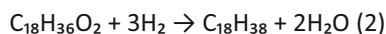
Once the lipid stream enters the hydro-processing section, its conversion is governed by two fundamental objectives: saturation of unsaturated bonds and removal of oxygen.

For example, oleic acid contains one carbon-carbon double bond. Hydrogenation converts it into saturated stearic acid:



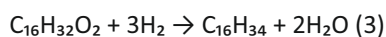
The degree of unsaturation of the feedstock is therefore important because each double bond requires hydrogen for saturation. After hydrogenation, oxygen removal becomes the central reaction sequence. Three principal pathways can contribute to this conversion.

The first is hydrodeoxygenation (HDO). In this pathway, oxygen is removed primarily as water. For stearic acid:

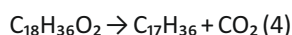


The important feature of this reaction is carbon retention. An 18-carbon fatty acid produces an 18-carbon hydrocarbon.

For palmitic acid:



The second route is decarboxylation, where the carboxyl carbon is removed as carbon dioxide:

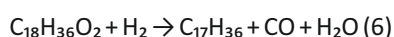


In this case, the C_{18} fatty acid becomes a C_{17} hydrocarbon.

Similarly:



The third route is decarbonylation, in which oxygen is removed through the formation of carbon monoxide and water:



Both decarboxylation and decarbonylation reduce the carbon number of the hydrocarbon product by one relative to the original fatty acid.

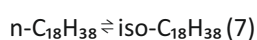
These parallel pathways explain an important feature of HEFA fuels. C_{16} – C_{18} lipid feedstocks do not produce a single hydrocarbon. Instead, the deoxygenation chemistry produces a distribution dominated by C_{15} – C_{18} hydrocarbons, depending on the reaction pathway and catalyst system.

The resulting hydrocarbons are largely straight-chain or normal paraffins. Although these molecules can provide excellent combustion quality, their low-temperature properties require further improvement.

3. Molecular Upgrading: From n-Paraffins to Fuel-Grade Hydrocarbons

The paraffins formed during deoxygenation are predominantly linear molecules. Long straight-chain hydrocarbons have a greater tendency to crystallise at low temperatures, which can limit their suitability for aviation and cold-weather diesel applications.

Hydro-isomerisation addresses this limitation by rearranging the carbon skeleton while retaining the same molecular formula:



The transformation from a normal paraffin to a branched paraffin is therefore structural rather than compositional. The molecular formula remains unchanged, but branching alters the physical behaviour of the fuel.

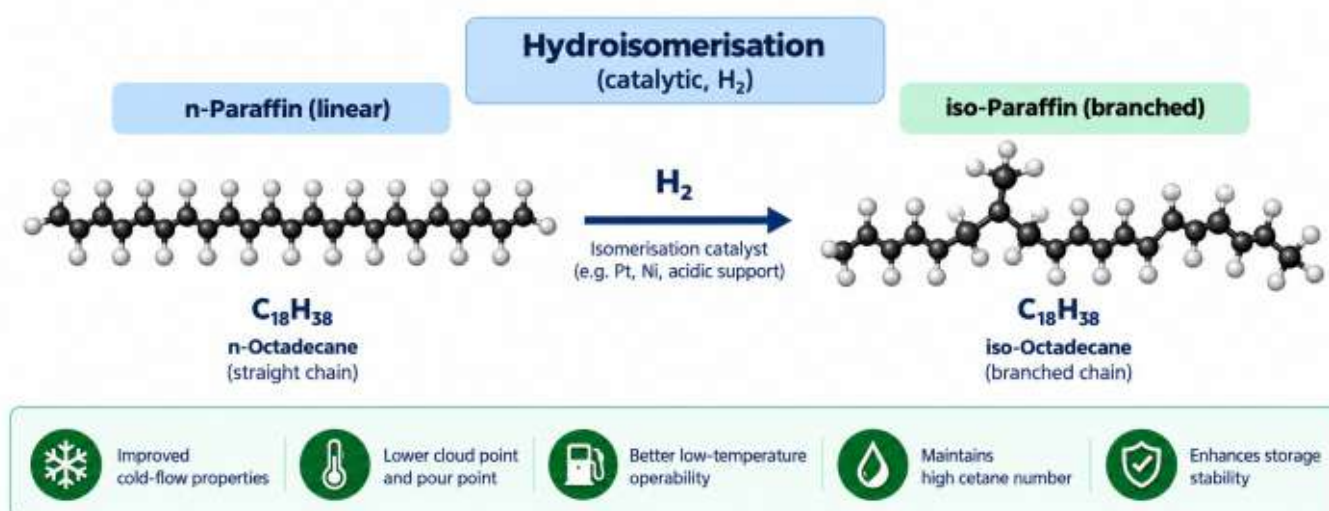
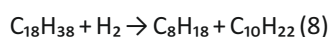


Figure 1. Schematic molecular transformation of n-paraffins into iso-paraffins during hydro-isomerisation.

Hydro-isomerisation is a critical step because it allows the cold-flow and low-temperature properties of HEFA-derived fuels to be adjusted without removing significant amounts of carbon.

Where a lighter product distribution is required, controlled hydrocracking may also be applied. A simplified reaction can be represented as:



Actual industrial hydrocracking produces a distribution of hydrocarbons rather than only two products, but the equation illustrates the underlying principle: long-chain hydrocarbons are cleaved into smaller molecules in the presence of hydrogen.

The overall HEFA conversion can therefore be understood as a sequence of molecular transformations:

C_{16} – C_{18} oxygenated lipids $\rightarrow$ C_{15} – C_{18} paraffins $\rightarrow$ branched paraffins $\rightarrow$ controlled aviation- and diesel-range hydrocarbons

This sequence provides the basis for HEFA's product flexibility.

The final hydrocarbon mixture is fractionated according to boiling range. The lighter middle-distillate fraction can be directed toward aviation-fuel production, while heavier middle-distillate hydrocarbons can be recovered as renewable diesel. Product allocation depends on the configuration and operating objectives of the facility.

4. Why HVO Is Different from Conventional Biodiesel

The distinction between renewable diesel/HVO and conventional FAME biodiesel is important when considering engine applications.

FAME biodiesel is produced primarily through transesterification, in which triglycerides react with an alcohol such as methanol: Triglyceride + Methanol → Fatty Acid Methyl Esters + Glycerol (9)

The resulting fuel molecules retain oxygen within their ester structure.

HEFA processing follows a fundamentally different route:

Lipid Feedstock + H₂ → Hydrocarbons + H₂O + CO₂ + CO (10)

The final renewable diesel is therefore predominantly hydrocarbon-based rather than ester-based.

This difference influences several fuel properties. HVO generally has very low oxygen and sulfur content and consists mainly of paraffinic hydrocarbons. The fuel can exhibit high cetane quality and favourable oxidation stability, while its cold-flow behaviour can be adjusted through hydro-isomerisation.

However, fuel quality must always be assessed against the applicable product specification and engine manufacturer's requirements. Renewable diesel should not simply be treated as chemically identical to petroleum diesel; its composition and physical properties differ, particularly in areas such as density and aromatic content.

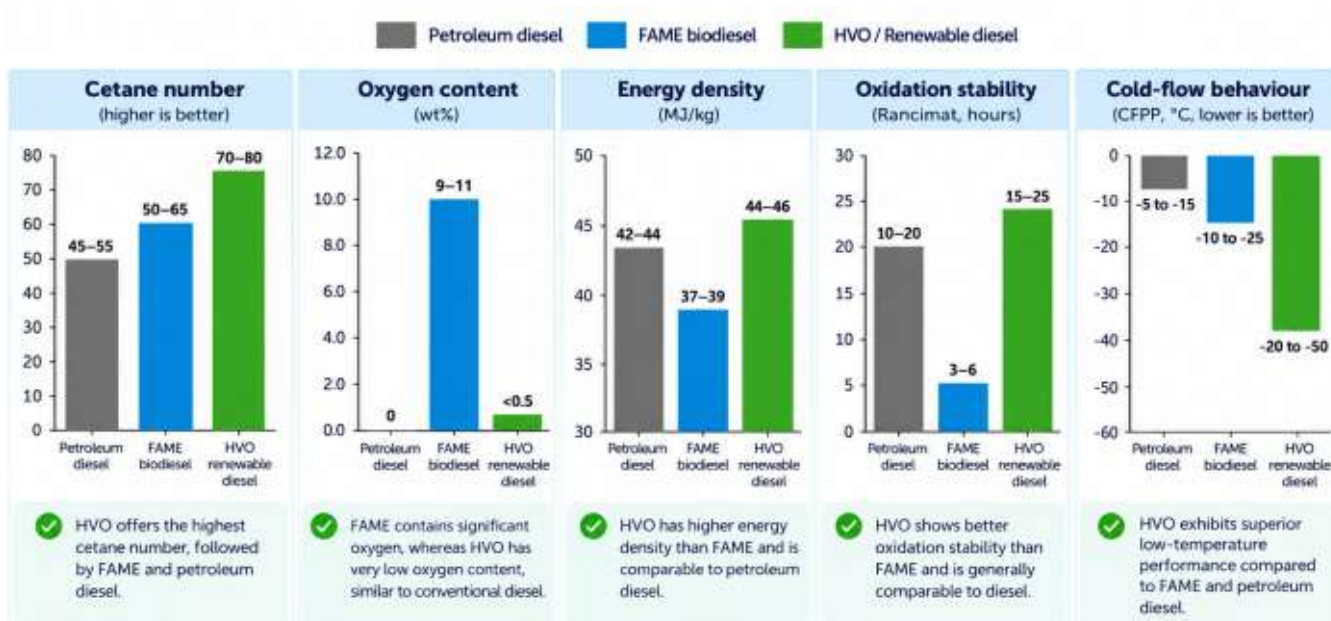


Figure 2. Technical comparison of petroleum diesel, FAME biodiesel and HVO using cetane number, oxygen content, energy density, oxidation stability and cold-flow behaviour.

The chemical similarity of HVO to conventional hydrocarbon fuels nevertheless creates an important opportunity: decarbonisation can potentially be achieved by changing the fuel supply without requiring the immediate replacement of all existing compression-ignition equipment.

This is particularly relevant for sectors where the equipment fleet has a long operational lifetime.

5. HEFA Beyond Aviation: Transport, Off-Road Engines and Generator Sets

The role of HEFA is often discussed primarily in the context of Sustainable Aviation Fuel. Aviation will remain an important market because of the limited number of alternatives available for long-distance flight.

HEFA-derived aviation-range hydrocarbons are highly paraffinic and can provide the required molecular characteristics for synthetic aviation blending components when produced and qualified according to the applicable fuel specifications.

Hydro-isomerisation is particularly important for aviation because fuel performance at low temperatures is a critical requirement. The ability to modify straight-chain paraffins into branched hydrocarbons is therefore directly linked to the suitability of the final product for aviation applications.

However, the same feedstock and hydro-processing platform can produce diesel-range hydrocarbons.

For on-road transportation, renewable diesel can offer a practical option for heavy-duty vehicles, logistics fleets, buses and commercial transport. These vehicles often operate continuously and require rapid refuelling, making complete fleet electrification more challenging in some applications.

For off-road engines, the potential is equally significant. Agricultural tractors, harvesters, excavators, loaders, construction machinery, mining equipment and forestry machines frequently operate under high load and in locations where large-scale charging infrastructure may be unavailable.

Replacing such equipment immediately can be economically difficult. Renewable diesel provides an alternative route in which the existing engine fleet may continue to operate with a lower-carbon fuel, subject to fuel specification and original equipment manufacturer approval.

Diesel generator sets represent another important application. Hospitals, data centres, telecommunications infrastructure, construction projects and remote industrial facilities depend on reliable backup or prime power. In many cases, replacing diesel generator systems requires substantial capital investment and may not be immediately practical.

The use of renewable diesel can therefore support a gradual reduction in fossil-fuel dependence while retaining existing generator infrastructure.

The relevance of HEFA-derived diesel for these applications is not that it eliminates all emissions at the point of use. Combustion still produces carbon dioxide. The potential environmental benefit is determined primarily through the complete lifecycle of the fuel, including feedstock origin and hydrogen production.

6. Hydrogen, Feedstock and Lifecycle Carbon Performance

Hydrogen is one of the defining inputs of the HEFA process.

It is required for saturation of unsaturated fatty acids, hydrodeoxygenation and, where applied, hydrocracking. Consequently, the environmental performance of HEFA cannot be assessed independently of the hydrogen supply.

6.1 Lifecycle Greenhouse-Gas Assessment

A simplified lifecycle framework can be expressed as:

$$GHG_{IC} = GHG_{feedstock} + GHG_{collection} + GHG_{H_2} + GHG_{process} + GHG_{transport} - GHG_{credits} \quad (11)$$

For waste-based HEFA, feedstock collection and processing may offer advantages compared with dedicated oil-crop systems. However, the magnitude of the lifecycle benefit depends on the treatment of waste feedstocks, transport distances, pretreatment requirements, hydrogen source and process energy.

Hydrogen can become one of the dominant contributors to lifecycle emissions if it is produced through carbon-intensive pathways. Conversely, the use of lower-carbon hydrogen can improve the overall carbon performance of the fuel.

This lifecycle perspective is particularly important because the same HEFA process can have different environmental outcomes depending on local energy systems and supply chains.

The availability of sustainable lipid feedstocks is another major constraint.

Used cooking oil and animal fats are attractive because they are associated with existing food and waste streams, but their total availability is limited. As demand for both SAF and renewable diesel increases, competition for these feedstocks is expected to intensify.

The future scale of HEFA will therefore depend not only on reactor technology but also on the development of reliable feedstock collection, quality control and traceability systems.

6.2 Feedstock Availability

The largest long-term challenge for HEFA expansion may be sustainable feedstock availability rather than basic conversion technology.

Potential feedstocks include:

- Used cooking oil;
- Animal fats;
- Waste industrial oils;
- Non-food lipid residues;
- Selected vegetable oils.

As SAF and renewable diesel demand increases, these feedstocks may experience competition between sectors.

A future HEFA industry therefore requires:

Feedstock mapping → Collection → Quality control → Traceability → Pretreatment → Conversion

For India, organised used-cooking-oil collection from restaurants, hotels, food-processing facilities and institutional kitchens could become an important component of a circular renewable-fuel supply chain.

6.3 Hydrogen and Low-Carbon Integration

Hydrogen is both a major reactant and an important determinant of HEFA lifecycle emissions.

A future HEFA facility can potentially integrate:

Renewable electricity → Electrolysis → Low-carbon H₂ → HEFA reactor

This integration can reduce dependence on conventional hydrogen sources.

The process can therefore be linked to:

- Solar energy
- Wind energy
- Renewable electricity
- Green hydrogen
- Low-carbon hydrogen

The overall sustainability of the plant should be evaluated using lifecycle analysis rather than assuming that hydrogen is inherently low carbon.

6.4 Catalyst Requirements

HEFA catalysts must simultaneously promote hydrogenation and oxygen-removal reactions while resisting contaminants from waste feedstocks.

Important catalyst characteristics include:

- High hydrogenation activity;
- High deoxygenation activity;
- Resistance to phosphorus and metals;
- Resistance to coke formation;
- Controlled hydrocracking;
- Appropriate isomerisation activity.

Catalyst deactivation can occur through:

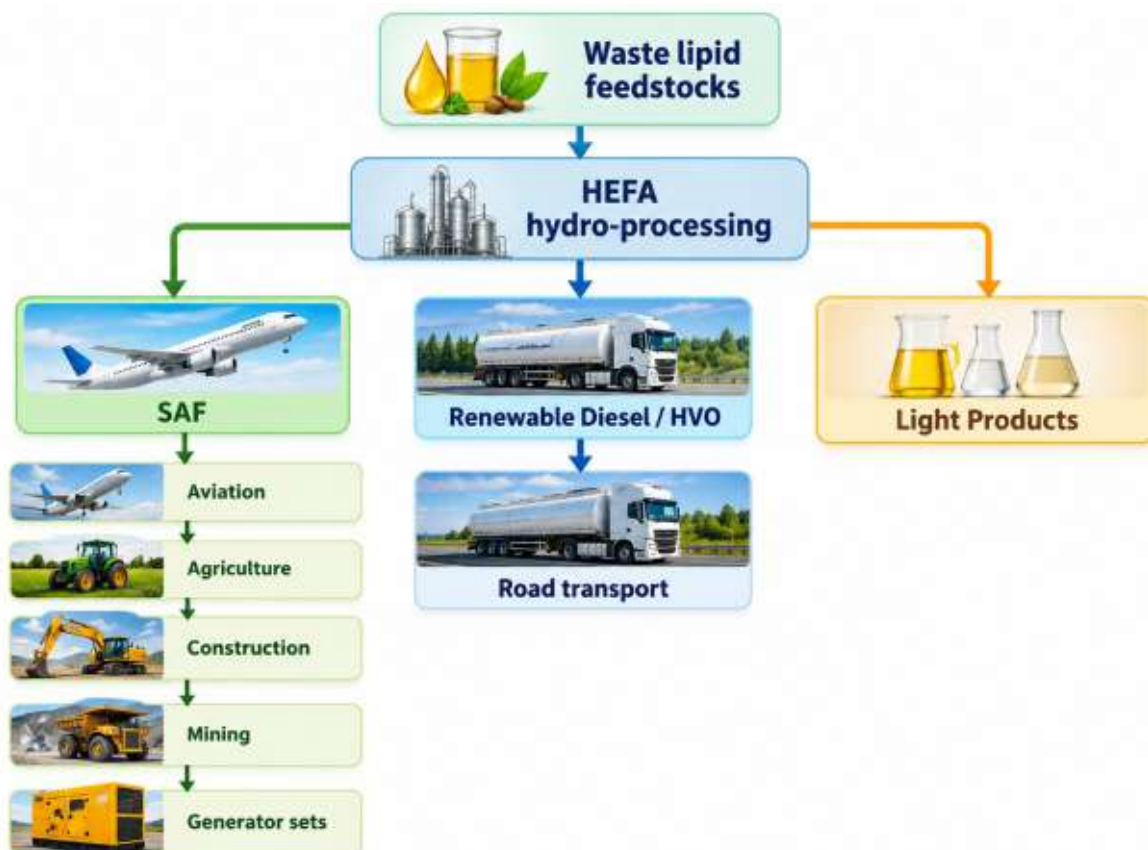
Contaminant deposition → Active-site blockage → Reduced conversion

and: Coke formation → Pore blockage → Reduced catalyst activity

Pretreatment therefore directly influences catalyst lifetime.

6.5 Multi-Sector HEFA Biorefinery Concept

The greatest strategic advantage of HEFA is product flexibility.



This configuration allows a renewable-hydrocarbon facility to serve multiple markets rather than relying exclusively on SAF demand.

7. Technical and Commercial Challenges

HEFA technology is commercially established, but large-scale expansion still faces several challenges.

The first is feedstock availability. High-quality waste oils are limited, and increased demand can raise feedstock costs.

The second is hydrogen consumption. Hydrogen is required throughout the conversion process, affecting both operating cost and lifecycle emissions.

The third is feedstock quality. Waste-derived oils are inherently variable and can contain contaminants that accelerate catalyst deactivation. Effective pretreatment is therefore essential.

The fourth is product optimisation. A process designed to maximise diesel-range hydrocarbons will not necessarily operate under the same conditions as one designed to maximise aviation-range products. The balance between hydro-isomerisation, hydrocracking and fractionation must be optimised according to market requirements.

Finally, engine and field validation remain important for expanding renewable diesel use in heavy-duty and stationary applications. Fuel properties, storage, seals, injection systems and original equipment manufacturer requirements must be considered before large-scale deployment.

These challenges do not diminish the importance of HEFA. Rather, they demonstrate that future success will depend on integrating feedstock management, hydrogen supply, catalytic conversion and fuel-market requirements.

8. Conclusions

HEFA technology provides a technically mature route for converting waste and renewable lipid feedstocks into high-quality hydrocarbon fuels. Its central chemistry involves hydrogenation followed by oxygen removal through hydrodeoxygenation, decarboxylation and decarbonylation. These pathways convert the C_{16} – C_{18} fatty acids commonly present in lipid feedstocks into predominantly C_{15} – C_{18} paraffinic hydrocarbons.

Hydro-isomerisation subsequently improves low-temperature fuel performance by converting straight-chain paraffins into branched structures, while controlled hydrocracking can adjust the carbon-number distribution of the final product.

The technology is widely recognised for Sustainable Aviation Fuel production, but its importance should not be restricted to aviation. The diesel-range product offers potential applications in heavy-duty road transport, agriculture, construction, mining, forestry and stationary generator systems.

This broader application potential is particularly important for sectors where complete electrification may require longer transition periods. HEFA-derived renewable diesel can provide a route for reducing reliance on fossil-derived liquid fuels while continuing to use suitable existing compression-ignition infrastructure.

The long-term sustainability of HEFA will depend on responsible feedstock sourcing, efficient pretreatment, improved catalyst performance and, critically, access to low-carbon hydrogen. Future HEFA facilities may therefore evolve from single-product fuel plants into flexible renewable-hydrocarbon platforms capable of supplying both aviation and diesel markets.

In this context, HEFA should be viewed not simply as a SAF technology, but as a broader conversion platform linking waste lipids, hydrogen and renewable hydrocarbons to some of the most difficult sectors to decarbonise.

Declaration of Competing Interest

The author declares that there are no known competing financial interests or personal relationships that could have influenced the work reported in this article.

Data Availability

No new experimental data were generated for this technical review. The discussion is based on published scientific literature, technical standards and publicly available information.

References

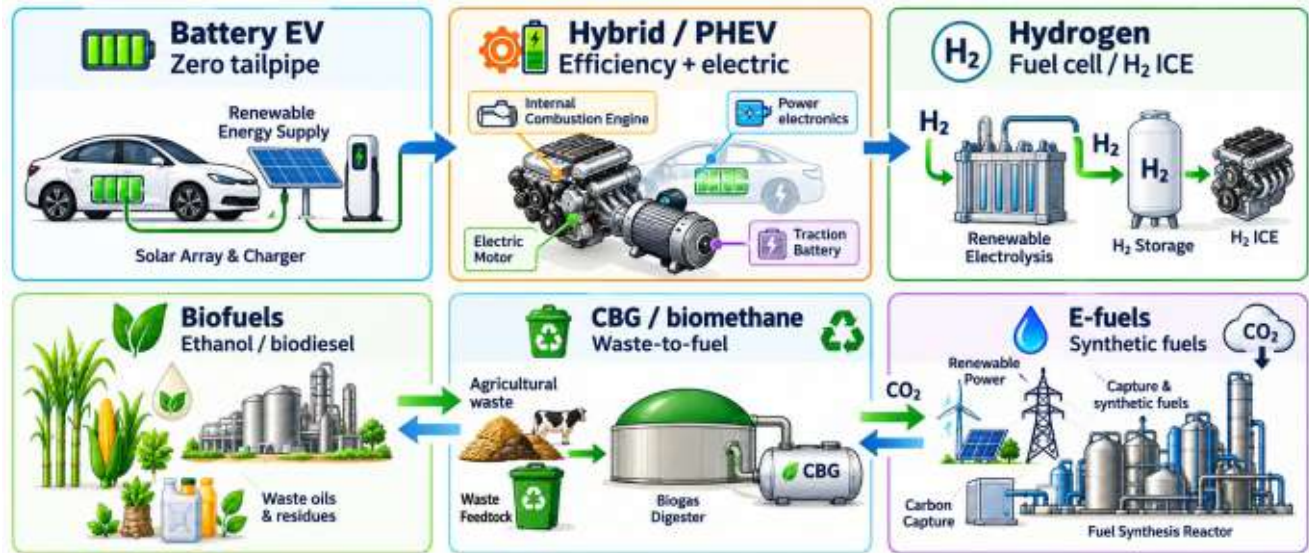
1. ASTM International. ASTM D7566: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.
2. ASTM International. ASTM D1655: Standard Specification for Aviation Turbine Fuels.
3. European Committee for Standardization. EN 15940: Automotive Fuels—Paraffinic Diesel Fuel from Synthesis or Hydrotreatment.
4. Huber, G.W., O'Connor, P. and Corma, A. Processing biomass in conventional oil refineries: Production of renewable diesel and related hydrocarbons.
5. Kalnes, T.N., Marker, T.L. and Shonnard, D.R. Green diesel: A second-generation biofuel.
6. Mäki-Arvela, P., Kubičková, M., Snåre, M., Eränen, K. and Murzin, D.Y. Catalytic deoxygenation of fatty acids and their derivatives.
7. Kubička, D. and Kaluža, L. Deoxygenation of vegetable oils and lipid feedstocks through catalytic hydroprocessing.
8. de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R. and Junginger, M. The feasibility of sustainable aviation fuels from different feedstocks and production pathways.
9. International Civil Aviation Organization. Sustainable Aviation Fuel technical and sustainability documentation.
10. International Energy Agency. Analysis of renewable fuels and sustainable aviation fuel pathways



Cleaner Vehicles Beyond EVs

Technology Pathways, Trade-offs, Data and An India-focused Roadmap

Sanjeev Chugh
Gen Lotus



A fit-for-purpose view of hybridisation, biofuels, CBG, hydrogen and e-fuels - with EVs retained as the benchmark, not the only answer.

Cleaner mobility is a portfolio, not a single powertrain

1. Executive Summary

The next phase of vehicle decarbonisation should move beyond a binary debate between internal-combustion engines and battery electric vehicles (BEVs).

EVs are scaling rapidly and will remain a central pillar of cleaner mobility.

Yet transport systems face multiple constraints at the same time: high oil-import dependence, uneven grid quality, charging availability, heavy-duty payload and utilisation requirements, mineral supply-chain concentration, and the need to reduce both greenhouse-gas emissions and local pollutants.

The evidence increasingly supports a portfolio strategy. Strong hybrids can cut fuel consumption without requiring external charging; plug-in hybrids can be useful where electric driving is frequent but long-distance flexibility is needed - although real-world usage must be verified. Ethanol and flex-fuel can decarbonise a large existing ICE fleet using India's established fuel distribution system.

CBG can convert organic waste into a drop-in gaseous fuel. Hydrogen fuel cells are technically attractive for some high-utilisation heavy vehicles, while renewable hydrogen - not fossil-derived hydrogen - is essential for a strong lifecycle climate case. E-fuels have a role where liquid fuels are hard to replace, but their energy-conversion losses make them less compelling for mass road transport.

ICCT, 2025 EU passenger-car LCA benchmark; values are directional.

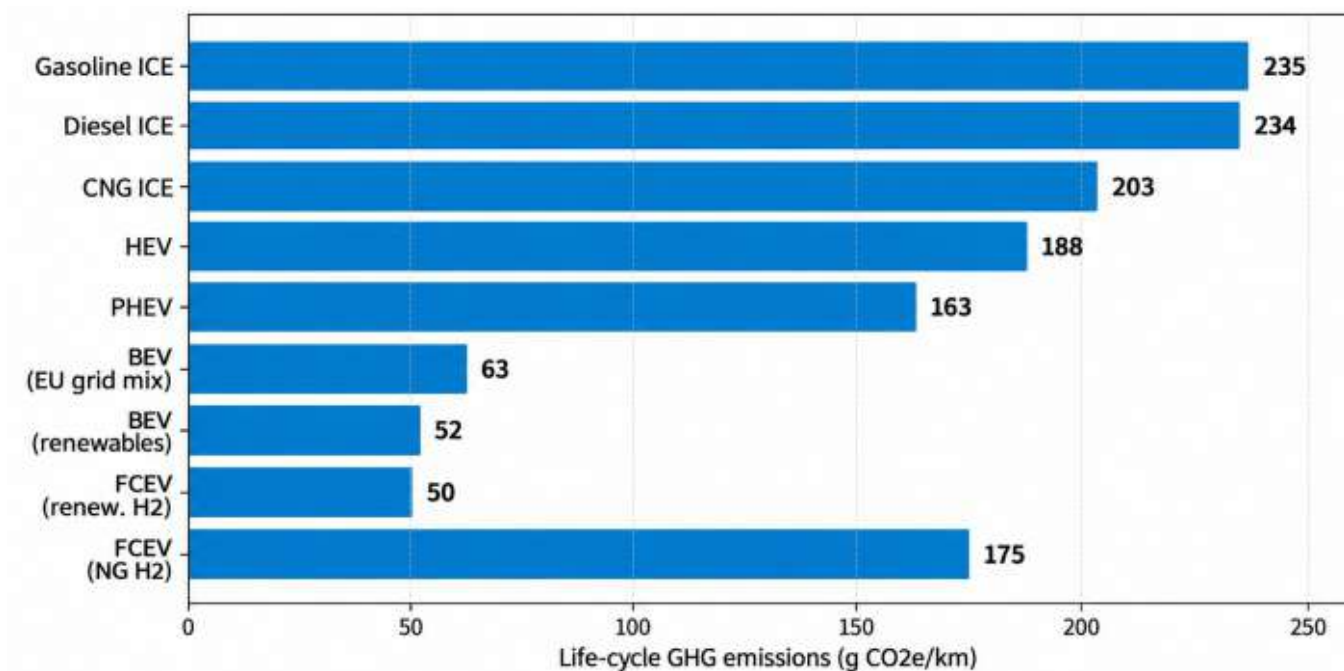


Figure 1. A lifecycle view shows why “cleaner” is not the same as “zero tailpipe”.

Indicator	Latest evidence	Why it matters
Global electric-car sales, 2025	>20 million; ~25% of new cars	EVs are now mainstream, not experimental.
Global road-transport emissions, 2024	>6 Gt CO ₂	The system is still emissions-intensive.
India ethanol blending, 2025-26	20% average	Biofuels are already a mass-market pathway.
India CBG obligation	1% FY25-26 -> 5% FY28-29	Waste-derived gas is moving from pilot to compliance.
India 2W sales, FY2025-26	21.7 million	2Ws are a critical scale opportunity for low-carbon fuels and EVs.

2. Why “Cleaner” Must Be Broader Than “Zero Tailpipe”

Tailpipe emissions are only one part of vehicle impact. A rigorous technology comparison should examine the full chain from energy or feedstock production through fuel processing, vehicle and battery manufacture, use, maintenance and end-of-life.

The appropriate question is therefore not “Which technology is cleanest in isolation?” but “Which technology delivers the lowest lifecycle impact for this duty cycle, using resources that India can supply reliably and affordably?”

Road transport remains a major climate problem. The IEA estimates road-sector emissions at just over 6 Gt CO₂ in 2024, up about 8% from 2015. More than 60% of road emissions come from passenger cars and vans, while trucks account for about 30% and 2/3-wheelers about 7%.

The challenge is particularly important for emerging economies, where road activity is still rising. India has an additional strategic dimension: oil security. PPAC reported crude-oil import dependence of about 88.2% on a POL-consumption basis in FY2024-25. Cleaner propulsion therefore has two simultaneous objectives - lower emissions and lower petroleum exposure.

IEA analysis also found that India's oil-demand growth slowed in 2025 while biofuel use in road transport rose sharply, illustrating how fuel substitution can complement electrification.

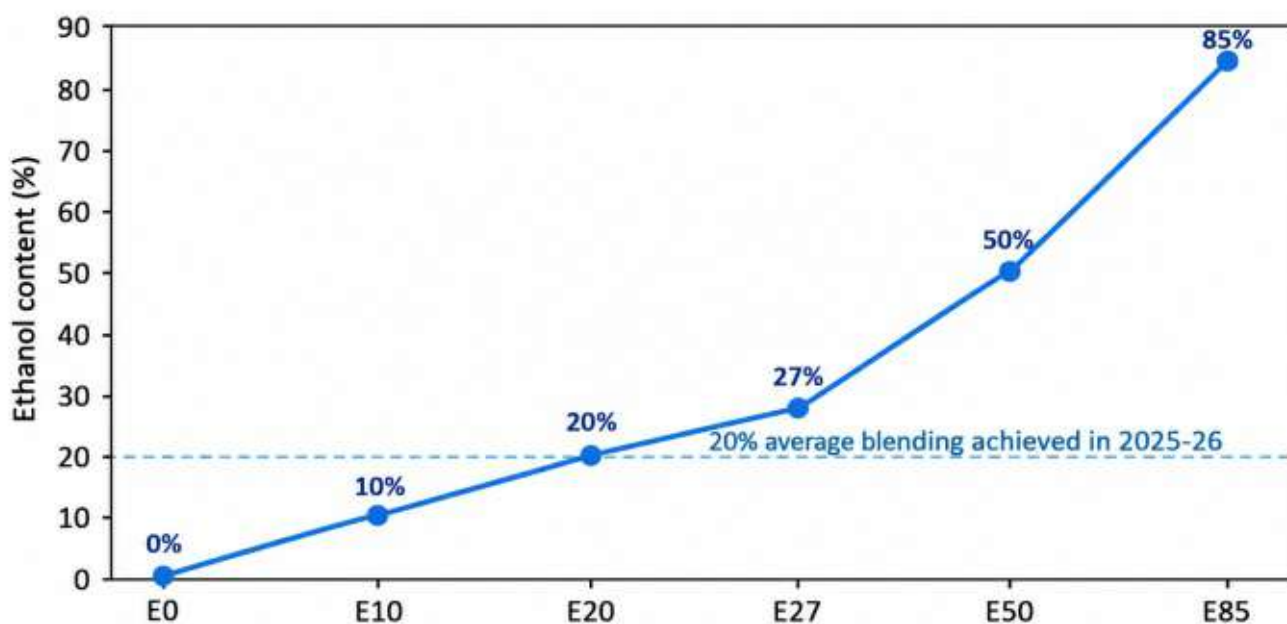


Figure 2. India's ethanol pathway illustrates how an existing fuel pool can be progressively decarbonised. PIB / Government of India: EBP programme data; 20% target achieved in ESY 2025-26.

- Climate: lifecycle CO₂e, not tailpipe CO₂ alone.
- Air quality: NO_x, PM, CO, HC, evaporative emissions and real-world driving behaviour.
- Energy security: imported oil, gas and critical minerals versus domestic renewable/feedstock potential.
- Infrastructure: charging, hydrogen stations, gas networks, fuel storage and distribution.
- Industrial readiness: technology cost, certification, service capability, component localisation and recyclability.

3. Technology Options at a Glance

Cleaner Mobility is a Portfolio, not a single Powertrain
 Selection depends on Infra, Fuel Availability, Local Air Quality, Resource Footprint & Cost



Figure 3. The cleaner-vehicle toolkit spans electric, hybrid, gaseous and renewable liquid-fuel pathways. Analytical synthesis; technology boundaries overlap in practice.

Pathway	Main strength	Main weakness	Best-fit applications
BEV	Highest drivetrain efficiency; zero tailpipe emissions	Charging, grid and battery supply-chain constraints	Cars, 2W/3W, urban fleets, many buses and trucks
HEV	High efficiency with no plug-in requirement	Still burns liquid fuel; modest lifecycle reduction vs BEV	Cars in mixed city/highway use
PHEV	Can cover short trips electrically with liquid-fuel backup	Real-world emissions can be far above test values if not charged	High-mileage cars with reliable charging access
Ethanol / flex fuel	Uses existing ICE architecture and fuel network	Feedstock, water/land-use and energy-content issues at high blends	2W, cars, fleet vehicles; particularly India
CNG / CBG	Fast refuelling; mature gas systems; CBG can be circular	Methane leakage and gas infrastructure; fossil CNG is not zero-carbon	Buses, fleets, selected commercial vehicles
FCEV / H2 ICE	Fast refuelling and potentially strong heavy-duty fit	Hydrogen cost, stations, storage; clean only with low-carbon H2	Heavy trucks, buses, captive corridors; some specialised uses
Biodiesel / HVO	Useful for legacy diesel fleets and heavy transport	Sustainable feedstock is finite; cost and certification	Heavy-duty, fleets, legacy diesel stock
E-fuels	Potential drop-in fuel and useful where liquid fuels are difficult to replace	Very high electricity requirement and cost	Aviation, maritime and niche high-value road uses

No technology should be evaluated solely on its tailpipe number. The strongest strategic portfolio is the one that maximises lifecycle emissions reduction per rupee of capital, per unit of renewable energy, and per unit of scarce infrastructure.

4. Hybrid Electric Vehicles: The High-Value Efficiency Bridge

Strong hybrids combine an internal-combustion engine with an electric motor and battery, recovering braking energy and allowing the engine to operate closer to efficient load conditions.

Unlike a BEV, a conventional HEV does not depend on external charging.

This is a major advantage where households lack charging access or where road users need rapid refuelling across large distances.

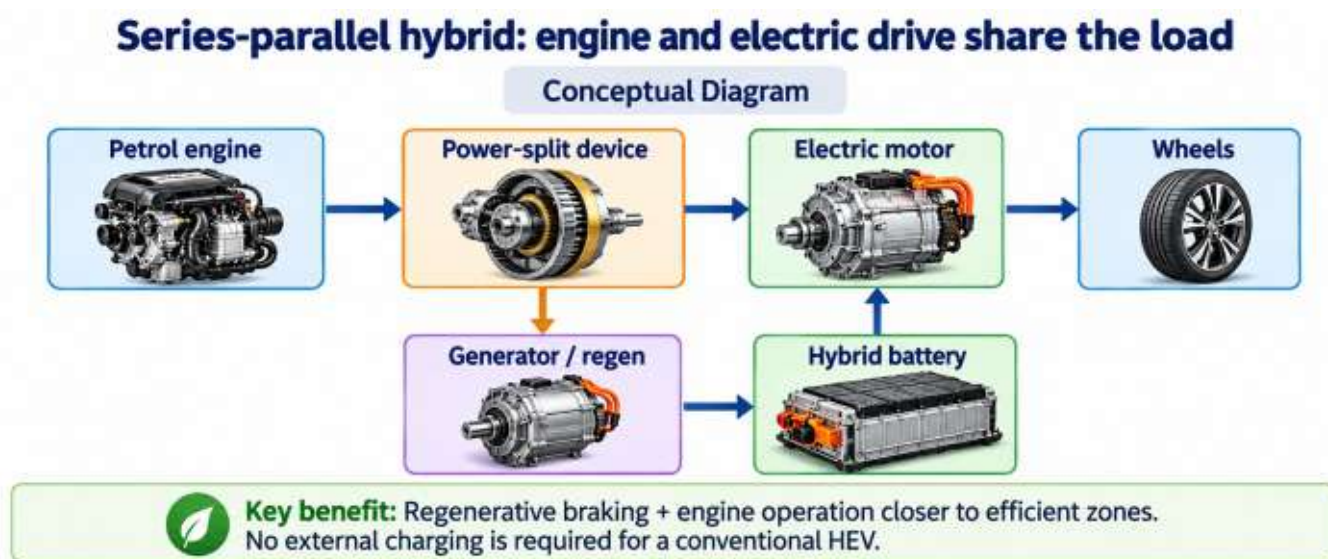


Figure 4. Simplified series-parallel hybrid architecture.

In India, the case for hybrids is strongest where annual mileage is high, urban traffic is intense, and charging access is uncertain. Current Indian products demonstrate that strong-hybrid SUVs can deliver substantially higher certified fuel economy than comparable pure-petrol configurations.

Pros

- No external charging infrastructure required for conventional HEVs.
- High efficiency in stop-go urban operation due to regenerative braking and electric assist.
- Smaller battery than a BEV; potentially lower mineral intensity per vehicle.
- Familiar refuelling behaviour and long range.

Cons

- Still consumes petrol or diesel and therefore remains exposed to fuel prices and combustion emissions.
- Higher system complexity than a conventional ICE vehicle.
- Lifecycle benefit is materially smaller than a BEV on a clean electricity system.
- Battery, inverter and power-electronics repair capability is required.

ICCT's 2025 EU passenger-car LCA estimated HEVs at about 188 g CO₂e/km versus 235 g for gasoline ICE cars - a roughly 20% lifecycle reduction. The result is useful as a directional benchmark; Indian fuel mixes, vehicle sizes and operating conditions will differ.

5. Plug-In Hybrids: Powerful, but Only When the Plug Is Used

PHEVs combine a larger battery and external charging with a combustion engine. In principle they can deliver much of the urban benefit of a BEV while preserving long-distance flexibility. In practice, the climate value depends heavily on actual charging frequency and electric kilometres. A PHEV that is rarely charged can behave like a heavier ICE vehicle with a small battery penalty.

This is no longer a theoretical concern. ICCT's June 2026 analysis of nearly one million European PHEVs found that real-world CO₂ emissions in 2023 were more than four times the official values, with the gap increasing from vehicles registered in 2021. The central reason was that official testing assumed a greater share of electric driving than occurred on the road.

Use case	PHEV value proposition	Key control
Daily commute < battery range	Very strong: many kilometres can be electric	Reliable home/work charging
Mixed city + highway	Strong if charging is frequent	Track real-world electric share
Long highway with little charging	Weak: engine becomes dominant	A strong hybrid or efficient ICE may be simpler
Corporate / fleet vehicle	Potentially strong	Fleet policy should mandate charging behaviour
High-performance / heavy SUV	Mixed	Avoid buying a PHEV purely for tax/test-cycle benefits

Pros

- Potential for large fuel savings in high-charge-use duty cycles.
- Long-distance flexibility without dependence on fast public charging.
- Useful transition technology where charging access is expanding but not yet universal.

Cons

- Two powertrains add cost, mass and complexity.
- Real-world emissions can be much higher than certification values.
- Battery may be carried even when it is not being used effectively.

Bottom line: PHEVs should be treated as a managed-use technology, not automatically as a clean vehicle. A simple KPI - the percentage of annual kilometres driven electrically - is more meaningful than brochure electric range alone.

6. Ethanol and Flex-Fuel Vehicles: An Indian Advantage

Ethanol is one of the few cleaner-fuel options that can immediately use a large existing vehicle and distribution base. India accelerated its EBP programme from about 1.5% blending in 2014 to 20% in 2025-26. Government data indicate the programme has reduced petroleum use and delivered large foreign-exchange savings, while current policy increasingly shifts attention from simply achieving E20 to using advanced feedstocks and flex-fuel architectures.

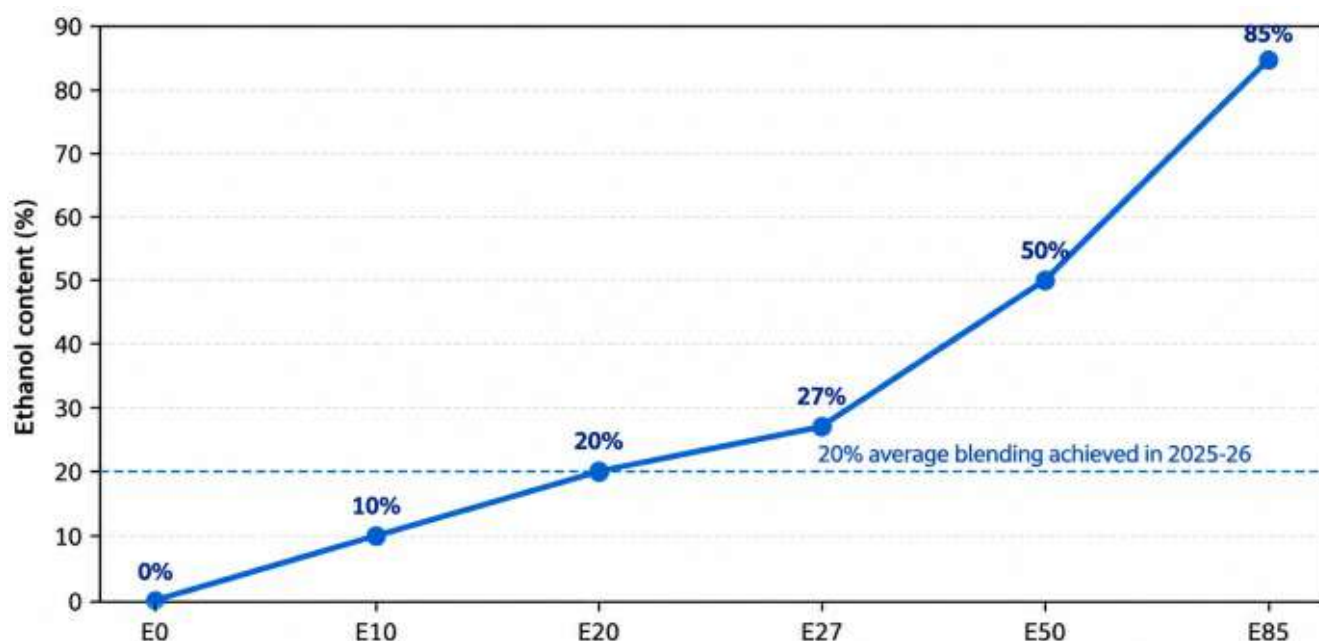


Figure 5. The blend ladder shows why higher ethanol content needs purpose-designed calibration, materials and fuel-system compatibility.

The two-wheeler opportunity is particularly significant.

SIAM reported 21.7 million domestic two-wheeler sales in FY2025-26.

Major 2W OEMs introduced E20-E85 flex-fuel versions of their ICE vehicles.

These examples show that the technology can be adapted to India's high-volume commuter segment while keeping the convenience of liquid-fuel refuelling.

Pros

- Drop-in compatibility at appropriate blend levels with existing liquid-fuel infrastructure.
- Domestic feedstocks can reduce oil imports and create agricultural/rural value.
- Particularly relevant to the very large installed base of 2Ws and ICE cars.
- Flex-fuel capability allows gradual evolution toward higher renewable content.

Cons

- Lower energy density means higher volumetric fuel consumption at high blends.
- Feedstock availability, water use, land-use effects and food-vs-fuel concerns require governance.
- High blends need compatible elastomers, corrosion protection, calibration and materials.
- Lifecycle benefit varies substantially by feedstock and production pathway.

The strategic opportunity is not “ethanol instead of EV”. It is ethanol plus efficiency plus electrification: reduce the fuel consumed per kilometre and progressively reduce the carbon intensity of the fuel itself.

Compressed biogas: a circular fuel pathway

India CBG blending obligation: 1% FY25-26 → 5% FY28-29



Main opportunity: use domestic waste and residues to displace fossil natural gas.

Main risks: feedstock logistics, project economics and methane leakage control.

Figure 6. CBG can turn organic residues into vehicle fuel and biofertiliser. Conceptual diagram; Indian CBG blending obligations sourced from PNGRB.

7. CNG and CBG: From Fossil Gas Bridge to Circular Gas Strategy

CNG is mature, fast to refuel and already supported by city-gas infrastructure in many Indian markets. Its long-term climate case is weaker than many people assume because methane leakage across the gas supply chain can materially erode the benefit. ICCT's 2025 EU passenger-car LCA estimated natural-gas cars at 203 g CO₂e/km, only about 13% lower than gasoline ICE cars in its benchmark.

CBG changes the strategic equation because the gas can be produced from waste and residues rather than fossil extraction.

PNGRB reports that India introduced a mandatory CBG blending obligation in the CNG/PNG segment at 1% for FY2025-26, rising to 5% by FY2028-29.

IEA's 2026 India Bioenergy Market Report estimates that liquid and gaseous biofuel demand could rise from 293 PJ in 2025 to 429 PJ in 2030 under its main case, with ethanol and CBG contributing much of the growth.

Pros

- Fast refuelling and established vehicle technology.
- CBG can monetise municipal, agricultural and food waste.
- Potentially strong fit for captive buses, commercial fleets and high-utilisation vehicles.
- Supports a circular-economy model when methane capture is effective.

Cons

- Fossil CNG remains a fossil fuel, not a zero-carbon solution.
- Methane leakage must be tightly controlled from production through distribution.
- CBG economics depend on collection radius, plant utilisation, tipping/feedstock contracts and offtake.
- Large-scale feedstock aggregation is operationally demanding.

Best strategy: use CNG where it provides an immediate practical benefit, but design future gas infrastructure to be progressively biomethane-ready, while treating methane management as a core emissions KPI.

Fuel-cell vehicle: hydrogen is converted back to electricity onboard

Tailpipe output is mainly water; lifecycle carbon depends on how hydrogen is produced.

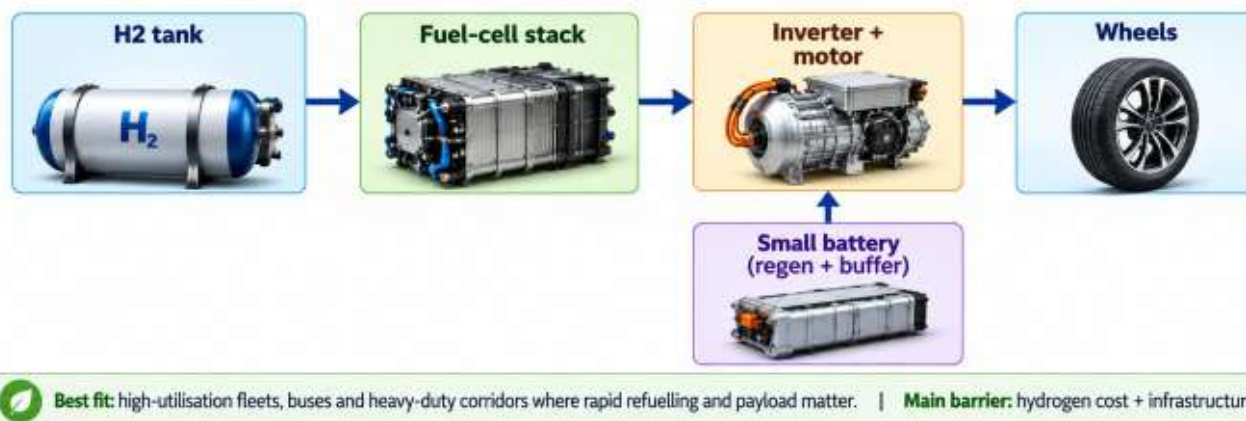


Figure 7. Simplified fuel-cell electric vehicle architecture.

U.S. Department of Energy AFDC architecture, redrawn conceptually for this report.

8. Hydrogen: Fuel Cells and Hydrogen ICE

Hydrogen is an energy carrier, not an energy source. A fuel-cell electric vehicle converts hydrogen into electricity onboard, driving an electric motor; an auxiliary battery captures regenerative braking and buffers power.

Hydrogen internal-combustion engines retain the familiar piston-engine concept but use hydrogen as the fuel, with different combustion and NOx-control requirements.

India has established a strategic platform through the National Green Hydrogen Mission. The mission targets at least 5 million tonnes per year of green-hydrogen production by 2030, associated renewable capacity of about 125 GW, over ₹8 lakh crore of investment, and nearly 50 million tonnes of annual greenhouse-gas abatement. The transport opportunity, however, is still at an early stage relative to industrial hydrogen demand.

IEA's 2026 Global Hydrogen Review reports that the global FCEV stock grew about 20% in 2025 to almost 130,000 vehicles. Heavy trucks remain the principal fast-growing road application, and China dominates commercial fuel-cell vehicle stock.

IEA also notes that fuel-cell trucks currently carry higher total costs than battery-electric or diesel alternatives in many markets.

Pros

- Fast refuelling and high energy density by mass.
- Potentially valuable for high-utilisation heavy-duty fleets where payload and refuelling time matter.
- Zero tailpipe CO₂ for FCEV; water is the main exhaust product.

Cons

- Green hydrogen is still expensive and infrastructure is immature.
- Hydrogen made from natural gas can have a materially weaker lifecycle result.
- Compression, storage, transport and station economics add cost and complexity.
- Safety systems, standards and maintenance capability must scale with the market.

Critical distinction: hydrogen is only as clean as its production route.

ICCT's 2025 EU LCA estimated 50 g CO₂e/km for an FCEV using renewable hydrogen versus 175 g/km when the hydrogen was produced from natural gas.



Figure 8. Advancing biofuels can widen the feedstock base and use existing vehicle/fuel assets. Conceptual diagram informed by IEA advanced-biofuel research.

9. Biodiesel, HVO and Advanced Biofuels

Not every transport segment can be replaced rapidly.

Legacy diesel trucks, buses and off-road equipment represent a huge installed asset base.

Biodiesel, renewable diesel (HVO) and other advanced biofuels can reduce the carbon intensity of these assets without immediately replacing vehicles. Their strategic value rises where vehicle downtime is expensive, liquid-fuel energy density matters, and fleet operators need a low-capex pathway.

The limiting factor is sustainable feedstock. IEA notes that biodiesel and HVO from fats, waste oils and grease are commercial today, but their supply is constrained. Cellulosic ethanol and biomass-to-liquid pathways could expand the resource base by using agricultural and forestry residues, municipal waste and other non-food feedstocks. India therefore has an opportunity to build a residue-based biofuel ecosystem rather than relying only on crop-derived fuels.

Pros

- Compatible with parts of the existing vehicle and fuel ecosystem, depending on specification and blend.
- Potential to decarbonise legacy fleets without immediate vehicle replacement.
- Waste/residue feedstocks can provide higher climate value than some conventional crop pathways.
- Useful complement to electrification for long-haul and specialised vehicles.

Cons

- Waste oils and fats are limited resources and face competing uses.
- Sustainability depends on feedstock traceability and land-use controls.
- Supply chains, standards and price premiums can limit scale.
- Not all “biofuel” pathways have the same lifecycle performance.

Strategic principle: count tonnes of sustainable feedstock, not only tonnes of announced production capacity. The best biofuel policy is one that rewards verified lifecycle carbon reduction rather than simply higher blending percentages.

10. E-Fuels: Valuable Niche, Weak Mass-Market Road-Fuel Economics

E-Fuels: Renewable Electricity - Hydrogen - Synthetic Fuel
High Conversion losses make a fuel less efficient than direct electrification

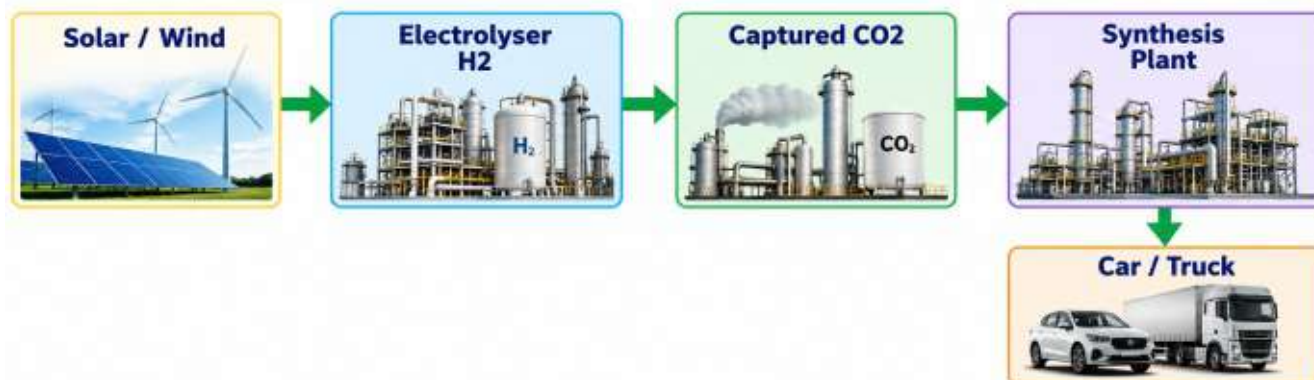


Figure 9. E-fuels combine renewable hydrogen with captured CO₂ to make synthetic liquid fuels.
Conceptual diagram; pathway described by IEA renewable-fuels analysis.

E-fuels are synthetic hydrocarbons made using hydrogen produced from electricity and a carbon source, typically captured CO₂. Their attraction is compatibility with liquid-fuel logistics and, in some pathways, existing combustion engines. Their weakness is the long energy chain: renewable electricity becomes hydrogen, hydrogen becomes synthetic fuel, and the fuel is finally burned in an engine. Each conversion step adds losses.

IEA's 2025 Renewables analysis revised down its e-fuel forecast because of weak investment momentum, while noting that renewable hydrogen and e-fuels remain relevant to transport.

The technology is most compelling where batteries are impractical and fuel molecules are difficult to replace - especially aviation and, in some cases, maritime uses.

For ordinary passenger cars, direct electrification generally delivers more kilometres of mobility per unit of renewable electricity.

Pros

- Potential drop-in use with existing liquid-fuel logistics.
- Can help preserve liquid-fuel characteristics where they are operationally important.
- Potentially low lifecycle CO₂ when renewable energy and sustainable carbon capture are used.
- Strategically relevant for aviation, shipping and specialist applications.

Cons

- Very high renewable-electricity requirement per kilometre versus direct EV use.
- Production cost remains high and project scale is limited.
- Sustainable CO₂ sourcing becomes a system constraint.
- Poor fit for mass-market road transport where direct electrification is practical.

Conclusion on e-fuels: Keep them in the technology toolbox, but reserve scarce renewable electricity and synthetic fuel capacity for segments where direct electrification has the weakest feasibility.

11. Comparative Lifecycle Evidence and Decision Matrix

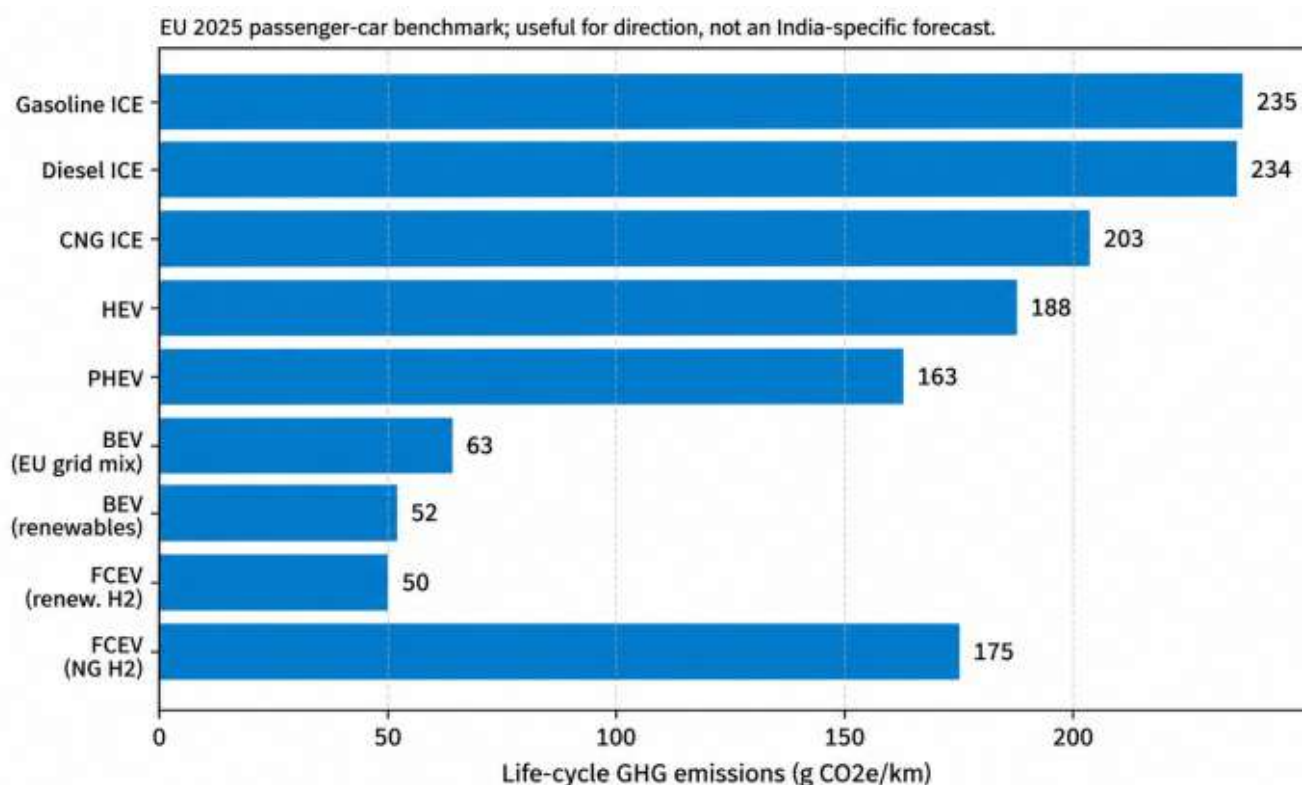


Figure 10. Lifecycle greenhouse-gas benchmark across major passenger-car powertrains.
ICCT, July 2025; EU passenger cars, 2025 technology/fuel assumptions.

The ICCT benchmark is particularly useful because it exposes two common analytical errors. First, production emissions should not be treated as the whole lifecycle. Second, “alternative fuel” is not synonymous with “low carbon”: the upstream energy source matters. The same fuel-cell vehicle can have a radically different climate outcome depending on hydrogen production.

Dimension	BEV	HEV	PHEV	Ethanol / CBG	FCEV / H ₂	E-fuel ICE
Tailpipe CO ₂	Zero	Low-medium	Low in EV mode	Lower fossil CO ₂ share; still combustion	Zero for FCEV	Combustion at tailpipe
Upstream dependence	Electricity + minerals	Liquid fuel + small battery	Electricity + liquid fuel	Feedstock + processing	Hydrogen + electricity	Large renewable electricity + CO ₂
Infrastructure burden	Charging/grid	Low	Medium	Low-medium	High	Low-medium
Energy efficiency	Very high	High	High when charged	Medium	Medium-high	Low
Best near-term fit	2W/3W, cars, fleets	Cars	Cars with charging	2W, ICE fleet, buses	Heavy duty/captive	Aviation / niche
Key risk	Grid/minerals/end-of-life	Fossil fuel use	Under-charging	Feedstock sustainability	H ₂ economics	Renewable energy intensity

The matrix should be read as a decision aid rather than a universal ranking.

A technology can move from “secondary” to “primary” when local electricity is carbon-intensive, fuel supply is unusually low-carbon, duty cycles are demanding, or infrastructure is already available.

12. India 2026-2035: A Fit-for-Purpose Cleaner Vehicle Strategy

Illustrative India 2026-2035 technology fit by use case

	Urban 2W/3W	Private cars	City buses	Long-haul trucks	Legacy fleet / fuel pool
					
Primary	BEV	HEV/PHEV	FCEV / BEV	BEV / FCEV	E20-E85 / CBG
Secondary	E20-E85	BEV	CBG / biogas	CBG / biofuels	HEV / PHEV
Watch / niche	H2 ICE	E-fuels	H2	E-fuels	E-fuels

The table is strategic guidance, not a policy mandate. Duty cycle, TCO, local fuel quality and infrastructure can change the ranking.

Figure 11. Illustrative technology fit by vehicle segment and use case.
Strategic synthesis; not a policy mandate or OEM product plan.

India should avoid a single-technology national mobility strategy. The country has an unusually large two-wheeler fleet, rapid urbanisation, rising freight demand, expanding renewables, a developing charging ecosystem, strong biofuel policy momentum and a strategic green-hydrogen programme. These characteristics favour technology segmentation.

Two-wheelers and three-wheelers are an especially important case. IEA reports that global electric 2/3W sales reached about 11 million in 2025, around 15% of the market, with China, India, Viet Nam and Türkiye accounting for about 95% of global electric 2/3W sales. India therefore has both a large EV opportunity and a large biofuel opportunity. The right policy is likely to encourage both - BEVs for duty cycles where charging is convenient, and high-efficiency flex-fuel / hybridised ICE pathways where liquid fuel remains the practical choice.

For passenger cars, a portfolio of BEV + strong hybrid + selected PHEV can manage different use cases. Strong hybrids are particularly valuable for customers who drive heavily in congested cities but do not have dependable charging. PHEVs should be targeted toward users with predictable charging and high annual kilometres, with real-world electric share monitored. For heavy transport, the technology debate should stay open between battery-electric, hydrogen fuel cell, CBG and advanced biofuels because route length, payload and refuelling infrastructure vary enormously.

Policy and industry KPIs that matter more than sales headlines

- Lifecycle CO_{2e} per vehicle-kilometre, including upstream energy/fuel.
- Real-world fuel/electricity consumption rather than certification values alone.
- Energy efficiency: km per kWh-equivalent or MJ per tonne-km.
- Infrastructure utilisation: charger/hydrogen/gas station throughput.
- Sustainable feedstock tonnes converted to verified low-carbon fuel.
- Battery and component recycling/recovery rates and domestic supply-chain resilience.

13. Conclusion: The Best Cleaner Vehicle Is the One That Fits the Job

The central lesson is not that EVs are overrated. EVs are one of the most important efficiency technologies in road transport, and their rapid growth is justified by high drivetrain efficiency and the ability to progressively decarbonise electricity. The lesson is that road transport is heterogeneous. A city commuter, a family SUV, a diesel tractor-trailer, a municipal bus and an emergency vehicle do not have the same energy, payload, refuelling or infrastructure requirements.

A resilient cleaner-vehicle strategy therefore uses a hierarchy. First, improve efficiency regardless of powertrain. Second, electrify where the duty cycle and electricity system make direct electrification efficient and economical. Third, use renewable liquid and gaseous fuels to reduce the carbon intensity of the installed fleet and hard-to-electrify applications. Fourth, build hydrogen systems where high utilisation and rapid refuelling justify the infrastructure. Fifth, reserve e-fuels for segments where liquid energy carriers remain difficult to replace.

Technology	Strategic verdict for India
BEV	Core pathway; expand especially in 2W/3W, urban fleets and suitable passenger cars.
Strong HEV	High-value bridge for cars; reduces fuel without charger dependence.
PHEV	Useful where charging is reliable; manage with real-world electric-distance KPIs.
Ethanol / Flex Fuel	Major India-specific lever for the huge ICE fleet, especially 2Ws and cars.
CNG -> CBG	Use existing gas networks, but shift the long-term focus toward biomethane and methane control.
Hydrogen FCEV / H2 ICE	Keep targeted pilots and corridors, primarily for high-utilisation heavy duty.
Biodiesel / HVO / advanced biofuels	Important for legacy diesel and difficult liquid-fuel applications; prioritise sustainable feedstocks.
E-fuels	Strategic niche; focus on aviation, shipping and specialised uses rather than mass road vehicles.

The strategic objective should be “lowest lifecycle emissions at lowest system cost and resource burden” rather than “maximum EV share” or “maximum ethanol share” in isolation. For India, the winning model is likely to be a blended transition: electrification for efficiency, hybridisation for practicality, biofuels for domestic fuel substitution, CBG for circularity, hydrogen for selected heavy-duty corridors and e-fuels for hard-to-electrify applications.

The ultimate measure of success is therefore not the number of technologies deployed. It is the tonnes of CO₂e, litres of imported oil, tonnes of local pollutants and units of scarce resources avoided per rupee invested - while maintaining mobility affordability, reliability and industrial competitiveness.

Sources and Visual Credits

1. IEA (2026), Global EV Outlook 2026 - Executive Summary; Trends in Other EV Modes; Electric Vehicle Batteries; Charging.
2. IEA (2025), Breakthrough Agenda Report 2025 - Road Transport.
3. IEA (2025), Renewables 2025 - Renewable Transport and Biogases.
4. IEA (2026), India Bioenergy Market Report - Outlook for Liquid and Gaseous Biofuels to 2030.
5. IEA (2026), Global Hydrogen Review 2026 - Demand.
6. ICCT (2025), Life-cycle greenhouse gas emissions from passenger cars in the European Union: A 2025 update and key factors to consider.
7. ICCT (2026), On the way to real-world CO2 values? Evidence from 2021-2023 on-board fuel consumption monitoring data.
8. Government of India / Press Information Bureau (2025-2026), Ethanol Blending in India; EBP programme milestones and E20 achievement.
9. Ministry of New and Renewable Energy / National Green Hydrogen Mission (2023 onward), India Green Hydrogen Mission targets and programme materials.
10. PPAC (2025), Snapshot of India's Oil & Gas Data - March 2025.
11. PNGRB (2025), CBG-CGD pipeline connectivity and CBG blending obligation materials.
12. SIAM (2026), Annual Report 2025-26 and FY2025-26 industry performance releases.
13. Maruti Suzuki India (2024-2026), Strong Hybrid technology and Victoris product information.
14. U.S. Department of Energy, Alternative Fuels Data Center - Fuel Cell Electric Vehicles and hybrid vehicle technical references.

Source URLs used in research

<https://www.iea.org/reports/global-ev-outlook-2026>
<https://www.iea.org/reports/breakthrough-agenda-report-2025/road-transport>
<https://www.iea.org/reports/renewables-2025/renewable-transport>
<https://www.iea.org/reports/india-bioenergy-market-report>
<https://www.iea.org/reports/global-hydrogen-review-2026/demand>
<https://theicct.org/publication/electric-cars-life-cycle-analysis-emissions-europe-jul25/>
<https://theicct.org/publication/real-world-co2-emission-values-vehicles-europe-jun26/>
<https://www.pib.gov.in/PressReleasePage.aspx?PRID=2281287>
<https://www.pib.gov.in/PressReleaseSelfframePage.aspx?PRID=1888547>
<https://ppac.gov.in/>
<https://pngrb.gov.in/>
<https://www.siam.in/knowledge/annual-reports>
<https://www.marutisuzuki.com/arena/victoris>
<https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work>

Visual note

Unless otherwise stated, figures in this report are original analytical diagrams/charts prepared from the cited data. They are intended for explanatory use and do not represent OEM engineering drawings or policy positions.

How Much Can ICE Pull Through BS-VII and Beyond?

India and Global Perspectives on the Continuing Evolution of Internal-Combustion and Hybrid Powertrains

Neelkanth Marathe

Emission Controls Manufacturers Association (ECMA)

The global automotive industry is undergoing one of the most significant powertrain transitions in its history. Battery-electric vehicles are expanding rapidly, while hybridisation, alternative fuels and increasingly efficient internal-combustion engines continue to evolve. Against this background, an important engineering and strategic question emerges: how much further can the internal-combustion engine (ICE) contribute to clean mobility through BS-VII and beyond?

The question is not necessarily about whether ICE will eventually disappear. Rather, it is about how the role of the internal-combustion engine can evolve as emission regulations become progressively more demanding and as vehicle markets move towards lower-carbon and eventually zero-emission mobility. This question is particularly relevant to India. The country's mobility ecosystem is exceptionally diverse, encompassing two-wheelers, three-wheelers, passenger vehicles, commercial vehicles, buses and heavy-duty applications. Differences in vehicle utilisation, infrastructure, customer economics, operating conditions, energy availability and total cost of ownership mean that the transition to future powertrains is unlikely to occur uniformly across all segments. Global reports show that electrification is advancing rapidly in some parts of the world. The International Energy Agency reports that global electric-car sales exceeded 20 million in 2025, representing approximately one-quarter of new-car sales. However, the global vehicle market continues to contain a large installed base of combustion vehicles, while hybrid vehicle availability is also increasing.

The engineering challenge for ICEs is changing from simply improving performance and efficiency to delivering very low emissions, high efficiency, durability and compatibility with evolving fuels. Hybridisation provides another pathway by allowing the engine to operate differently within a more integrated powertrain. Potential role of ICE in conventional and hybrid modes, the relevance of BS-VII-type emission requirements, India's specific circumstances, global trends, alternative fuels, heavy-duty applications, lifecycle considerations and the possible evolution of ICE beyond BS-VII, etc. are required to be examined.

The future of ICE, therefore, should not be considered only in terms of the survival of a particular engine architecture. Its continuing relevance will depend on whether it can deliver clean, efficient, durable and economically viable mobility while integrating effectively with hybridisation, renewable and low-carbon fuels, digital controls and increasingly stringent environmental requirements.

Few technologies have had a greater influence on modern mobility than the internal-combustion engine. For more than a century, ICE has powered passenger cars, motorcycles, three-wheelers, trucks, buses, agricultural equipment, construction machinery and many other applications. It has benefited from enormous investments in engineering, manufacturing, supply chains, infrastructure and service networks.

However, the automotive industry is now entering a fundamentally different phase.

Air-quality requirements are becoming more stringent. Climate objectives are becoming increasingly important. Governments and markets are encouraging electrification. Battery technology is improving. Charging infrastructure is expanding. At the same time, customers continue to demand affordability, range, reliability, rapid refuelling and operational flexibility. The result is not a simple transition from one technology to another. Instead, the industry is moving towards a portfolio of powertrain solutions.

Battery-electric vehicles are one important part of this transition. Hybrid vehicles provide another pathway. Internal-combustion engines continue to evolve. Alternative fuels introduce additional possibilities.

The important question for engineering is therefore if ICE can continue to make a meaningful contribution to clean mobility while meeting the progressively higher environmental expectations represented by BS-VII and future regulations ICE is still considered as today's conventional powertrain while its long-term role is facing increasing pressure from electrification and tightening environmental requirements.

The Indian automotive market differs significantly from many mature automotive markets. India has a large two-wheeler population, substantial three-wheeler usage, rapidly growing passenger-vehicle ownership, extensive commercial-vehicle activity, high utilisation of buses and trucks, diverse climatic conditions, different customer economics; and a large existing/old generation vehicle fleet.

In spite of supporting policies, subsidies, field supports and schemes; EV penetration in India is going slow and differs substantially between various categories. This diversity makes a single powertrain pathway difficult to apply uniformly. For some applications, electrification may provide compelling operational advantages. For others, especially where long range, high utilisation, payload, rapid refuelling or infrastructure limitations are important, combustion or hybrid solutions may continue to have a role. The engineering objective should, therefore, be to determine where and how each powertrain can deliver the required environmental and operational outcome.

BS-VII as an Engineering Inflection Point

BS-VII is best viewed as part of the continuing evolution towards lower real-world emissions rather than merely tightening of emission limits, referring to the directions given by different international regulations. The European Union's Euro 7 Regulation, adopted in 2024, applies emission and battery-durability requirements to a broad range of vehicles and includes requirements covering internal-combustion and hybrid vehicles. It also incorporates real-driving considerations and additional pollutants and durability provisions.

In the present context, the significant for ICE lies in the fact if ICE vehicles can remain clean under a broad range of operating conditions and throughout its useful life, beyond meeting only conventional laboratory-based emission limits. This is going to fundamentally change the engineering priorities. Future ICE development, therefore, will increasingly need to combine:

- engine efficiency
- emission control
- thermal management
- controls
- diagnostics
- durability
- fuel compatibility
- real-world validation
- lifecycle considerations

The conventional ICE vehicle will continue to face increasing environmental requirements. The challenge is, therefore, to improve its overall environmental performance without relying on any single technology. At a broad level, the engineering pathway consists of several complementary areas:

- reducing energy required to move the vehicle
- improving conversion efficiency
- controlling combustion-related emissions
- managing exhaust emissions
- reducing losses
- improving thermal behaviour
- increasing durability
- optimising controls
- adapting to evolving fuels

Substantial emission reductions have been already demonstrated through successive regulatory stages, notably in India when India leap-frogged from BS-IV to BS-VI, skipping BS-V.

The future of ICE should be evaluated segment by segment rather than as a single technology category. A small passenger car, a motorcycle, a city bus and a long-haul truck have very different operating conditions.

ICE in Hybrid Mode

Hybridisation potentially changes the role of the engine more fundamentally than simply adding an electric motor. The engine and electrical system can be coordinated, which creates the possibility of:

- reducing unnecessary engine operation
- supporting low-speed operation electrically
- recovering energy during deceleration
- assisting during transient conditions
- reducing engine load variability
- improving overall energy utilisation

The exact extent of these benefits depends on the architecture, operating strategy, vehicle application and duty cycle. The engine can increasingly be treated as an energy-conversion unit within a larger system, rather than the sole source of propulsion.

This is one of the most important reasons why ICE is considered as a valuable candidate for hybrids. Hybridisation may be particularly relevant where customers require:

- long driving range
- rapid refuelling
- high vehicle utilisation
- lower fuel consumption
- reduced urban emissions
- conventional infrastructure
- reduced dependence on large battery capacity

Hybrid vehicles can potentially occupy an intermediate position between conventional ICE vehicles and fully electric vehicles. The importance of this pathway is reflected in the global market.

The engine's role in a hybrid vehicle can differ substantially from its role in a conventional vehicle. In a conventional vehicle, the engine needs to accommodate a broad range of:

- speeds
- loads
- transients
- acceleration requirements
- idling conditions
- operating environments

In a hybrid mode, some of these requirements may be supported by the electrical system. This can potentially provide greater freedom in engine operating strategy. However, hybridisation also introduces new engineering considerations. Repeated engine starts and stops can affect thermal conditions. Engine operation may become more intermittent. The emission-control system must remain effective when the engine restarts. Therefore, hybridisation does not eliminate the emission-control challenge.

It only changes its nature. Therefore, the engineering focus moves towards coordination between the engine, electrical system, thermal state, after treatment systems and vehicle controls.

Opportunity for making ICE further cleaner

It is essential to understand how much cleaner ICE can become further. Clean enough criteria depend on the regulatory objective, pollutant, duty cycle and useful-life requirement. Modern ICE vehicles already demonstrate substantially lower regulated emissions than earlier generations. Future regulation may require additional reductions and wider operating coverage. The challenge is therefore one of diminishing margins. As emissions become lower, further improvement requires greater attention to:

- transient behaviour
- cold operation
- system ageing
- control accuracy
- real-world variability
- fuel properties
- component interactions
- system integration

A major determinant of future ICE viability will be its ability to demonstrate environmental performance outside controlled laboratory conditions. Factually vehicles operate under varied conditions:

- congestion
- acceleration
- deceleration
- gradients
- different temperatures
- different altitudes
- payload changes
- air-conditioning loads
- driver behaviour
- varying maintenance conditions

Future emission engineering therefore needs to address the complete operating envelope. Therefore, it is likely to become important to judge the consistency of ICE vehicles maintaining the low emissions across its actual operating life, rather than achieving isolated laboratory performance.

Urban driving presents a particular challenge for combustion vehicles. Short trips and frequent stops can result in repeated engine starts and periods of low thermal activity.

Consequently, the first few minutes of operation can have disproportionate importance.

For future ICE and hybrid vehicles, engineering attention will increasingly focus on:

- rapid achievement of effective emission control
- appropriate engine operating conditions
- thermal management
- control coordination
- minimising unnecessary operation

Hybridisation can change the urban operating pattern, but it does not automatically solve the thermal challenge. The engine and emission-control system must still operate effectively whenever the engine is running.

Fuel will influence the Future of ICE

The future of ICE cannot be separated from the future of fuel. India has already undergone a major transition in ethanol blending. In India, presently, average ethanol blending reached 20%, while discussions are going on to raise blending level in future beyond 20%.

The ICE fleet of the future may not necessarily operate on exactly the same fuels as the ICE fleet of the past. Therefore, potential pathways include:

- ethanol-blended petrol
- higher ethanol blends for compatible vehicles
- compressed natural gas
- biogas-derived fuels
- biomethane
- LNG in appropriate applications
- synthetic fuels
- potentially hydrogen-based pathways

Each fuel introduces different engineering considerations and challenges. The important point is that ICE should be evaluated together with its energy source.

It is required to ascertain if progressively cleaner liquid fuels can extend the environmental contribution of ICE and, therefore, it is essential to study the complete lifecycle of the fuel and vehicle, that grossly depends upon compatibility, availability, production pathways and environmental performance. Evolution of fuel may, therefore, become as important as engine evolution.

ICE and Ethanol

Ethanol is particularly relevant to India because it is already integrated into India's fuel strategy. Many laboratory studies and field trials have reported data about durability, drivability, startability, corrosion resistance, material compatibility, emissions and fuel efficiency of vehicles running on E20 blended fuel.

CNG, Biomethane and Other Gaseous Fuels

Gaseous fuels provide another pathway for combustion-based mobility. India already has a substantial CNG ecosystem, while biomethane and related renewable-gas pathways may offer opportunities for reducing lifecycle carbon intensity where sustainable feedstocks and appropriate infrastructure are available in order to define:

- fuel availability
- storage
- vehicle packaging
- range
- refuelling infrastructure
- combustion performance
- gaseous emissions
- lifecycle carbon intensity
- economics

The future role of gaseous-fuel ICE should therefore be evaluated by application.

Urban mobility, commercial vehicles and high-utilisation fleets may have different requirements from private passenger vehicles.

Hydrogen and ICE

Hydrogen introduces another potential pathway. Hydrogen can be used in fuel cells or, under appropriate conditions, in combustion engines. Hydrogen combustion does not eliminate all emission-control considerations. Although carbon-containing exhaust emissions can be substantially reduced, combustion conditions can still result in nitrogen-oxide formation. Therefore, hydrogen ICE should be considered as a potentially different form of combustion technology rather than as an automatic zero-emission solution. Its relevance will depend on:

- hydrogen availability
- production pathway
- infrastructure
- vehicle application
- efficiency
- storage
- cost
- lifecycle environmental performance

Heavy-Duty Vehicles and ICE

Heavy-duty applications such as trucks and buses have different operating requirements compared to passenger cars. Heavy-duty applications often involve:

- high annual mileage
- high payload
- long operating hours
- demanding duty cycles
- long-distance operation
- limited tolerance for downtime
- substantial energy requirements

Commercial mobility is driven strongly by economics. For a commercial operator, a vehicle represents an operating asset. Important considerations include:

- purchase cost
- fuel or energy cost
- range
- payload
- downtime
- maintenance
- residual value
- infrastructure
- financing
- operating reliability

Therefore, the future powertrain choice cannot be evaluated solely by its laboratory emission performance. It must also deliver the required transport service economically.

This creates potential opportunities for different powertrain technologies in different applications.

Two-Wheelers: ICE Versus Electrification

India's two-wheeler market is enormous and highly diverse. Electric two-wheelers have demonstrated significant growth. Presently, about 6% electric two-wheelers exist on Indian roads. At the same time, the majority of the segment remains non-electric. For ICE two-wheelers, future competitiveness will depend on:

- affordability
- fuel economy
- reliability
- low emissions
- compactness
- durability
- fuel compatibility
- customer expectations

Three-Wheelers and Urban Commercial Mobility

Three-wheelers is an interesting commodity in Indian scenario. India has already experienced substantial electrification in this segment of the order of nearly more than 50% owing to prevailing operating economics and duty cycles strongly supporting transition to electrification relatively quickly for 3-W segment. However, the remaining ICE and alternative-fuel fleet still represents a significant engineering opportunity opening the room for cleanest, most practical and economically sustainable solution for three-wheeler duty cycle.

Passenger Vehicles: The Broadest Powertrain Portfolio

Passenger vehicles are likely to remain one of the most diverse powertrain markets including potential configurations:

- conventional ICE
- mild hybrid
- full hybrid
- plug-in hybrid
- battery electric
- gaseous-fuel vehicles
- potentially other emerging pathways

This diversity reflects different customer requirements and customer prioritise such as:
purchase affordability;

- long range
- rapid refuelling
- urban efficiency
- highway capability
- low running cost
- performance
- access to charging

While the global direction is clearly towards electrification, but at the same time, the global vehicle market remains heterogeneous.

According to IEA report, in 2025, conventional ICE models still represented about 60% of available car models globally, while hybrids represented around 10% and electric models nearly 30%. This illustrates an important point that the transition is underway, but the global powertrain landscape still remains diverse.

Different regions are moving at different speeds because of differences in:

- regulation
- infrastructure
- energy systems
- vehicle prices
- consumer preferences
- industrial policy
- local manufacturing
- operating conditions

Europe: Regulation as a Driver of Change

Europe provides an important example of regulatory pressure on conventional powertrains. Euro 7 has established a broad emissions framework covering combustion and hybrid vehicles, together with requirements concerning battery durability and other aspects of vehicle environmental performance. At the same time, European CO₂ standards are influencing powertrain strategies. This demonstrates that future ICE development will increasingly be shaped by two parallel objectives, needing to improve simultaneously:

- control of conventional pollutants
- reduction of greenhouse-gas emissions

China: A Rapidly Changing Landscape

China provides another distinct example. IEA reports stats that electric cars accounted for nearly 55% of Chinese car sales in 2025. This demonstrates how quickly a market can change under the following conditions:

- scaling of EV manufacturing
- competition in vehicle prices
- expansion of model availability
- development of charging infrastructure
- reinforcement of policy and industrial strategies

China therefore represents an important reference point for the future competitive environment. However, India's conditions are different.

India: A More Diverse Transition

India's transition is likely to have its own characteristics based on diversified presence such as:

- high two-wheeler dependence
- rapidly growing passenger-vehicle ownership
- extensive commercial mobility
- substantial public transport requirements
- significant rural mobility
- diverse climatic conditions

- varying charging availability
- strong interest in energy security

presently, India's electrification is particularly visible in two- and three-wheelers, while passenger-car electrification remains at a lower level. It also identifies differences in electrification prospects between buses, trucks and other vehicle categories. This suggests that India may experience multiple powertrain transitions simultaneously.

Forthcoming emission regulations such as BS-VII and ICE

For ICE, BS-VII can become an engineering catalyst. It can encourage development in efficiency, durability, controls, sensing, real-world validation, fuel compatibility, thermal management, system integration, and lifecycle performance. The key challenge will be achieving these improvements economically. Therefore, it would be important to note that combustion powertrain still remains competitive in a changing energy ecosystem?"

The Hybrid Bridge

Hybridisation may provide one of the most important pathways for ICE beyond the next regulatory transition. It allows the industry to combine elements of two propulsion approaches. The engine provides the benefits associated with liquid or gaseous fuels and established refuelling infrastructure. The electrical system provides opportunities for energy recovery and electric propulsion during selected operating conditions. The result is not necessarily a compromise. It can be considered a system integration opportunity.

The eventual importance of hybridisation will depend on economics, regulations, customer acceptance, battery costs, fuel prices, infrastructure and vehicle segment.

ICE as a Range Extender

Another possible role for ICE is as a range-extending energy source. In such an architecture, propulsion may be predominantly electric while the combustion engine performs a more limited energy-generation role. This fundamentally changes the operating requirements of the engine. The engine's operating pattern can potentially be different from that of a conventional vehicle because the electrical system can provide short-term propulsion flexibility. Therefore, the future ICE does not necessarily have to look like today's ICE. Its role may evolve from a direct propulsion towards an integrated energy conversion.

Importance of Efficiency

As emission limits become increasingly stringent, efficiency will become an important differentiator. Every unit of energy that does not need to be generated or consumed reduces the burden on the entire vehicle system. Therefore, future ICE engineering will focus increasingly on:

- reducing energy losses
- optimising operating conditions
- reducing vehicle energy demand
- improving thermal utilisation
- coordinating with hybrid systems
- integrating with efficient transmissions and controls

Vehicle-Level Efficiency

It is important not to evaluate ICE efficiency independently from the vehicle. A highly efficient engine installed in a heavy or aerodynamically inefficient vehicle may not produce the expected overall result fuel economy. Similarly, a hybrid system should be assessed based on actual vehicle energy consumption rather than individual component efficiency. Therefore, BS-VII and beyond should encourage vehicle-level engineering metrics, that broadly includes:

- fuel consumption
- energy consumption
- real-world emissions
- lifecycle emissions
- durability
- total cost of ownership

Old fleet on the road

The discussion about future powertrains often focuses on new-vehicle sales. However, the existing vehicle fleet remains on the road for many years. Consequently, India's environmental trajectory will depend on both the performance of new vehicles and the ageing and replacement of the existing fleet. This makes durability, maintenance, inspection and fleet renewal important parts of the overall clean-mobility strategy. Future ICE vehicles will enter a fleet that still contains vehicles developed under earlier emission standards. Therefore, BS-VII should be considered as part of a long-term fleet transformation rather than as an isolated product regulation.

Coexistence of powertrain technologies

For a period of transition, coexistence of ICE and EV is likely to be an important feature in global markets including India. The two technologies are not identical and have fundamental differences. Both technologies have different potentials as regards appropriate environmental and operational performance for particular applications. Therefore, the importance of these technologies for a specific application is required to be assessed because, for example:

- urban two-wheelers may have strong electrification potential
- high-utilisation fleets may have different requirements
- long-distance heavy-duty applications may face different infrastructure challenges
- passenger cars may support several powertrain pathways

Future of ICE

Looking beyond BS-VII, the ICE landscape could evolve in several broad directions opening new engineering pathways, supported by market and policy developments:

- Continued improvement is happening in efficiency and emissions.
- Hybrid ICE is having increasing integration with electrical systems.
- Alternative-fuel ICE will demonstrate greater use of low-carbon or renewable fuel pathways where appropriate.
- A more specialised role for combustion engines within electric propulsion systems is expected through Range-extender applications
- Heavy-duty applications
- Continued development is going for heavy-duty applications where energy density, range, payload and infrastructure remain important.
- There is going to be potential use of increasingly low-carbon fuels where technically and economically viable.

A Possible ICE Roadmap

A broad roadmap for ICE could therefore be represented as follows focusing on:

- real-world emissions
- durability
- cold-start performance
- fuel compatibility

- diagnostics
- system integration
- improved vehicle efficiency
- advanced controls
- thermal optimisation
- reduced energy losses
- greater fuel flexibility
- engine-electrical powertrain integration
- energy management
- use of regenerative energy
- system-level efficiency
- renewable fuels
- bio-derived fuels
- renewable gaseous fuels
- synthetic fuels where applicable
- lifecycle assessment

Opportunity for segment wise ICE applications

ICE may increasingly concentrate in applications where its characteristics provide particular operational value. This is not a prediction of market shares. It is a framework for considering how the role of ICE could evolve for different use segments.

ICE & Hybrid Powertrain Opportunities by Vehicle Segment

Segment	Potential ICE / Hybrid Role	Major Engineering Focus
 Two-wheelers	 Transition pathway with increasing electrification and efficient ICEs	 Cost, efficiency, emissions, durability
 Three-wheelers	 Mixed powertrain ecosystem	 Urban duty cycle, TCO, emissions
 Passenger cars	 Broad mix of ICE, hybrid and EV	 Efficiency, emissions, customer economics
 Premium / SUV	 Hybrid and electrified ICE pathways may remain relevant	 Energy efficiency, performance, range
 LCVs	 Mixed solutions	 Payload, utilisation, TCO
 City buses	 Strong electrification potential alongside other pathways	 Duty cycle, infrastructure, lifecycle cost
 Intercity buses	 Multiple solutions	 Range, payload, refuelling / charging
 Heavy trucks	 Potentially diverse transition	 Payload, range, energy density, TCO
 Specialised purpose vehicles	 ICE may remain relevant in selected applications	 Reliability, fuel flexibility, durability

How Much ICE Can “Pull”?

The future contribution of ICE will grossly depend on several interacting variables.

Key Factors Shaping the Future of ICE, Hybrid & Clean Mobility

01		Regulation	How rapidly emission and CO ₂ requirements tighten	
02		Technology	How effectively ICE and hybrid systems continue to improve	
03		Fuel	How rapidly low-carbon and renewable fuels become available	
04		Battery economics	How quickly battery costs and performance improve	
05		Infrastructure	Availability of charging and alternative-fuel infrastructure	
06		Industrial capability	India's ability to develop and manufacture competitive systems	
07		Energy security	Availability and diversity of domestic energy sources	
08		Lifecycle performance	Overall environmental impact rather than tailpipe emissions alone	

Technology Neutrality

Technology neutrality does not mean that every powertrain will have the same environmental performance. Instead, it means that the environmental objective should be established independently from the technology used to achieve it. This allows innovation to continue. An engineering framework; based on the aspects of delivering required performance at the appropriate cost and scale; can find their appropriate applications encouraging competition between:

- ICE
- hybrids
- battery-electric systems
- gaseous fuels
- renewable fuels
- hydrogen pathways
- future technologies

Opportunities for India

India has an opportunity to become a major centre for clean-powertrain engineering. Instead of simply importing future powertrain solutions, India can explore capability of developing solutions specifically suited to its requirements. This includes improving ICE and hybrid systems as well as developing electric and alternative-fuel technologies. The objective should be to create Indian engineering solutions for Indian mobility challenges, while maintaining global competitiveness through some of the following opportunities existing in India:

- a large domestic market
- extensive automotive manufacturing
- strong engineering talent
- a growing component industry
- research institutions
- testing infrastructure
- a diverse set of real-world operating condition

A major change in the approach is anticipated. Instead of focusing on ICEs merely complying forthcoming stricter emission regulations such as BS-VII, there is going to emphasis on making combustion-based mobility genuinely clean, efficient and durable under real operating conditions. This kind of shift in approach will lead to innovation creating space for hybridisation, alternative fuels, software, thermal management and other engineering developments.

The fundamental question is how much can ICE pull through BS-VII and beyond? ICEs would exist significantly in different roles:

- ICE can potentially continue to contribute significantly where its strengths—energy density, range, refuelling convenience, existing infrastructure, durability and manufacturing maturity—remain valuable, provided that its environmental performance continues to improve.
- Hybridisation can further change the role of the engine by integrating it with electrical propulsion.
- Alternative and renewable fuels may provide additional pathways where their lifecycle benefits, availability and economics are appropriate.

Conclusion

The internal-combustion engine is entering a new phase. Its future cannot be assessed simply by looking at the conventional ICE vehicle of today. The engine is evolving into a component of increasingly integrated powertrain systems. Hybridisation can change its operating role. Alternative fuels can change its energy source. Digital controls can change how it operates. Advanced emission management can change its environmental performance. Improved durability can extend its useful contribution.

On the other hand, battery-electric vehicles are advancing and will continue to transform in many vehicle segments. India's transition is developing differently across two-wheelers, three-wheelers, passenger vehicles, buses and small commercial vehicles.

For ICE, it should not be viewed merely as a regulatory barrier. It should be viewed as an opportunity to demonstrate how far combustion-based mobility can evolve. The future ICE will need to be substantially cleaner, more efficient, more intelligent and more integrated than today's ICE. The future hybrid will need to demonstrate that combining combustion and electric propulsion can provide measurable environmental and efficiency benefits. Alternative fuels will need to demonstrate credible lifecycle advantages.

Electric vehicles will continue to expand where their economics, infrastructure and duty cycles support them.

Ultimately, the future will be determined not by one technology alone, but by the ability of the automotive ecosystem to deliver the right clean-mobility solution for the right application. The question, therefore, is not whether ICE can survive unchanged. The more meaningful question is whether ICE can continue to evolve fast enough to remain a relevant part of clean mobility through BS-VII and beyond. The engineering answer will depend on innovation, integration, affordability, fuel evolution, regulation, infrastructure and—most importantly—the ability to deliver measurable environmental performance in the real world. The journey beyond BS-VII should therefore be seen not as the end of ICE, but as a test of how far the technology can evolve within an increasingly diversified clean-mobility ecosystem.

The future may not belong to one powertrain. It may belong to the powertrain that delivers the required mobility service with the lowest practical environmental impact over its complete lifecycle.

Key Takeaways

- ICE is unlikely to remain unchanged; its role will evolve.
- Hybridisation can change the engine from the sole propulsion source into an integrated energy-conversion element.
- Forthcoming emission regulations, such as BS-VII, will increasingly emphasise real-world and lifetime performance.
- Fuel evolution will be an important determinant of the future ICE pathway.
- India's diverse vehicle segments require different powertrain strategies.
- Two-wheelers and three-wheelers are likely to experience different transition dynamics from passenger cars and heavy-duty vehicles.
- Heavy-duty applications require separate consideration because of payload, range, utilisation and infrastructure requirements.
- Alternative fuels can potentially extend the relevance of combustion-based mobility where their lifecycle benefits are demonstrated.
- Electrification will continue to expand and will be particularly relevant where operating economics and infrastructure support it.
- The long-term objective should be clean, efficient, affordable and durable mobility—not the preservation of any particular technology.

Petrol with 20 percent Ethanol (E20): The Debate

K K Gandhi

Member - Expert Advisor Group for MoRTH, Convenor - CAPR, Auto & Fuel Expert

There have been divergent views shared in the debates raging in the Media and Social networks on the effect of E 20 blend on the vehicles.

Brazil first introduced mandatory 5 percent ethanol blend in Petrol in February 1931, which was increased to about 50 percent in 1943 during World war II. The National Alcohol Program was however launched in November 1975 following the 1973 crisis. In 1993 the Central Government made law to introduce 22 percent ethanol blend. The commercial production of Flex fuel vehicles was introduced in 20023 giving the flexibility to the consumer to use any ration of Petrol and Ethanol.

In India IIT Delhi, Indian Institute of Petroleum, Automotive Research Association of India, IOC etc carried out limited studies way back in Nineties. India introduced 5 percent blend through a pilot project (E5) at some location in 2001 to study the vehicle performance. The formal launch of E 5 started in 2003 in Nine States and 4 Union Territories. Further the program was expended across 20 states in November 2006. The 10 percent blend was introduced across India in June 2022 which was increased to 20 percent (E20) from April 2026.

Let us look at the same in a holistic view. Everyone is correct from their point of view depending on which side of the coin they are looking. Looking from technical perspective:

As we all know that the Calorific Value of Ethanol (~27 MJ/kg) is approximately 35 percent lower than Petrol (~44 MJ/kg). Therefore, under similar conditions we would need to burn higher volume of E20 to produce similar mileage. The drop could vary from 2 to as high as 10 percent under similar standard conditions. The same would depend upon the design features of the vehicle / engine.

Further due to slightly higher density of Ethanol (~789 kg/m3) compared to petrol (~740 kg/m3), ethanol will settle down in case of phase separation due to long period of non-usage of the vehicle and hygroscopic nature of ethanol. In that case when starting after a long period of non-usage, neat Ethanol may be pumped to the carburettor / fuel injector leading to starting problem and damage to engine etc. as the vehicle has not been designed for Ethanol.

The Auto manufacturers have designed their vehicles for E20 since April 2023 but what about the vehicles manufactured earlier?

Further 2 wheelers are more vulnerable. This segment is very / more important as almost about 2/3rd petrol is used by two wheelers and they were using carburettor technology not long back. The carburettor float / pin etc. degradation can get accelerated and can get damaged due to E20 higher solvent properties which may lead to starting problem / flooding of the engine etc. etc.

Looking from the Social perspective in India there can be mis use of the blend where people can try to add water to E 20 blend leading to phase separation and mis use of ethanol thus separated for drinking. The Economic impact on agricultural supply chain has led to other products like sugar, eggs etc which have seen increase in their cost due to diversion of sugar cane, maize etc to Ethanol blending program. There are concerns regarding local ground water depletions.

Therefore, there is a need to take a 360-degree perspective on the same taking into consideration **Technical, Economic, & Social aspects.**

The way forward would be continue dispensing both E20 and E10 till the old vehicles get phased out.

The E20 could be logically priced lower because of the lower energy content per litre basis compared to petrol to compensate the lower mileage.

This way we would meet both the concerns of the consumer and move towards energy security goal of the country.

Need to use more of surplus food grains, waste etc for the Ethanol program.

Beyond ISO 22241: Ensuring AdBlue® Quality from Production to Vehicle Tank for Reliable SCR Performance

Critical Quality Control Parameters, Supply Chain Risks, and Field Experience in Diesel Exhaust Fluid Management

Germán Orduy Rey
Yara International ASA

1. Introduction

The reduction of nitrogen oxide (NOx) emissions has become one of the primary challenges facing the transportation industry. Heavy-duty vehicles, agricultural machinery, construction equipment, marine engines, and stationary power generation systems must comply with increasingly stringent environmental regulations aimed at reducing atmospheric pollution and improving air quality.

Among available NOx control technologies, Selective Catalytic Reduction (SCR) has emerged as the most effective solution, routinely achieving conversion efficiencies exceeding 95% under optimized operating conditions. Modern SCR systems depend on the controlled injection of AdBlue®, a high-purity aqueous urea solution that serves as a safe carrier for ammonia generation within the exhaust stream.

Although ISO 22241 establishes internationally recognized quality requirements for AdBlue®, numerous field investigations have shown that contamination occurring after production can significantly impair SCR performance. Poor quality fluid may lead to ammonia deficiency, injector fouling, catalyst poisoning, deposit formation, increased NOx emissions, and premature system failure.

This paper examines the complete quality lifecycle of AdBlue®, from production through final use in diesel vehicles, and provides practical recommendations for maintaining product integrity throughout the supply chain.

2. Fundamentals of SCR Chemistry

2.1 Composition of AdBlue®

AdBlue® is an aqueous solution consisting of:

- 32.5 % high-purity automotive-grade urea
- 67.5 % deionized water

The chemical formula of urea is: $\text{CO}(\text{NH}_2)_2$

The concentration of 32.5 % has been specifically selected because it provides the lowest freezing point of approximately -11°C while ensuring optimal ammonia generation.

Contrary to common perception, AdBlue® is not itself the reducing agent responsible for NOx removal. Instead, it serves as a transportation medium for urea, which subsequently decomposes into ammonia inside the exhaust system.

2.2 Stability of AdBlue® During Storage and Handling

One question frequently raised by operators and end users concerns the potential formation of ammonia during the storage and transportation of AdBlue®. From a technical perspective, it is important to understand that, under normal storage conditions, AdBlue® remains a highly stable product.

The composition of AdBlue®, consisting of 32.5% high-purity urea dissolved in demineralized water, is specifically designed to ensure long-term stability when stored in accordance with ISO 22241 recommendations. As a result, significant ammonia formation does not normally occur during storage, transportation, or routine handling operations.

To understand why, it is necessary to examine the conditions required for urea decomposition. The conversion of urea into ammonia is a thermally activated process that occurs primarily within the vehicle's exhaust aftertreatment system. Several conditions must be present simultaneously for this reaction to proceed at a significant rate: Elevated temperatures, Water evaporation, Sufficient thermal residence time, Contact with hot exhaust gases.

In practice, these conditions exist only within the exhaust system, where AdBlue® is injected before reaching the SCR catalyst. Within the exhaust system, the water contained in the solution rapidly evaporates, and the remaining urea undergoes thermolysis and hydrolysis reactions, ultimately generating ammonia (NH_3), the active reducing agent responsible for converting nitrogen oxides (NOx) into harmless nitrogen and water.

In contrast, storage tanks, IBCs, road tankers, Mini bulk installations, and dispensing systems operate under conditions that are fundamentally different from those found within an exhaust system. Temperatures remain relatively moderate, water remains in solution, and the thermal energy required to initiate significant urea decomposition is absent. Consequently, the generation of ammonia within properly managed AdBlue® storage systems is negligible.

For this reason, AdBlue® can be transported, stored, and handled safely throughout the supply chain without creating ammonia-related hazards under normal operating conditions. This inherent stability is one of the reasons AdBlue® has become a practical and reliable solution for supporting SCR technology on a global scale, provided that proper storage, handling, and contamination control practices are maintained.

2.3 Urea Thermolysis and Hydrolysis

The conversion of urea into ammonia occurs only after injection into the exhaust stream.

Thermolysis : Urea decomposes thermally according to:

$\text{CO}(\text{NH}_2)_2 \rightarrow \text{NH}_3 + \text{HNCO}$ where HNCO is isocyanic acid.

Hydrolysis : The isocyanic acid subsequently reacts with water vapor: $\text{HNCO} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2$

Overall Reaction : Combining Equations (1) and (2): $\text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2$

Each mole of urea generates two moles of ammonia, which becomes the active reducing agent for SCR reactions.

2.4 Standard SCR Reaction

$4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$

The final products are environmentally benign: Nitrogen and water.

2.5 Temperature Effects on SCR Performance

Temperature is the dominant factor governing SCR efficiency. The impact of temperature on SCR performance is presented in Table 1.

Exhaust Temperature	SCR Behavior
<180°C	Incomplete decomposition
180-220°C	Initial ammonia formation
220-250°C	Increasing conversion
250-400°C	Optimum operating range
400-450°C	High conversion maintained
>500°C	Possible NH_3 oxidation

Table 1. Influence of Temperature on SCR System Performance

Maximum NOx reduction efficiencies above 95% are typically achieved between 250°C and 400°C.

3. Impact of AdBlue® Quality Deviations on SCR Performance

3.1 Urea Concentration Deviations

ISO 22241 specifies a urea concentration of : $32.5 \pm 0.7\%$ "(m/m).

Low Concentration

The concentration of urea is one of the most critical quality parameters of AdBlue®, as SCR systems are designed and calibrated to operate with a solution containing 32.5% automotive-grade urea dissolved in demineralized water. Any deviation from this specification can directly affect the efficiency of the NOx reduction process.

When the urea concentration is lower than the prescribed limits, the amount of ammonia generated within the exhaust system is reduced. Since ammonia is the active reagent responsible for converting nitrogen oxides (NOx) into nitrogen and water, insufficient ammonia availability limits the SCR catalyst's ability to perform its intended function.

As a result, the overall efficiency of the emissions control process decreases, potentially leading to higher NOx emissions and reduced aftertreatment performance.

The main consequences of low urea concentration include:

Lower NOx conversion efficiency, as insufficient ammonia is available for the reduction reactions occurring within the SCR catalyst.

Increased risk of regulatory non-compliance, particularly in regions where strict emission standards such as Euro VI, Euro VII, EPA, or BS-VII apply.

Reduced SCR system effectiveness, resulting in a deterioration of the vehicle's ability to maintain its designed emissions performance.

In modern vehicles equipped with advanced onboard diagnostics (OBD), persistent operation with low-concentration AdBlue® may also trigger fault codes, warning messages, torque limitations, or inducement strategies intended to ensure continued compliance with emissions regulations.

For this reason, maintaining the correct urea concentration is essential not only for achieving optimal NOx reduction, but also for preserving SCR system reliability and ensuring long-term regulatory compliance.

High Concentration

Just as insufficient urea concentration can negatively affect SCR performance, excessive urea concentration can also create operational challenges within the aftertreatment system. SCR systems are specifically engineered to operate with AdBlue® containing 32.5% urea by weight, and significant deviations above this target may alter the behavior of the fluid during injection, evaporation, and decomposition.

When the urea concentration is too high, the amount of dissolved solids within the solution increases, making the product more prone to crystallization and deposit formation under certain operating conditions. This is particularly critical in areas of the exhaust system where temperatures are not sufficiently high to ensure complete evaporation and decomposition of the injected AdBlue®.

The main consequences of excessive urea concentration include:

- Crystallization, resulting from the formation of solid urea deposits within the dosing and exhaust systems.
- Deposit formation, which may occur on exhaust pipe surfaces, mixers, and SCR components.
- Injector fouling, caused by the accumulation of deposits around the dosing nozzle, leading to impaired spray characteristics and reduced dosing accuracy.
- Ammonia maldistribution, where the generated ammonia is not evenly distributed across the catalyst surface, reducing the overall efficiency of the NOx reduction process.

Over time, these effects can lead to higher maintenance requirements, reduced SCR efficiency, increased backpressure, and potential emissions-related faults. In severe cases, excessive deposit accumulation may require cleaning or replacement of critical aftertreatment components.

For this reason, maintaining the correct AdBlue® concentration is essential. Regular quality control checks, including concentration verification using a calibrated refractometer, help ensure that the product remains within the ISO 22241 specification and performs as intended throughout the vehicle's operating life.

3.2 Biuret Contamination

Biuret is formed through urea condensation: $2\text{CO}(\text{NH}_2)_2 \rightarrow \text{NH}_2\text{CONHCONH}_2 + \text{NH}_3$

This is biuret: $\text{NH}_2\text{CONHCONH}_2 \rightarrow \text{C}_2\text{H}_5\text{N}_3\text{O}_2$

Elevated biuret levels can undergo further reactions to form more complex compounds such as ammonium cyanurate, cyanuric acid, ammelide, and melamine. These compounds can generate solid deposits in the mixer, injector, and at the SCR catalyst inlet, reducing SCR efficiency and increasing maintenance costs.

Key impacts include:

- Reduced Ammonia Availability
- Slower decomposition kinetics
- Increased deposit formation
- Injector obstruction and flow maldistribution
- The issue is particularly critical at low exhaust temperatures (200-250 °C)

These effects can lead to lower NO_x conversion efficiency and more frequent cleaning or maintenance interventions. An example of deposit accumulation observed in an SCR exhaust system is shown in Figure 1. Such deposits are typically associated with incomplete urea decomposition and the formation of by-products derived from biuret and related compounds. The accumulation of these solid residues can restrict flow passages, impair ammonia distribution, and negatively affect overall SCR performance.

3.3 Aldehydes

Aldehydes represent another category of contaminants that must be carefully controlled in AdBlue® production. These compounds are typically generated through urea degradation processes or may originate from low-quality raw materials used during manufacturing. In particular, the use of fertilizer-grade urea instead of Automotive Grade Urea (AGU) can significantly increase the risk of aldehyde contamination. Historically, aldehydes and formaldehyde-based compounds have been used in fertilizer production as anti-caking agents and granulation aids, making fertilizer-grade urea unsuitable for the manufacture of AdBlue® intended for SCR applications.

Although aldehydes are generally present at very low concentrations, their impact on SCR catalyst performance can be significant over time. The primary concern is their tendency to interact with the catalyst surface, reducing the availability of active catalytic sites required for NO_x reduction reactions.



Figure 1. Solid deposits observed during inspection of an SCR system

This phenomenon, often referred to as catalyst surface masking, progressively decreases the effectiveness of the catalyst by limiting the contact between ammonia, NO_x, and the active catalyst coating.

The main consequences of excessive aldehyde contamination include:

- Reduced active catalyst surface area, limiting the number of sites available for NO_x reduction reactions.
- Slower reaction kinetics, resulting in less efficient conversion of nitrogen oxides under comparable operating conditions.

Progressive losses in SCR efficiency, which may become increasingly apparent over the lifetime of the catalyst. Unlike some contaminants that cause immediate operational issues, the effects of aldehydes are often gradual and cumulative. As catalyst activity declines, the SCR system may have to be replaced.

3.4 Insoluble Matter

Insoluble matter is an important contamination parameter in AdBlue® quality control. Typical sources include dust, rust, sand, plastic fragments, and crystallized residues introduced during manufacturing, storage, transport, or handling.

Although these particles do not change the chemical composition of AdBlue®, they can negatively affect SCR system operation by blocking filters, restricting injectors, reducing spray quality, and causing non-uniform ammonia distribution within the

catalyst. As modern SCR systems rely on precise dosing and effective mixing, even small amounts of particulate contamination can reduce NO_x conversion efficiency. For this reason, proper filtration, clean equipment, dedicated transfer systems, and good handling practices are essential to maintain product quality and ensure reliable SCR performance.

3.5 Trace Metal Contamination

Trace metal contamination is one of the most serious risks to SCR system performance and durability. Metals such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), copper (Cu), and zinc (Zn) may originate from non-demineralized water, incompatible equipment, fertilizer contamination, or poor handling practices. These metals can permanently poison the active sites of the SCR catalyst, reducing NO_x conversion efficiency, accelerating catalyst aging, and impairing overall system performance. Unlike particulate contamination, catalyst poisoning is often irreversible and may ultimately require catalyst replacement.

For this reason, ISO 22241 specifies very strict limits for trace metals, making contamination prevention through proper raw materials, compatible equipment, and dedicated logistics systems essential for maintaining SCR efficiency and catalyst life.

4. Manufacturing Quality Assurance of AdBlue®

4.1 Raw Material Qualification

Manufacturing quality begins with rigorous raw material control. Key requirements include:

- Good quality of raw material (Automotive-grade urea).
- High-purity deionized water
- Batch-specific Certificates of Analysis
- Verification of impurity levels

4.2 Water Purification Systems

Water quality is one of the most critical variables in AdBlue® production, as demineralized water represents approximately 67.5% of the final AdBlue® composition. Even when high-quality Automotive Grade Urea is used, inadequate water purification can introduce contaminants that compromise compliance with ISO 22241 requirements and negatively affect SCR system performance.

For this reason, AdBlue® manufacturers typically employ advanced water treatment technologies such as reverse osmosis, deionization, ultrafiltration, and polishing systems to ensure that the purified water meets the stringent quality standards required for automotive applications.

However, installing a water treatment system is only part of the solution. Equally important is the implementation of a comprehensive monitoring program capable of verifying that water quality remains consistently within specification over time.

Routine monitoring should include the following parameters: Conductivity, Trace metals, Silica, Chlorides, Microbiological contamination, Conductivity.

From a manufacturing perspective, it is often said that the quality of AdBlue® can never exceed the quality of the water used to produce it. For this reason, leading producers treat water purification as a critical control point within the production process.

By continuously monitoring conductivity, trace metals, silica, chlorides, and microbiological contamination, manufacturers can ensure that the purified water remains suitable for the production of AdBlue®. This proactive approach helps protect SCR systems, maintain ISO 22241 compliance, and ensure consistent product quality throughout the entire supply chain.

4.3 Dissolution and Blending Controls

Critical manufacturing parameters are:

- Urea concentration
- Density
- Refractive index
- Mixing time
- Dissolution temperature

4.4 Contamination Prevention in dissolution tanks and production equipment

All process equipment must utilize ISO 22241-compatible materials. Approved materials for dissolution tanks are. Stainless Steel, HDPE (High-Density Polyethylene), PP (Polypropylene) and PVDF: (Polyvinylidene Fluoride).

5. Packaging Requirements for Automotive Grade Urea to produce AdBlue®

Packaging represents a frequently underestimated contamination risk.

5.1 Flexible Intermediate Bulk Container Requirements

Recommended packaging characteristics include:

- 100% virgin polypropylene construction
- No recycled polymers
- Food-grade polyethylene liner
- Heat-sealed inner liner
- Full batch traceability

5.2 Contamination Prevention for packaging material

Packaging materials must be free from: Dust, Fibers, Oils, Lubricants and Metallic residues.

Manufacturing should be carried out in clean, well-controlled environments to minimize the risk of contamination.

Materials to avoid for AdBlue® storage and packaging: PVC (Polyvinyl Chloride), Polycarbonate (PC), ABS (Acrylonitrile Butadiene Styrene), Polyamides (PA, Nylon), Polystyrene (PS), Recycled polyethylene of unknown origin, Carbon steel, Brass, Copper, Galvanized steel, Zinc-containing alloys.

6. Storage of Automotive-Grade Urea Prior to Dissolution

Before the dissolution process, automotive-grade urea must be stored under carefully controlled conditions to preserve its purity and ensure compliance with ISO 22241 quality requirements. The primary objectives of storage management are to prevent contamination and minimize moisture absorption, both of which can adversely affect the quality of the final AdBlue® solution.

To maintain product integrity, the following storage conditions are recommended:

- Temperature: 5°C to 30°C
- Relative Humidity: Below 60%
- Exposure to Sunlight: Direct sunlight should be avoided
- Inventory Management: First-In, First-Out (FIFO) principle should be applied

It is important to understand that solid urea is hygroscopic and can readily absorb moisture from the surrounding atmosphere. Excessive exposure to humidity may lead to caking, agglomeration, and variations in the dissolution process. Likewise, prolonged exposure to elevated temperatures or direct solar radiation may negatively impact product handling, storage stability, and overall product quality.

From a quality assurance perspective, storage conditions must be designed to eliminate all potential sources of contamination. One of the most common risks is the introduction of non-demineralized water during storage operations or tank cleaning activities. Even small quantities of untreated water may introduce undesirable impurities, such as calcium, magnesium, sodium, and other minerals, which can compromise compliance with ISO 22241 specifications.

Another critical risk is cross-contamination with fertilizer-grade urea products, particularly in facilities where automotive-grade urea and agricultural fertilizers are handled or stored within the same infrastructure. Fertilizer residues, dust, or transfer through shared equipment can significantly affect the purity of the raw material intended for AdBlue® production.

Special attention must also be given to the materials of construction used in storage and handling systems. Contact with incompatible materials, including carbon steel, copper, brass, or zinc-containing components, can result in the release of trace metal contaminants into the product. These metallic impurities are especially critical because SCR systems are highly sensitive to contamination and may suffer injector fouling, catalyst poisoning, or reduced NOx conversion efficiency.

Also, prolonged storage at elevated temperatures may accelerate urea degradation reactions, leading to the formation of by-products such as biuret, ammonia, and insoluble compounds. The presence of these degradation products may negatively impact the quality of the final AdBlue® solution and reduce its suitability for automotive applications.

Storage tanks and containers must also remain properly sealed at all times. Poorly closed tanks can allow the ingress of ambient moisture, airborne dust, and particulate matter. Such contamination not only affects the quality of the stored urea but may also create operational challenges during dissolution and downstream filtration processes.

For these reasons, automotive-grade urea must always be physically segregated from fertilizers, fuels, chemical products, lubricants, cleaning agents, and maintenance materials. This segregation is essential to eliminate any risk of cross-contamination, which could compromise the quality of the urea and ultimately affect the performance and durability of Selective Catalytic Reduction (SCR) systems utilizing AdBlue®.

Therefore, strict adherence to these storage practices is a fundamental prerequisite for ensuring the production of a high-purity AdBlue®, safeguarding SCR system reliability, and maintaining full compliance with automotive industry standards and ISO 22241 requirements.

7. Controls During AdBlue® Manufacturing

The production of AdBlue® is a highly controlled process in which product quality depends not only on the purity of the raw materials, but also on the effective management of every stage of manufacturing. Because SCR systems are extremely sensitive to impurities, each production step must be monitored through clearly defined control measures designed to prevent contamination and ensure full compliance with ISO 22241 requirements.

From a manufacturing perspective, quality must be built into the process rather than verified only at the end. For this reason, modern AdBlue® production facilities establish a series of Critical Control Points (CCPs) that continuously safeguard product integrity from raw material receipt through final product release. Those Critical Control Points are:

7.1. Incoming Urea Acceptance

The first and probably the most important control point is the verification of incoming automotive-grade urea. Each batch must be assessed to confirm compliance with the required purity specifications before it enters the production process. This includes verification of supplier documentation, traceability records, visual inspection, and laboratory analysis when necessary. Accepting off-specification urea may introduce contaminants that cannot be completely removed during subsequent processing stages.

7.2. Water Purification

Water quality is equally critical, as demineralized water represents approximately 67.5% of the final AdBlue® composition. The water purification system must consistently produce water with extremely low levels of dissolved minerals, organic compounds, and particulate matter. Continuous monitoring of conductivity and routine maintenance of reverse osmosis, deionization, or other purification systems are essential to ensure compliance with ISO 22241.

7.3. Equipment Compatibility

All equipment that comes into contact with the product must be constructed from materials proven to be compatible with AdBlue®. Storage tanks, pipelines, valves, pumps, filters, and fittings should be manufactured from approved materials such as high-grade stainless steel or specified plastics. The use of incompatible materials may introduce trace metal contamination, which can significantly affect SCR system performance and durability.

7.4. Tank Cleaning Verification

Cleaning procedures must be rigorously controlled and documented. Before production begins, tanks and transfer lines must be inspected to confirm the complete removal of residues from previous operations. Verification activities may include visual inspections, rinse water analysis, cleaning records review, and, where applicable, validation testing. Even trace amounts of foreign substances may cause an entire production batch to fall outside specification.

7.5. Concentration Adjustment

One of the most critical process parameters is achieving the correct urea concentration. AdBlue® must contain 32.5% high-purity urea dissolved in 67.5% demineralized water. Concentration measurements should be performed using calibrated instruments and verified throughout the dissolution process. Deviations from the specified concentration can affect SCR dosing accuracy, NOx reduction performance, and regulatory compliance.

7.6. Final Filtration

Before the product is transferred to finished-product storage or packaging, it should pass through a final filtration stage. This step removes any residual particles that may have entered the process during manufacturing, transfer, or handling operations. Effective filtration provides an additional safeguard against particulate contamination and helps ensure the cleanliness standards required for modern SCR systems.

7.7. Laboratory Release Testing

The final quality gate before product distribution is laboratory release testing. Representative samples from each production batch must be analyzed to verify compliance with all applicable ISO 22241 parameters. Typical analyses include urea concentration, refractive index, alkalinity, insoluble matter, and contaminant levels. Only after successful completion of all required tests should the batch be approved for shipment and customer use.

A fundamental principle adopted by best-in-class AdBlue® manufacturing facilities is that contamination prevention is far more effective than contamination detection. While analytical testing remains an essential component of quality assurance, relying solely on laboratory results is insufficient. Once contamination has occurred, significant product losses, rework, disposal costs, and potential customer claims may already be unavoidable.

For this reason, leading manufacturers focus on preventive controls, robust operating procedures, equipment compatibility, personnel training, and strict housekeeping practices. By eliminating contamination risks at their source, producers can consistently manufacture high-purity AdBlue®, protect SCR system performance, and maintain full compliance with the stringent requirements of the automotive industry.

8. Storage, Logistics and Distribution of AdBlue®

Once AdBlue® has been successfully manufactured and released in accordance with ISO 22241 requirements, the primary quality risk shifts from production to logistics and distribution. In fact, many AdBlue® quality incidents do not originate in the manufacturing plant, but rather during transportation, storage, handling, or dispensing operations.

As industry professionals, we must always remember that AdBlue® is not a hazardous chemical, but it is an extremely sensitive product from a purity perspective. Even minor contamination introduced during logistics can render an otherwise compliant batch unsuitable for use in modern SCR systems. Therefore, maintaining product integrity throughout the entire supply chain is just as important as controlling the manufacturing process itself.

8.1. Dedicated Logistics Systems

One of the fundamental principles of AdBlue® logistics is that all equipment coming into contact with the product should be dedicated exclusively to AdBlue® service. Shared equipment significantly increases the risk of cross-contamination and should be avoided whenever possible.

This requirement applies to all fluid-contact components, including Storage tanks, Road tankers, Pumps, Hoses, Loading arms, Couplings, Filters.

The rationale behind dedicated logistics systems is straightforward. Trace residues from fuels, lubricants, detergents, chemicals, or other industrial products can introduce contaminants at concentrations sufficient to damage SCR components or cause the final product to fall outside ISO 22241 specifications.

Experience has shown that contamination events frequently occur not in large industrial facilities, but at the final stages of the distribution chain where product handling is often performed by end users with limited technical knowledge of AdBlue® quality requirements.

8.2. Industry Experience: Lessons Learned from the Early Adoption of AdBlue® in France

Allow me to share a practical example from our own experience during the early years of AdBlue® adoption in France. Around 2015, when Euro VI vehicles became widespread and AdBlue® usage increased significantly across the transportation sector, many end users had only a limited understanding of the quality requirements associated with the product.

At that time, we encountered numerous contamination incidents throughout the logistics chain. One particularly common practice was the transfer of AdBlue® from the IBCs supplied by distributors into other containers available on site.

In several cases, customers transferred AdBlue® into drums that had previously been used to store lubricants or other petroleum-based products. Although these drums had been washed before reuse, the cleaning procedures were often superficial and insufficient to eliminate residual contamination.

The consequences were predictable. Small quantities of lubricant residues, additives, metallic particles, or cleaning chemicals entered in contact with the stored AdBlue® and subsequently contaminated vehicle SCR systems. In some cases, fleets experienced injector fouling, crystallization problems, SCR system malfunction warnings, reduced NOx conversion efficiency, and costly repairs.

These incidents became valuable learning opportunities for both suppliers and customers. As the industry matured, awareness of AdBlue® purity requirements increased substantially. End users gradually recognized that AdBlue® must be handled with the same rigor applied to pharmaceutical-grade or high-purity industrial products rather than as a conventional automotive fluid.

At the same time, suppliers implemented additional preventive measures to strengthen product security throughout the distribution chain. Examples of these measures included:

- Tamper-evident seals on IBCs and tanks
- Sealed dispensing systems.
- Security devices indicating whether an IBC had been opened.
- Tamper indicators on minibulk installations.
- Improved operator training programs.
- Enhanced customer awareness campaigns.

Furthermore, telemetry systems were progressively introduced on fixed AdBlue® storage installations, particularly mini-bulk systems ranging from 5,000 to 19,000 liters. These systems allow suppliers and customers to remotely monitor tank levels, consumption patterns, refill requirements, and abnormal operating conditions.

Today, telemetry has become an important tool not only for inventory management but also for improving supply reliability and reducing the need for uncontrolled product transfers that might increase contamination risks.

8.3. Approved Materials to be in contact with AdBlue®

Material compatibility is another critical aspect of AdBlue® storage and distribution. Because AdBlue® is slightly alkaline and highly sensitive to trace contaminants, all product-contact surfaces must be manufactured from approved materials that do not react with the solution or release metallic impurities.

8.4. Recommended Materials

The following materials are widely accepted for AdBlue® applications: Stainless steel storage tanks, HDPE (High-Density Polyethylene), PP (Polypropylene), PTFE (Polytetrafluoroethylene), PVDF (Polyvinylidene Fluoride).

These materials provide excellent chemical compatibility and minimize the risk of contamination throughout storage, transport, and dispensing operations.

8.5. Prohibited Materials

The following materials should never come into contact with AdBlue®: Copper, Brass, Bronze, Carbon steel, Zinc-coated materials.

These materials can release metallic ions into the solution. Even trace levels of certain metals may poison SCR catalysts, promote deposit formation, interfere with dosing systems, and ultimately compromise vehicle emissions performance. For this reason, material compatibility verification should always be included in the design, installation, inspection, and maintenance of AdBlue® infrastructure.

8.6. Temperature Management

Temperature control represents another essential component of AdBlue® logistics management.

AdBlue® begins to freeze at approximately -11°C. Fortunately, freezing does not permanently damage the product, provided that it is allowed to thaw naturally and remains uncontaminated. However, storage systems should be designed to accommodate the volume expansion that occurs during freezing.

At the opposite end of the temperature range, prolonged exposure to elevated temperatures should be strictly avoided. Continuous storage above 30°C may increase biuret formation, accelerate product aging and chemical degradation, increase ammonia generation and reduce overall product shelf life. Additionally, direct exposure to sunlight should be minimized because solar heating can significantly increase storage temperatures, particularly in IBCs and outdoor storage tanks. For this reason, best-in-class AdBlue® installations are typically equipped with shaded storage areas, insulated tanks, or temperature-controlled systems where climatic conditions require additional protection.

8.7. Key Takeaway

The quality of AdBlue® is not determined solely by manufacturing excellence. A perfectly compliant batch can become unsuitable for use if contamination is introduced during storage, transportation, or dispensing. Therefore, successful AdBlue® distribution relies on three fundamental principles:

- Dedicated and contamination-free logistics systems.
- Strict use of approved materials.
- Effective temperature and inventory management throughout the supply chain.

In practice, the most successful AdBlue® programs are those that combine technical controls, employee training, customer education, and continuous monitoring. As we have learned from the industry's experience over the past decade, prevention remains significantly more effective and less costly than correcting contamination after it has occurred.

9. Customer Storage and Handling

The responsibility for maintaining AdBlue® quality does not end when the product leaves the manufacturing facility or distribution terminal. In reality, the final stage of the supply chain, namely storage and handling at the customer site, is often where the greatest risk of accidental contamination exists.

A batch of AdBlue® may fully comply with ISO 22241 requirements when delivered, yet become unsuitable for use if improper storage or handling practices are applied at the point of consumption. For this reason, end users must adopt operational procedures that provide the same level of product protection maintained throughout production and distribution.

From a practical standpoint, several fundamental measures should be implemented to preserve product integrity during on-site storage and dispensing operations.

9.1. Dedicated Storage Tanks

AdBlue® should always be stored in tanks specifically designed and dedicated for AdBlue® service. Storage tanks previously used for fuels, lubricants, chemicals, cleaning products, or other industrial fluids should never be repurposed without proper engineering evaluation and validation. Even trace residues from previous products can introduce contaminants capable of affecting SCR system performance and vehicle emissions compliance.

9.2. Closed Transfer Systems

Whenever possible, product transfers should be performed using closed systems. Open filling operations increase the likelihood of contamination from airborne dust, dirt, rainwater, and foreign materials.

Closed transfer systems not only improve product protection but also reduce operator intervention and the risk of handling errors.

9.3. Filtered Vents

Although storage tanks require pressure equalization during filling and dispensing operations, air entering the tank should pass through appropriate filtration systems.

Filtered vents help prevent the ingress of dust particles, moisture, insects, and other environmental contaminants that could compromise AdBlue® purity over time.

9.4. Temperature Monitoring

The storage temperature of AdBlue® should be monitored regularly, particularly in outdoor installations exposed to seasonal temperature variations.

Excessive temperatures can accelerate product degradation and reduce shelf life, while prolonged freezing conditions may require specific tank designs and thawing procedures. Continuous temperature monitoring enables operators to identify potentially unfavorable storage conditions before product quality is affected.

9.5. Employee Training

One of the most effective quality controls remains proper personnel training. Operators responsible for receiving, transferring, storing, and dispensing AdBlue® must understand that the product is highly sensitive to contamination. Procedures that may be acceptable for diesel fuel, lubricants, or other automotive fluids are not necessarily suitable for AdBlue®.

Training programs should cover contamination risks, approved materials, transfer procedures, housekeeping practices, emergency response measures, and basic quality awareness principles.

9.6. Prevention of Fuel Contamination

Particular attention must be given to preventing accidental mixing with diesel fuel, gasoline, lubricants, or hydraulic oils.

Among all contamination scenarios, fuel contamination is one of the most severe because even very small quantities can render a complete tank of AdBlue® unusable. In addition, contaminated products may cause extensive damage to pumps, dosing units, injectors, sensors, and SCR aftertreatment systems.

For this reason, dedicated filling connections, clear labeling, color-coding practices, and operator awareness are strongly recommended.

9.7. Management of Returned Product

A final principle that deserves special attention concerns the handling of returned customer product. Once AdBlue® has left the controlled supply chain, its storage history and level of exposure to potential contaminants can no longer be guaranteed. Even when the product appears visually acceptable, contamination may not be detectable without comprehensive laboratory analysis.

Therefore, as a matter of good manufacturing and distribution practice, returned AdBlue® should never be reintroduced into saleable inventory. This policy eliminates uncertainty regarding product quality and protects both the supplier and the end user from the risks associated with unknowingly distributing contaminated material.

9.8. Key Takeaway

From a quality perspective, the customer site should be viewed as an extension of the AdBlue® supply chain rather than its final destination. Dedicated storage equipment, controlled transfer procedures, temperature monitoring, proper employee training, and strict contamination prevention measures are essential to preserving product quality. Ultimately, maintaining ISO 22241 compliance requires continuous attention to detail from production through final consumption.

10. Incompatible Materials and Previous Banned Last Cargoes

One of the most critical aspects of AdBlue® logistics is the control of contamination risks associated with transport and storage equipment. Due to the extremely high purity requirements defined by ISO 22241, even trace quantities of incompatible substances may compromise product quality, resulting in off-specification AdBlue® and potential damage to Selective Catalytic Reduction (SCR) systems.

When assessing the suitability of a transport vehicle, storage tank, or transfer system for AdBlue® service, special attention must be paid to the product transported immediately before the AdBlue® load. Certain materials can leave residues that are difficult to remove completely and may introduce unacceptable levels of contaminants into the product.

The following categories of previous cargoes are generally considered incompatible with AdBlue® service and should therefore be excluded from the approved cargo history.

As a practical implementation of these contamination control principles, Yara has developed a dedicated guidance document entitled "HOPS_7-06_Att_09_Air1_Banned_Last_Cargoes". This document is distributed to transport service providers and carriers involved in the handling of Air1® AdBlue® products.

The purpose of this procedure is to ensure that transport equipment previously carrying prohibited substances is not utilized for AdBlue® transportation. The document defines a "Banned Previous Cargo List", applicable specifically to the immediate last cargo only, and is based on substances known to contribute undesirable contaminants, this list is the following:

List of Banned Previous Cargoes for Air1. Applicable to Immediate Last Cargo ONLY: Aluminium Mono Chloride (ALCL), Aluminium Chloride, Calcium Bromide Solution, Calcium Carbonate Slurry, Carbon Tetrachloride (CTC; Tetrachloromethane, Perchloromethane), CN solution – CN9, CN17, Diethylene Triamine Penta Acetic Acid, DCDP – deoxycytidine-diphosphate, Epichlorohydrin (EPI, 1,2-Dichloroethane), Ethylene Dichloride (EDC: 1,2-Dichloroethane), Ferric Chloride Solutions / Iron Chloride (FECL), Furfural, Formaldehyde, Hydrochloric Acid, Nutriox, Nitric Acid, Perchloroethylene (PCE; perc; Tetrachloroethylene), Potassium Hydroxide Solution (KOH), Potassium Formate (Aviform), Propylene Di Chloride (1,2-dichloropropane), Raffinate (Phos Acid solution), Phosphoric Acid, Sodium Chlorate Solution, Sodium Hydroxide Solution, Sulphuric Acid, Styrene, Trichloroethylene (EHC50), Tricresyl Phosphate (EHC110), Versene – ethylenediaminetetraacetic acid, Aldehydes, Acetaldehyde (ethanal), Butyraldehyde (butanal), Benzaldehyde, Cinnamaldehyde, Formaldehyde (methanal), Propionaldehyde (propanal), Retinaldehyde, Tolualdehyde.

As a key technical takeaway, we can say that as AdBlue® quality requirements are measured in parts per million for certain contaminants, contamination control must be considered a fundamental quality assurance activity rather than a logistical formality. The verification of previous cargo history, combined with dedicated equipment and strict cleaning procedures, constitutes one of the most effective safeguards for ensuring compliance with ISO 22241 and protecting SCR system performance in the field.

11. Future Challenges: Euro VII and BS-VII

The evolution of emissions legislation continues to drive significant technological developments in diesel aftertreatment systems. Looking ahead, forthcoming regulations such as Euro VII in Europe and BS-VII in India will impose even more demanding requirements on vehicle manufacturers, requiring SCR systems to deliver consistently high performance under a broader range of operating conditions.

From an AdBlue® perspective, these regulatory developments are particularly important because the SCR system's ability to reduce NOx emissions depends directly on the quality, availability, and accurate dosing of AdBlue® throughout the vehicle's service life.

Historically, emissions compliance was primarily evaluated under controlled laboratory conditions. Future regulations, however, place much greater emphasis on real-world vehicle operation, meaning that emission control systems must perform effectively not only during certification testing but throughout normal day-to-day use.

11.1 Extended Low-Temperature Operation

One of the most significant technical challenges facing the next generation of SCR systems is the ability to maintain high NOx conversion efficiency during prolonged operation at low exhaust gas temperatures. As emission regulations become increasingly stringent, SCR systems will be required to deliver consistent performance not only under highway driving conditions, but also during urban operation where exhaust temperatures frequently remain below the catalyst's optimal operating window.

This challenge is particularly relevant because modern commercial vehicles and passenger cars are increasingly exposed to operating profiles characterized by frequent stop-and-go traffic, low engine loads, low average speeds due to traffic congestion. Under these conditions, exhaust gas temperatures may remain too low to achieve optimal ammonia generation and catalytic activity. As a consequence, the efficiency of the NOx reduction process may be significantly reduced if the SCR system is not specifically designed to operate effectively in such environments.

To overcome these limitations, vehicle manufacturers are investing heavily in advanced thermal management technologies and increasingly sophisticated dosing strategies. Modern SCR systems are now capable of continuously adapting AdBlue® injection rates based on operating conditions, exhaust flow, catalyst temperature, and engine load, thereby maximizing NOx conversion efficiency while minimizing the risk of deposit formation.

A particularly important development in this area has been the introduction of advanced AUS 32 formulations specifically designed for low-temperature SCR operation. One example is the product Yara OptiSpray® which incorporates a proprietary surfactant additive that improves droplet atomization and spray homogeneity. The resulting enhancement in urea evaporation and exhaust-gas mixing reduces deposit formation within the SCR system, helping to maintain ammonia availability and NOx conversion efficiency under low-load and low-temperature operating conditions.

From an engineering perspective, improved atomization offers several advantages. It increases the contact surface area between the injected droplets and the hot exhaust gases, accelerates thermolysis and hydrolysis reactions, and reduces the likelihood of liquid film formation on exhaust pipe surfaces. This is particularly important because poor evaporation at low temperatures can lead to the formation of deposits such as cyanuric acid, melamine derivatives, and other urea decomposition by-products, which may eventually restrict exhaust flow or impair SCR performance.

As SCR systems become more sensitive and operate closer to their performance limits, the quality of AdBlue® itself becomes increasingly important. Under low-temperature conditions, the system has less tolerance for impurities, incorrect concentration, or contamination. Any deviation from ISO 22241 specifications may negatively affect droplet formation, decomposition behavior, ammonia generation, and ultimately NOx conversion efficiency.

For this reason, future Euro VII and BS-VII vehicles will require not only more advanced aftertreatment technologies, but also an even greater level of discipline throughout the AdBlue® supply chain. Manufacturers, distributors, fleet operators, and end users will all play a critical role in ensuring that the product delivered to the vehicle maintains the purity, concentration, and quality necessary to support these increasingly demanding emission performance targets.

In summary, extended low-temperature operation represents one of the most important challenges for future SCR systems. Success will depend on a combination of advanced catalyst technology, intelligent dosing strategies, products such as OptiSpray®, and strict adherence to AdBlue® quality standards. Together, these elements will enable the next generation of diesel vehicles to achieve high NOx conversion efficiency across the full range of real-world operating conditions.

11.2. Real-World Emissions Compliance

Future legislation will require emissions control systems to demonstrate compliance under a wider range of real-world driving scenarios. Factors such as altitude, ambient temperature, vehicle load, driving style, and route profile can all influence SCR system performance. As a result, the margin for error within the aftertreatment system becomes smaller. In this environment, AdBlue® can no longer be viewed simply as a consumable fluid. Instead, it must be considered an integral component of the emissions control system, with quality standards equivalent to those applied to critical engine and aftertreatment components.

11.3. Increased Catalyst Durability Requirements

Regulatory authorities are also extending durability requirements for emission control systems. Future SCR catalysts will be expected to maintain their performance over longer vehicle lifetimes and higher accumulated mileages. This means that catalysts must be protected against progressive degradation mechanisms such as thermal aging, poisoning, deposit formation, and contamination.

Even trace levels of metallic impurities, insoluble particles, or other contaminants introduced through poor-quality AdBlue® have the potential to accelerate catalyst deterioration. Therefore, maintaining ISO 22241 compliance throughout the supply chain will become increasingly important as vehicle durability targets continue to rise.

11.4. Stricter Onboard Diagnostics (OBD)

Another major trend is the implementation of more advanced onboard diagnostic systems. Future OBD strategies will be capable of detecting a wider range of SCR-related malfunctions, including catalyst efficiency losses, dosing irregularities, sensor failures, and fluid quality deviations. Vehicles will continuously monitor the performance of the emissions control system and identify abnormalities much earlier than previous generations. As these diagnostic systems become more sophisticated, the use of contaminated or off-specification AdBlue® will be detected more rapidly, increasing the importance of proper product handling and quality assurance practices throughout the distribution chain.

11.5. Higher SCR Conversion Efficiency Targets

Ultimately, future regulations aim to further reduce NOx emissions by increasing overall SCR conversion efficiency. Achieving these targets will require a highly optimized interaction between engine calibration, exhaust gas management, catalyst technology, sensors, electronic controls, and AdBlue® dosing systems. In such highly integrated systems, the tolerance for fluid contamination or quality deviations will continue to decrease. Manufacturers will expect consistently high-purity AdBlue® to ensure reliable dosing, predictable decomposition characteristics, and stable catalyst performance throughout the vehicle's operational life.

11.6 Looking Ahead

As we look toward the future of diesel emissions control, it is important to recognize that success will not be determined solely by advances in catalyst technology, engine calibration, or aftertreatment engineering. Equally important is the ability of the entire AdBlue® supply chain, from raw material production and manufacturing to logistics, storage, distribution, and final use, to consistently provide AdBlue® that complies with the quality requirements of ISO 22241.

Throughout our years of experience in the AdBlue® industry, we have witnessed a remarkable transformation in the global approach to NOx emissions control. We have had the opportunity to witness a remarkable transformation in the global perception of NOx emissions control. In the early years, the adoption of SCR technology and AdBlue® was concentrated primarily in Europe and North America, where increasingly stringent emissions legislation drove investment in advanced aftertreatment systems.

Today, however, the landscape is changing rapidly. The awareness of the environmental and public health impacts associated with NOx emissions has expanded far beyond these traditional markets. Governments, vehicle manufacturers, fleet operators, and industrial stakeholders across Latin America, Asia, India, and North Africa are increasingly investing and implementing legislations to reduce emissions from trucks, buses, passenger vehicles, agricultural machinery, construction equipment, marine engines, and stationary diesel engines.

This global expansion presents both opportunities and challenges. While the demand for SCR technology continues to grow, many emerging markets initially lacked the local infrastructure necessary to produce and distribute high-quality AdBlue® in accordance with international standards. Simply importing finished AdBlue® from Europe is not always the most efficient or economical solution, particularly in regions located far from established production centers.

For this reason, the industry has progressively adapted its approach. As a global leader in the AdBlue® value chain, Yara International has evolved from being merely a supplier of finished AdBlue® to becoming a provider of complete emissions-control solutions. A key element of this strategy has been the supply of high-purity Automotive Grade Urea (AGU), enabling local production of AdBlue® in countries where domestic manufacturing capacity is being developed.

In parallel, the deployment of mobile AdBlue® production units has created new opportunities to manufacture compliant AdBlue® closer to the point of consumption. These systems allow producers, distributors, and industrial operators to prepare AdBlue® locally using certified Automotive Grade Urea and properly purified water while maintaining compliance with ISO 22241 requirements.

This approach offers several advantages. It reduces transportation costs, improves supply security, ensures product freshness, and facilitates the development of local distribution networks. And it helps ensure that vehicle operators in emerging markets have access to the same high-quality AdBlue® used in the most advanced emissions-control programs worldwide.

The environmental benefits are significant. When high-quality AdBlue® is used in a properly functioning SCR system, NOx emissions can be reduced by up to 95%, making SCR technology one of the most effective solutions currently available for controlling diesel engine emissions. As regulatory frameworks continue to evolve around the world, maintaining access to compliant AdBlue® will become increasingly important for achieving national air-quality objectives and supporting sustainable transportation strategies. Looking ahead, the future of AdBlue® is closely linked to the global expansion of clean diesel technologies. Euro VII, BS-VII, and similar regulations that are expected to emerge in other regions will place even greater emphasis on emissions performance throughout the entire life of the vehicle. Under these conditions, product quality will no longer be viewed simply as a manufacturing requirement; it will become a strategic factor in ensuring regulatory compliance, protecting SCR system durability, minimizing operating costs, and achieving long-term environmental goals.

Ultimately, the industry's mission extends beyond supplying a fluid. It is about building a reliable global ecosystem capable of delivering high-purity AdBlue® wherever it is needed, whether in Europe, India, Asia, Latin America, North Africa, or any other region committed to reducing emissions and improving air quality. The continued success of SCR technology will depend not only on innovation inside the vehicle, but also on the collective commitment of producers, distributors, regulators, and end users to uphold the highest standards of quality throughout the entire supply chain.

12. Conclusions

As we conclude this paper, we would like to emphasize a fundamental principle that has guided our work throughout the development of the AdBlue® industry: the performance of an SCR system depends not only on advanced catalyst technology and sophisticated engine management, but also on the quality and integrity of the AdBlue® supplied to the vehicle.

Over the past decade, we have witnessed the remarkable success of SCR technology in reducing NOx emissions from diesel engines. Under optimized operating conditions, modern SCR systems can achieve NOx conversion efficiencies exceeding 95%, making them one of the most effective tools available for improving air quality and supporting sustainable transportation. However, such performance can only be achieved when high-quality AdBlue® is consistently available throughout the entire supply chain.

Our experience has repeatedly demonstrated that contamination remains the greatest threat to AdBlue® quality. While ISO 22241 provides a robust framework governing product specifications, handling, storage, and distribution, real-world operations show that risks can arise at every stage of the value chain. Deviations in urea concentration, elevated levels of biuret or aldehydes, insoluble matter, and particularly trace metal contamination can adversely affect SCR performance, reduce catalyst efficiency, and shorten system life.

For this reason, we strongly believe that the most effective strategy is not simply to detect contamination, but to prevent it. This requires a fully dedicated, contamination-free, and traceable supply chain extending from the production of AdBlue® through logistics, storage, distribution, and final vehicle dispensing. Every participant in the value chain has a role to play in safeguarding product quality.

Looking toward the future, the importance of AdBlue® quality will continue to increase as emissions regulations become more demanding around the world. Euro VII, BS-VII, and emerging standards in many other regions will require aftertreatment systems to operate efficiently under increasingly challenging conditions and over longer vehicle lifetimes. In such an environment, maintaining product integrity will no longer be viewed solely as a quality management objective, but as a critical factor in regulatory compliance, operational reliability, and environmental performance.

At Yara International, we have had the privilege of contributing to the global development of SCR technology and AdBlue® since its earliest stages. As demand for NOx reduction solutions continues to expand beyond Europe and North America into India, Latin America, Asia, North Africa, and many other regions, we remain committed to supporting this transition through the supply of high-quality AdBlue®, Automotive Grade Urea, technical expertise, innovative production and distribution solutions.

Ultimately, we believe that the future success of SCR technology will depend on a shared commitment to quality across the entire industry. By maintaining the highest standards in production, logistics, storage, and handling, we can ensure that AdBlue® continues to deliver its full potential, helping reduce emissions, improve air quality, and support a more sustainable future for diesel-powered transportation and industry worldwide.

References :

- ISO 22241-1/3/4:2019 - AUS 32 (AdBlue®): Quality, Handling, Storage, Transportation and Refilling Requirements.
- Interkat GmbH, Hydrolysis Catalyst (H-Kat) Technical Documentation.
- Southwest Research Institute (SwRI), Investigation into Improved Decomposition of Urea-Water Solution in SCR Systems.
- Bernhard Schaber et al., Thermodynamics and Reaction Mechanism of Urea Decomposition, Physical Chemistry Chemical Physics.
- Koebel, M., Elsener, M., Kleemann, M., Urea-SCR: A Promising Technique to Reduce NOx Emissions from Automotive Diesel Engines.
- MDPI Catalysts, Modeling of Urea Decomposition in SCR Systems.
- SAE International Technical Papers on SCR Systems and Diesel Exhaust Fluid Quality Management.
- VDA AdBlue® Quality Assurance Guidelines.
- EFIC and AUS 32 Industry Best Practice Guidelines for DEF Production, Storage and Logistics.
- This document has been prepared using a combination of published technical references, international standards, industry publications, and Yara's practical experience supporting the AdBlue® value chain from the early stages of SCR technology implementation.



Optimized R-SiC DPF design for LD applications under evolving emission regulations in India

Naoki Kawamura, Sri Harsha S

Engineering Group Manager / Assistant Manager

IBIDEN CO. LTD. Email: sriharsha.ind@ibiden.com

Abstract

In the Indian automotive market, diesel powertrains continue to play an essential role in the light-duty commercial vehicle segment despite increasing electrification. Concurrently, emission norms are tightening—transitioning from BS VI Phase 2 toward WLTP adoption and prospective BS VII standards, coupled with extended durability targets (up to 200,000 km) and Real Driving Emissions (RDE) compliance. Under real-world Indian operating conditions characterized by frequent stop-and-go driving, low exhaust gas temperatures, and high soot accumulation, aftertreatment systems face severe thermal and backpressure challenges. This paper presents an optimized Recrystallized Silicon Carbide (R-SiC) Diesel Particulate Filter (DPF) solution. By leveraging a sharp, narrow pore size distribution, Variable Plugging Layout (VPL) cell geometry, and high thermal conductivity, the proposed R-SiC DPF achieves high particle number (PN) filtration efficiency, minimal lifetime pressure loss under high ash loading, and superior thermal robustness during severe regeneration events.

Keywords

Diesel Particulate Filter; Robustness; Filtration; Emission, Light Duty Vehicles;

1. Introduction

While hybridization and battery electric vehicles are expanding, diesel engines remain the backbone of India's commercial transport sector. The regulatory landscape is evolving rapidly:

- Test Cycle Harmonization: Replacement of the Modified Indian Driving Cycle (MIDC) with the dynamic Worldwide Harmonized Light Vehicles Test Cycle (WLTC) introduces higher vehicle velocities and elevated exhaust mass flow rates.
- Stricter PN Limits: Stringent PN limits (6.0×10^{11} #/km) transitioning toward sub-23 nm (PN10) thresholds.

Light-duty vehicle usage in India is characterized by low average vehicle speeds, heavy traffic congestion, and variable payload conditions. These boundary conditions result in low exhaust gas temperatures, limiting passive soot regeneration opportunities. As soot rapidly builds up, subsequent active regeneration events—particularly under drop-to-idle (DTI) scenarios—can trigger catastrophic thermal spikes. Substrates must therefore demonstrate high soot mass limits (SML), chemical inertness against accumulated ash, and minimal backpressure elevation over vehicle lifetimes.

2. Methodology / Experimental Setup

2.1 Microstructure and Thermal Characteristics

The evaluated DPF utilizes recrystallized silicon carbide (R-SiC) with SiC–SiC necking formed via recrystallization, avoiding secondary oxide bonding phases. Key material attributes

include:

Pore Structure: A narrow pore size distribution centered at an optimal pore diameter compared to conventional cordierite, aluminum titanate (AT), and standard Si-SiC substrates.

(Refer fig.1)

Thermal Conductivity: High intrinsic thermal conductivity enabling rapid heat dissipation across the substrate volume.

Chemical Resistance: Exhibits no chemical reaction during heat exposure (1200 °C for 3 hours) with metal oxide ash constituents including MgO, Fe₂O₃, CuO, ZnO, Fe₂(SO₄)₃, and Ca₃(PO₄)₂. (Refer fig.2)

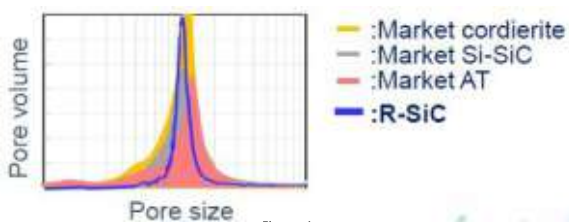


Figure: 1



Figure: 2



MISSION

**We contribute to
the progression of society
through innovative technology
with respect for both individuals
and the global environment**

SPIRIT



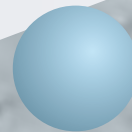
Trust through Integrity



"Wa" Teamwork and



Challenge w



IBI-T



N

y,
uals
nt.

IBIDEN WAY

**Synergy
with Passion
TECHNO innovation**

2.2 Variable Plugging Layout (VPL) Geometry

To decouple surface filtration area from channel volume, a Variable Plugging Layout (VPL) was integrated into a 7 mil / 300 cpsi.

Flow Pattern: Upgrades conventional 4-direction inlet flow to an 8-direction flow pattern by enlarging inlet channel cross-sections while expanding outlet diameters.

Pressure Drop Formulation: Total loss is governed by $\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5$. Refer below figure 3.

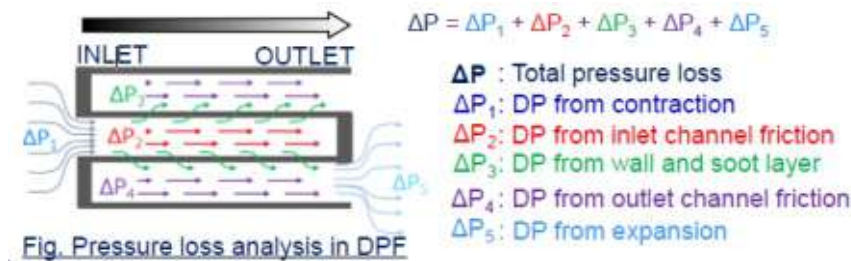
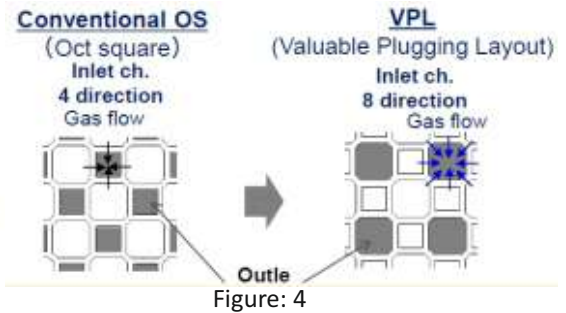


Figure: 3



where components represent contraction (ΔP_1), inlet friction (ΔP_2), wall and soot cake permeation (ΔP_3), outlet friction (ΔP_4), and expansion losses (ΔP_5). By switching from a 4-direction inlet flow (conventional octagonal-square) to an 8-direction inlet flow with enlarged outlet channels (refer fig.4), VPL increases both inlet volume and filtration area. This simultaneously reduces wall-permeation friction (ΔP_3) and outlet channel gas velocity friction (ΔP_4). It also increases the ash accumulation capacity of the substrate.

2.3 Experimental Setup

PN Filtration Testing: Benchmarked 7 mil R-SiC against commercial 7 mil and 9 mil SiC substrates over MIDC and WLTC cycles.

Durability & Ash Simulation: Evaluated pressure drop over a 200,000 km lifecycle under 340 kg/h exhaust flow at 400 °C with 6 g/L soot loading (0.1 L/1000 km oil consumption, 1.0% ash content, 350 kg/m³ ash density, bottom-channel packing accumulating 50 g ash at 200,000 km).

Drop-to-Idle (DTI) Regeneration: Evaluated coated 7 mil / 300 cpsi filters (D10.5" × L7") on a 7.2 L Euro VI diesel engine. Postinjection stabilized inlet temperature at 600 °C across soot loads of 3.0–6.0 g/L, followed by an immediate cut to idle.

3. Results and Discussion

3.1 PN Emissions under Transient Driving Conditions

Comparative speed traces show WLTC exhibits higher velocities (~130 km/h) and frequent aggressive accelerations compared to MIDC (refer fig.5). Due to its sharp pore size distribution, the 7mil R-SiC prevents soot breakthrough during aggressive high-flow transients. Competitor substrates require thicker wall dimensions (9 mil) to approach similar levels, which inherently increases initial clean backpressure (refer fig. 6).

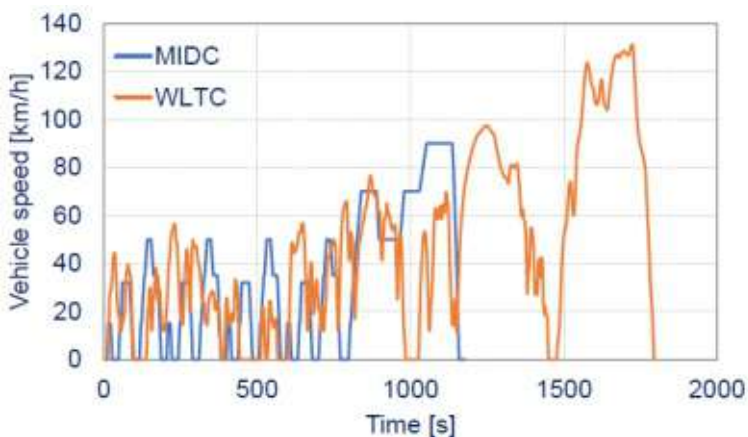


Figure: 5



Figure: 6

3.2 Pressure Loss Evolution Across Operating Lifespan

Pressure drop simulations highlight the long-term advantages of the VPL geometry over conventional cell architectures:

Baseline State (0 km): The 7/300 VPL demonstrates an initial pressure loss roughly 40% lower than conventional 7/300 configurations due to enlarged inlet volume and greater effective filtration surface.

High Mileage (160,000 to 200,000 km): In conventional designs, accumulated ash chokes the inlet volume and accelerates wall velocity, causing a steep backpressure surge.

Conversely, VPL's 8-direction inlet flow provides superior ash-storage capacity and suppresses backpressure escalation through the 200,000 km threshold, directly preventing fuel consumption penalties and supporting CAFE compliance.

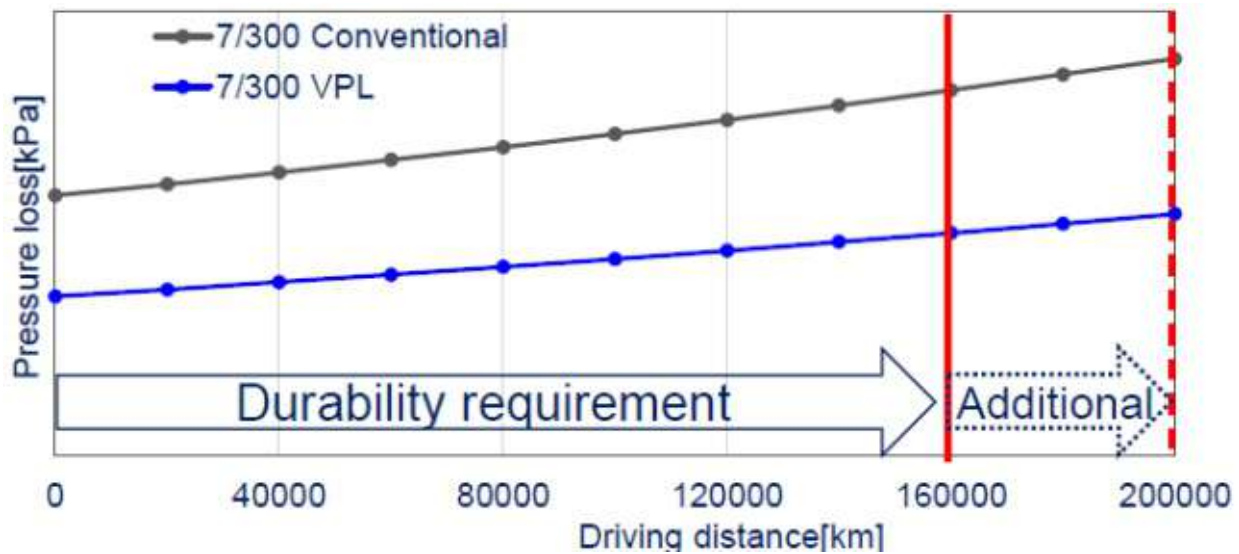


Figure: 7

3.3 Regeneration Thermal Control and Soot Mass Limit

The drop-to-idle (DTI) test simulates a sudden loss of exhaust cooling gas flow during soot burn-off. At an elevated soot pre-load of 6.0g/L, the competitor SiC substrate reached 1110 °C, whereas the R-SiC substrate suppressed peak core temperature to ~830 °C—a 280 °C difference. Maximum thermal gradients were reduced from >115 °C/cm to ~72 °C/cm (a 40 °C/cm reduction). (Refer figure 8 & 9)

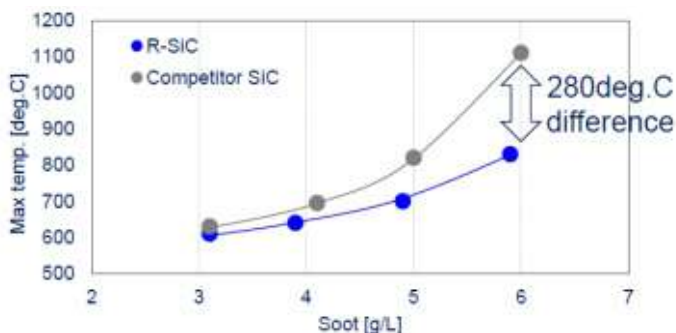


Figure: 8

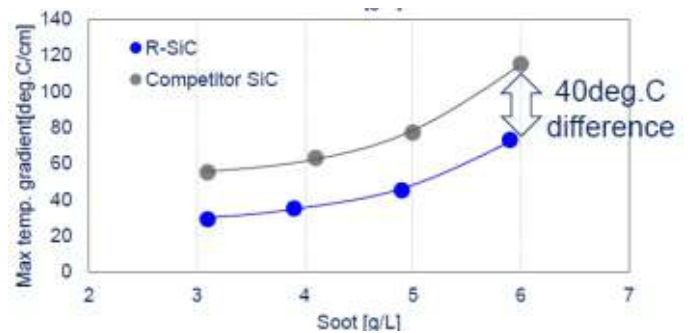


Figure: 9

The high thermal conductivity of recrystallized SiC dissipates localized heat rapidly, eliminating thermal hot spots and lowering internal ring-off stress. This provides engine calibrators with expanded soot regeneration margins under demanding urban driving conditions.

4. Conclusion

IBIDEN's optimized R-SiC DPF technology addresses the competing technical requirements posed by India's evolving emissions roadmap: High Filtration: Sharp pore size distribution guarantees sustained PN compliance across dynamic WLTC transients. Extended Durability: The VPL geometry minimizes ash-induced backpressure escalation, supporting 200,000 km durability while conserving fuel economy. Thermal Robustness: High material thermal conductivity lowers DTI peak temperatures by 280 °C, offering high soot capacity and regeneration calibration freedom for Indian light-duty commercial vehicles using in India market due to high soot capacity. DPF substrate and coating. So, collaboration activity is needed, so we would like to have good communication with OEM and supply chain.

AECC Fact Sheet

Heavy-Duty vehicles

a robust Euro 7 for a clean and competitive industry

The Automotive Omnibus risks weakening core elements of Euro 7 that would prove counterproductive for competitiveness, investment certainty, and the green transition.



SIMPLIFICATION SHOULD NOT RESULT IN DEREGULATION

The Automotive Omnibus discussions should centre on how to achieve targeted simplification to reduce red tape and improve legal clarity without undermining environmental objectives and industrial confidence. Pollutant emissions requirements have resulted in technology innovation for decades.



HEAVY-DUTY VEHICLES EURO 7 DELAY UNDERMINES COMPETITIVENESS

There are significant economic costs associated with regulatory uncertainty and potential Euro 7 delays due to underutilised engineering capacity, delayed deployment of new technologies, and existing investment obligations.



TECHNOLOGY IS AVAILABLE

As European Heavy-Duty vehicles manufacturers are global leaders, they already have engineered solutions for their models to be able to meet stricter targets that will apply as of 2027 in USA. Consequently, Euro 7 exhaust emissions controls are ready.

ROBUST EURO 7 STANDARDS ARE NEEDED FOR TECHNOLOGY-NEUTRALITY

Robust pollutant emission standards are key to ensure that all powertrains deliver on decarbonisation without compromising air quality and public health. Robust Heavy-Duty vehicles Euro 7 standards are a must to enable technology-neutrality in the upcoming review of the Heavy-Duty vehicles CO₂ emissions standards.

AECC Fact Sheet

Light-Duty Vehicles debunking myths on VEEFs⁺

Policymakers must underpin climate ambition with technology-neutrality, without compromising on air quality and public health via a robust Euro 7.

⁺Vehicle category running Exclusively on Eligible Fuels (VEEF)

Myth #1:

Zero emission at tailpipe is technology-neutral

Debunk: Tailpipe emissions only reflect the use phase. **Targeting zero tailpipe emissions neglects net-zero technologies**, which compensate tailpipe emissions elsewhere in the life cycle. A total Life Cycle Assessment (LCA) provides a more accurate perspective of vehicle emissions.



Myth #2:

Only battery and fuel cell vehicles are zero emission

Debunk: No powertrain technology results in zero emissions over the whole life cycle. **LCA data shows all technologies result in similar emission reduction when using renewable electrons/molecules.** A Vehicle category running Exclusively on Eligible Fuels (VEEF) is therefore to be added to the CO₂ emissions standard ZEV definitions.



Myth #3:

Renewable fuels are for aviation/maritime only

Debunk: Aviation and maritime cannot finance the transition of the fuel manufacturing industry alone. Refineries are multi-fuel production plants so road transport can be included to unlock required economies of scale; accelerating emissions reduction and reducing overall decarbonisation costs.



Myth #4:

VEEFs have negative impact on air quality

Debunk: VEEFs will comply with Euro 7 pollutant emissions standard. **It is therefore crucial Euro 7 is not watered down and reassessed** to allow technology-neutrality in the CO₂ emissions standard without compromising air quality and public health. Emission control technologies have already been developed for a more ambitious Euro 7 standard.



AECC CALLS ON POLICYMAKERS TO ESTABLISH A VEEF CATEGORY WHILE ENSURING A ROBUST EURO 7

The final Automotive Package will then drive a competitive, clean and technology-neutral automotive transition, contributing to both climate mitigation and clean air while offering consumers choice.



TAU POWER ELECTRONICS



Cleaner, Smarter Technology

Founded by industry veteran Ashwath Ram, Tau Power brings over 70 years of combined experience in technology and manufacturing to create high-precision sensor solutions in India. Our mission is to enable OEMs to meet global emission standards while enhancing operational efficiency through cutting-edge sensor technology.



EGTS Sensors



NOx Sensors



UQS Sensors



Delta P Sensors



Oxygen Sensors

TAU POWER ELECTRONICS PVT. LTD.



Office - 701 & 702, Aquila
Plot No. 101, Anand Park, Aundh, Pune 411007

Factory - 247/2, Phase 2, Rajiv Gandhi Infotech Park
Hinjawadi, Pune 411057

✉ info@tau-power.com

🌐 www.tau-power.com

MEXAcube

THE EVOLUTION OF INFRARED GAS ANALYSIS TECHNOLOGY



"MEXAcube" our new automotive exhaust emission measurement analyzer. Built using HORIBA's cutting-edge IRLAM™ technology, this analyzer provides unparalleled accuracy and reliability, addressing modern emission measurement challenges with precision. "MEXAcube utilizes HORIBA's breakthrough IRLAM™ (**InfraRed Laser Absorption Modulation**) technology, which sets a new standard for emission measurement by leveraging three core components: the **QCL-IR laser**, the **Herriot Cell**, and an innovative **Concentration Calculation Algorithm**." It is also equipped to **test Alternative fuels**, including **Hydrogen** engines, supporting the path toward decarbonization.

Key Features

- A wide range of applications, from laboratory testing to on-road testing, while maintaining measurement accuracy as good as a MEXA.
- 87% reduction in power consumption and an 86% decrease in volume compared to conventional MEXAs. A 50% reduction in the number of cables, which simplifies installation. Offers exceptional lifetime value by eliminating the need for external utilities.
- High water vapor application to support decarbonized fuels.

Technical Features

- QCL-IR Laser
- Herriot Cell
- Concentration Calculation Algorithm

Specification

- NEW COMPACT can analyze multi-component gases, including CO₂, CO, NO, NO₂, N₂O, HCHO, NH₃, CH₄, and THC(FID), with precision.

Advancing Emission Measurement and Control through IRLAM Technology

HORIBA

ABSTRACT

The automotive industry is undergoing a transformative shift toward carbon neutrality, driven by stringent emission regulations such as Euro 7 and China 7. These regulations demand high-precision, real-time measurement of multiple gaseous pollutants, including emerging components like NH_3 , N_2O , and HCHO . Traditional infrared gas analyzers face limitations in sensitivity, selectivity, and portability, especially under real-world driving conditions.

To address these challenges, HORIBA has developed a next-generation gas analysis technology—Infrared Laser Absorption Modulation (IRLAM™)—which integrates a proprietary Quantum Cascade Laser (QCL), a compact Herriott Cell, and a patented Concentration Calculation Algorithm. This paper presents the application of IRLAM in MEXAcube, a compact, portable emissions measurement system capable of simultaneously analyzing nine critical components in both laboratory and real-world environments.

1. INTRODUCTION

The global automotive sector is rapidly evolving to meet the dual imperatives of sustainability and regulatory compliance. With the introduction of flex fuels (E20, E85, Methanol, Biofuels) and the tightening of emission norms under Euro 7, China 7, and India's BS-VI, the need for advanced emission measurement technologies has become more critical than ever.

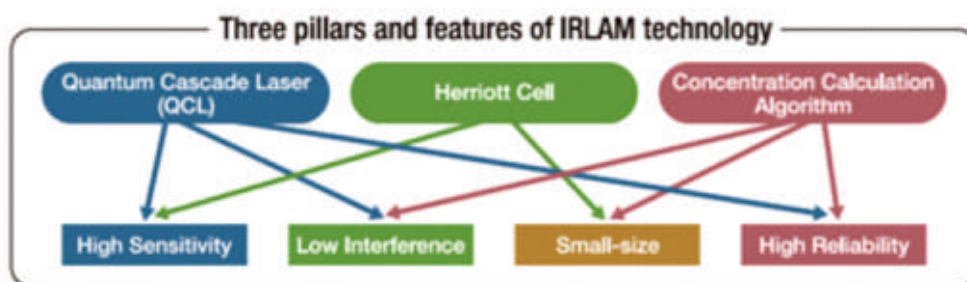
Traditional gas analyzers, such as NDIR and FTIR, while effective in controlled environments, often struggle with interference effects, low sensitivity, and bulky configurations that limit their applicability in real driving emissions (RDE) testing. Moreover, the increasing focus on unregulated pollutants like ammonia (NH_3), nitrous oxide (N_2O), and formaldehyde (HCHO) necessitates a paradigm shift in gas analysis technology.

In response, HORIBA has developed IRLAM™, a proprietary infrared laser-based technology that overcomes the limitations of conventional systems. IRLAM is built on three core innovations:

- Quantum Cascade Laser (QCL): A narrow-band, tunable laser source optimized for gas-specific absorption.
- Herriott Cell: A compact, multi-pass gas cell enabling long optical paths in a small volume.
- Concentration Calculation Algorithm: A patented, feature-based method that reduces computational load while maintaining high accuracy.

These technologies are integrated into MEXAcube, a compact emissions measurement system designed for both laboratory and on-road applications. MEXAcube supports the measurement of CO , CO_2 , NO , NO_2 , N_2O , NH_3 , HCHO , CH_4 , and THC , making it a versatile tool for current and future regulatory needs.

This paper explores the design, performance, and application of MEXAcube, demonstrating how IRLAM technology is paving the way for safe and sustainable mobility.



* IRLAM is a registered trademark or trademark of HORIBA, Ltd. in Japan and other countries.

Figure 1.: Three Pillars of IRLAM technology

2. IRLAM TECHNOLOGY OVERVIEW

Emission measurement using infrared spectroscopy has long been a cornerstone of automotive testing. However, conventional methods such as NDIR and FTIR face limitations in sensitivity, selectivity, and computational efficiency—especially when measuring trace gases in complex mixtures. HORIBA's Infrared Laser Absorption Modulation (IRLAM™) technology represents a significant advancement in this domain, offering high sensitivity, low interference, and compact design.

2.1 Quantum Cascade Laser (QCL)

At the heart of IRLAM is a Quantum Cascade Laser (QCL), a semiconductor laser source that emits light in the mid-infrared region (4–10 μm)—where many gases exhibit strong absorption characteristics. Unlike broadband sources, QCLs offer narrow-band, tunable emission, allowing precise targeting of absorption wavelengths specific to the gas of interest while avoiding interference from coexisting gases.

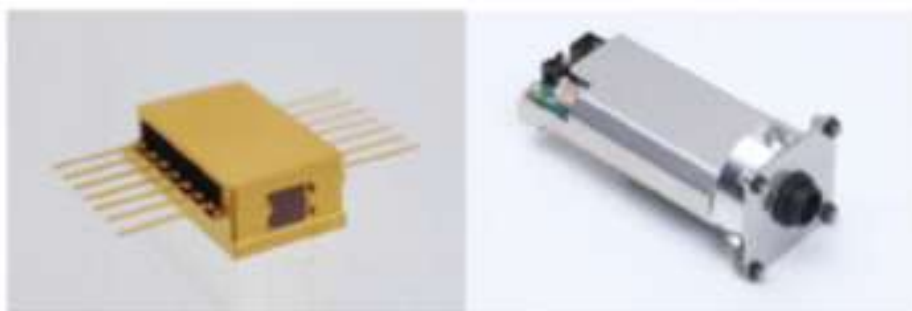


Figure 2.: QCL Element (left), QCL Module (Right)

2.2 Herriott Cell – Compact Multi-Pass Gas Cell

To enhance sensitivity, IRLAM employs a Herriott Cell, a compact multi-pass gas cell designed with two concave mirrors. This configuration allows the infrared beam to reflect multiple times, achieving an optical path length of over 5 meters within a gas volume of just 50 mL.

This design not only improves detection limits but also ensures fast response times, even at low gas flow rates. The cell's robust construction makes it suitable for portable and vibration-prone environments, such as RDE testing.

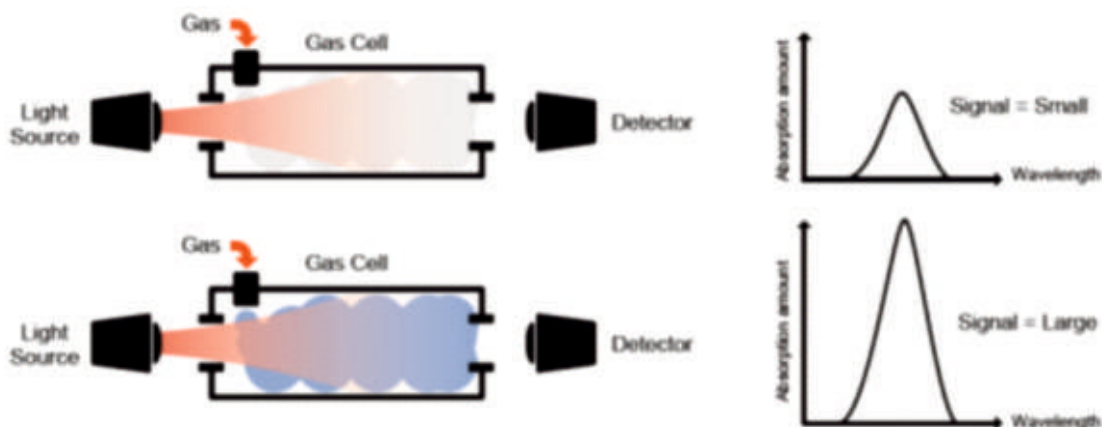


Figure 3.: Relationship between optical path length and signal magnitude

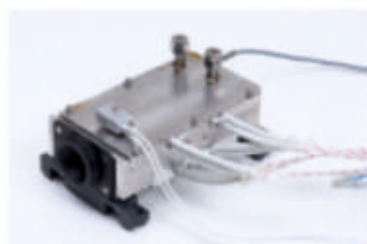


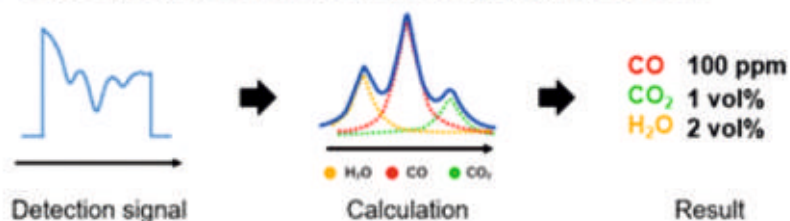
Figure 4.: Appearance of the Herriott cell

2.3 Concentration Calculation Algorithm

Traditional infrared analyzers rely on spectral fitting—a computationally intensive method requiring high-performance processors. IRLAM introduces a feature-based concentration calculation algorithm, which extracts key signal features and converts them into abstract numerical values called feature quantities. These are then compared with pre-measured reference features to determine gas concentrations.

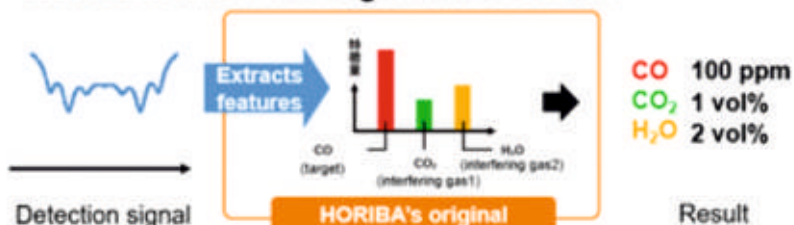
This approach reduces the computational load dramatically, enabling real-time analysis using embedded microcontrollers, without compromising accuracy.

● Conventional conc. calculation algorithm for QCL



The calculation, which use spectral fitting, takes time so requires high performance computer.

● New conc. calculation algorithm for IRLAM



Feature-based approach can use only a few numerical values, thus significantly reducing the amount of calculations.

Figure 5.: Appearance of the Herriott cell

2.4 Environmental Robustness and Reliability

IRLAM analyzers are engineered to withstand temperature fluctuations, pressure variations, and mechanical vibrations. Extensive testing under diverse environmental conditions ensures that the analyzers maintain $\pm 2\%$ accuracy over extended periods and across challenging operating environments.

Table 1: Performance Comparison – Conventional vs IRLAM Technology

Parameter	Conventional IR	IRLAM Technology
Sensitivity	Moderate	High
Interference Resistance	Low	High
Computational Load	High	Low
Portability	Limited	Compact
Environmental Stability	Moderate	Robust

3. MEXAcube SYSTEM DESIGN

The MEXAcube is latest compact emissions measurement system, designed to meet the evolving demands of both laboratory testing and real driving emissions (RDE). It integrates the full capabilities of IRLAM™ technology into a single, portable unit capable of measuring nine critical gas components: CO, CO₂, NO, NO₂, N₂O, NH₃, HCHO, CH₄, and THC.



Figure 6.: HORIBA MEXAcube

3.1 Design Philosophy and Objectives

The development of MEXAcube was guided by three core principles:

- Ease of Use: Simplified setup, reduced cabling, and intuitive operation.
- Reliable Testing: High correlation with conventional lab analyzers and robust performance under variable conditions.
- Support for Carbon Neutrality: Compatibility with alternative fuels and readiness for future emission regulations.

3.2 Integrated IRLAM Architecture

MEXAcube incorporates all three pillars of IRLAM technology:

- QCL Laser Source: Tunable mid-infrared laser for selective gas detection.
- Herriott Cell: Multi-pass optical cell with a 5-meter path length in just 50 mL volume.
- Feature-Based Algorithm: Enables real-time concentration calculation using embedded microcontrollers.

This integration allows MEXAcube to deliver high sensitivity, low interference, and fast response times in a compact form factor.

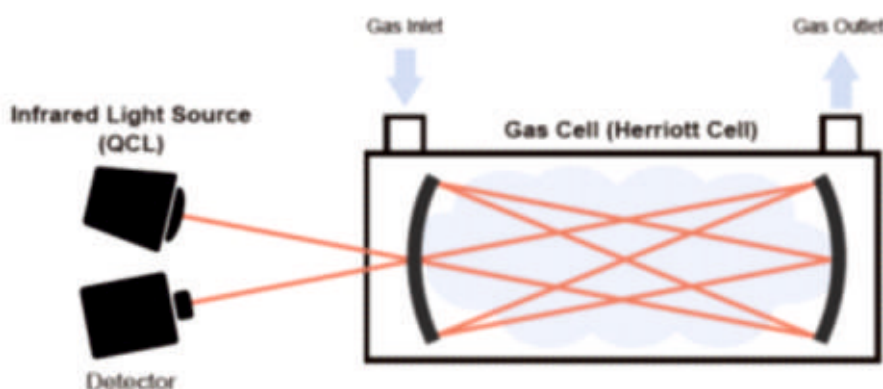


Figure 7: Basic configuration of the optical system of MEXAcube

3.3 Measurement Capabilities

MEXAcube supports simultaneous measurement of the following components:

Table 2: MEXAcube Component Measurement Overview

Component	Measurement Principle	Range
CO	IRLAM (QCL-IR)	0–8000 ppm / 0–12 vol%
CO ₂	IRLAM (QCL-IR)	0–20 vol%
NO	IRLAM (QCL-IR)	0–2000 ppm
NO ₂	IRLAM (QCL-IR)	0–800 ppm
N ₂ O	IRLAM (QCL-IR)	0–1000 ppm
NH ₃	IRLAM (QCL-IR)	0–1500 ppm
HCHO	IRLAM (QCL-IR)	0–50 ppm
CH ₄	IRLAM (QCL-IR)	0–2000 / 0–10000 ppm
THC	FID	0–10000 ppm

3.4 Compact and Portable Configuration

Compared to previous systems (e.g., MEXA-ONE), MEXAcube offers:

- 80% reduction in power consumption
- 86% reduction in volume
- 50% fewer cables and pipes

This makes it ideal for RDE testing, engine development, and certification workflows.

3.5 Environmental and Operational Robustness

MEXAcube is designed to operate reliably under:

- Temperature range: -10°C to 45°C
- Altitude: Up to 3000 m
- Humidity: $\leq 80\%$ RH
- Vibration: Tolerant up to 2G

3.6 Regulatory Readiness

MEXAcube is fully equipped to meet the requirements of Euro 7 and China 7, including:

- PN10, NH_3 , N_2O , CH_4 , HCHO, and NMOG
- Real-time RDE testing
- Support for alternative fuels (H_2 , biofuels)

Table: MEXAcube Compliance with Future Emission Regulations

Regulation	Components Covered	RDE Ready	Fuel Compatibility
Euro 7	CO, NOx, NH_3 , N_2O , CH_4 , HCHO	Yes	Yes
China 7	CO, NOx, NH_3 , N_2O , THC, HCHO	Yes	Yes

4. PERFORMANCE EVALUATION

To validate the effectiveness of IRLAM technology and the MEXAcube system, a series of performance evaluations were conducted. These included long-term stability tests, response time comparisons, and correlation studies with conventional laboratory analyzers.

4.1 Improved Robustness

The below graphs show the results of temperature, air pressure and vibration tests, which are within 2% of the reading scale from -10°C to 45°C and from 100 to 70 kPa, and stable even when subjected to 5 G vibration.

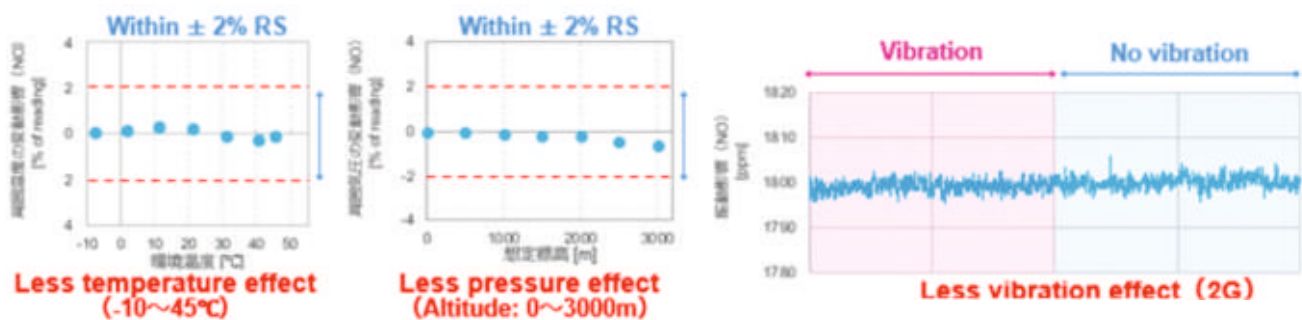


Figure 8: MEXAcube Robustness against temperature, pressure, and vibrations

4.2 Correlation with Laboratory Analyzers

To assess measurement accuracy, MEXAcube was benchmarked against HORIBA's established laboratory analyzers (NDIR, CLD, and IRLAM-based systems). The results showed high correlation coefficients ($R^2 > 0.96$) across key components including CO, NO, NH₃, and CH₄.

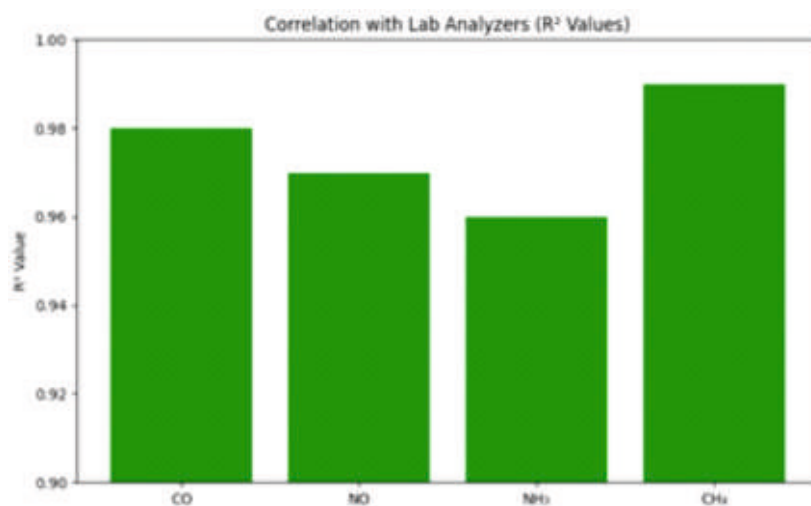


Figure 9: MEXAcube correlation with lab analyzers (R² Values)

5. CONTRIBUTION TO CARBON NEUTRALITY AND FUTURE MOBILITY

Achieving carbon neutrality (CN) in the automotive sector requires a multi-pronged approach that goes beyond electrification. Technologies that support alternative fuels, low-emission combustion, and real-time emissions monitoring are essential to accelerate the transition to sustainable mobility. MEXAcube, powered by IRLAM technology, is designed to support this transformation.

5.1 Enabling Measurement for CN Fuels

As the industry shifts toward hydrogen, biofuels, and e-fuels, emission analyzers must adapt to measure low-concentration and unregulated components. MEXAcube is capable of detecting trace levels of:

- NH₃: Common in hydrogen combustion and SCR systems
- N₂O: A potent greenhouse gas from combustion and after-treatment
- HCHO: Emitted during cold starts and from alcohol-based fuels

These capabilities make MEXAcube suitable for next-generation engine development and fuel validation.

6. CONCLUSION AND FUTURE SCOPE

The development and deployment of IRLAM™ technology and the MEXAcube emissions measurement system mark a significant advancement in the field of automotive emission control. By addressing the limitations of conventional infrared analyzers, IRLAM enables high-sensitivity, low-interference, and real-time gas analysis in both laboratory and real-world environments.

MEXAcube, as a compact and versatile platform, integrates these capabilities into a single unit capable of measuring nine critical components, including emerging pollutants such as NH₃, N₂O, and HCHO. Its performance has been validated through long-term stability tests, rapid response benchmarks, and high correlation with established laboratory systems.

The system's readiness for Euro 7, China 7, and alternative fuel testing positions it as a future-proof solution for OEMs, research institutions, and regulatory bodies. Furthermore, its contribution to carbon neutrality—through reduced operational footprint and support for CN fuels—aligns with the global push toward sustainable mobility.

Future Scope

- Integration with PN10 and PM modules for complete RDE compliance.
- Expansion into hydrogen and e-fuel engine platforms.

Integrated Design of an E20-Optimized SI Engine: Combustion, Fuel System, Thermal Management and Control

Dr Sarmistha Nandy

Consultant- Energy Transition & Industrial Decarbonization; India, UAE

Abstract

India has reached an average ethanol blending level of approximately 20% in petrol during ESY 2025–26, making E20 operation a practical design condition for the national spark-ignition vehicle fleet. Rather than treating ethanol blending only as a compatibility problem for existing engines, this paper proposes an integrated engine architecture in which ethanol-related fuel properties are considered at the design stage. A conceptual 1.5-L four-cylinder spark-ignition engine is proposed with a higher-efficiency combustion system, high-pressure fuel injection, validated ethanol-compatible materials, optimized thermal management, wideband lambda feedback, fuel-composition estimation and adaptive engine calibration. A 3D CAD-oriented architecture is presented together with an analytical assessment of stoichiometric air-fuel ratio and volumetric energy density. The manuscript defines a simulation and validation programme covering 1-D engine modelling, 3-D computational fluid dynamics, thermal/structural analysis, engine dynamometer testing, emissions evaluation and durability testing. The proposed design is not presented as an experimentally validated engine; instead, it establishes a reproducible engineering framework for developing an E20-oriented four-wheeler powertrain while retaining the ability to operate with lower ethanol blends.

Keywords: E20; ethanol-blended petrol; spark-ignition engine; four-wheeler; 3D CAD; combustion chamber; GDI; adaptive ECU; thermal management; emission control.

Research integrity statement

All numerical performance values identified as targets or analytical illustrations are not claimed as experimental results. Validation is proposed through simulation and controlled engine testing.

1. Introduction

India's Ethanol Blended Petrol (EBP) programme has progressively increased ethanol use in petrol. Government data indicate average blending of approximately 12% in ESY 2022–23, 14.6% in ESY 2023–24, about 19.2% in ESY 2024–25 and 20% during the reported period of ESY 2025–26. As of July 2026, the Government has stated that no decision has been taken to increase the nationwide base blending level beyond E20, while higher blends such as E85 are reserved for certified flex-fuel vehicles. [1]

The technical question has therefore moved beyond whether ethanol can be blended with petrol. It is increasingly a question of how spark-ignition engines can be designed and calibrated so that E20's lower volumetric energy content, oxygenated chemistry, high octane quality and charge-cooling effect are accommodated without compromising drivability, durability, fuel economy or emission-control performance.

The Automotive Research Association of India (ARAI) has identified E20 assessment of in-use BS III, BS IV and BS VI two- and four-wheelers as a research area covering tailpipe emissions, fuel economy, durability and material compatibility. [2] This provides a strong basis for investigating not only the compatibility of existing engines but also the architecture of future E20-oriented engines.

Recent Indian engineering work has also demonstrated the continuing relevance of dedicated ethanol-oriented engine development. A 2026 SAE technical paper describes modification of a 1.2-L naturally aspirated engine for E20–E100 flex-fuel operation, including fuel-contact material upgrades, compression-ratio optimization, heated fuel rail, intake-camshaft changes and blend-specific EMS calibration. [3] The present proposal therefore focuses on a different research contribution: an integrated E20-oriented four-wheeler engine architecture in which combustion, fuel delivery, thermal management, sensing, control and after-treatment are developed as one system.

2. Research Gap

A substantial body of literature examines ethanol-gasoline blends through engine tests, fuel-property analysis and reviews of combustion performance. Research has reported the influence of ethanol on air-fuel ratio, cylinder pressure, thermal efficiency, heat release, octane quality and vehicle fuel economy. [4,5] However, many studies evaluate individual fuel or calibration parameters rather than proposing an integrated architecture that connects the ethanol fuel property to hardware selection, combustion geometry, thermal management, adaptive control and emission after-treatment.

The research gap addressed in this paper is therefore the development of a transparent design framework for a four-wheeler engine in which E20 is treated as a primary design condition. The contribution is conceptual and methodological: it defines the architecture, preliminary design targets, modelling strategy, validation matrix and control logic required to convert the concept into a validated prototype.

3. Objectives

- Develop a preliminary 3D architecture for an E20-oriented four-cylinder spark-ignition engine.
- Use ethanol's octane and charge-cooling characteristics as design inputs rather than treating them only as constraints.
- Reduce the fuel-economy penalty associated with ethanol's lower volumetric energy density through combustion and control optimization.
- Provide a fuel system and material strategy suitable for long-term E20 exposure.
- Develop adaptive fuel, ignition, lambda and thermal-control logic for variable ethanol concentration.
- Maintain emission-control performance through precise lambda control, close-coupled three-way catalysis and EVAP management.
- Define a reproducible CFD, 1-D simulation, dynamometer and durability validation programme.

4. Proposed Engine Architecture

A 1.5-L four-cylinder, four-stroke spark-ignition engine is selected as a representative passenger-car platform. The proposed architecture is deliberately specified as a design envelope rather than a fixed production specification; bore, stroke, compression ratio, injection pressure and valve timing would be optimized after 1-D and 3-D simulation.

Parameter	Preliminary design proposal
Engine configuration	4-cylinder, 4-stroke SI
Displacement	Approximately 1.5 L
Fuel capability	E0–E20; optional flex-fuel extension
Compression ratio	11.5:1–12.0:1 design range; to be validated for knock margin
Valvetrain	DOHC, 16 valves, variable valve timing
Fuel system	High-pressure gasoline direct injection (GDI)
Ignition	Coil-on-plug
Control	Wideband lambda + knock + pressure/temperature sensing
Thermal management	Liquid cooling + piston oil jets + catalyst thermal strategy
After-treatment	Close-coupled three-way catalyst
Emission target	BS-VI-compliant development pathway

5. 3D Engine Design Proposal

The proposed 3D architecture integrates the cylinder head, intake system, fuel rail, injectors, combustion chamber, cooling jacket, manifold exhaust, catalyst interface and accessory drive into a single package. The 3D model is intended to support packaging, CFD mesh generation, component accessibility, thermal analysis and subsequent prototype development.



Figure 1. Conceptual 3D CAD-oriented engine architecture. The image is a design visualization and not a production-certified CAD drawing.



Figure 2. Conceptual integration of the proposed E20-optimized engine within a four-wheeler powertrain architecture.

The vehicle-level layout illustrates the integration of the engine with the fuel, cooling, exhaust and drivetrain systems, providing a basis for subsequent packaging and prototype development.

5.1 Key 3D sub-systems

- Cylinder head: centrally located spark plug, optimized intake/exhaust port geometry and variable valve timing capability.
- Combustion chamber: compact chamber with controlled tumble to improve mixture preparation and flame propagation.
- Fuel system: high-pressure rail and multi-hole GDI injectors positioned to reduce wall wetting.
- Cooling system: water jacket geometry designed for uniform head and cylinder temperature distribution.
- Piston assembly: E20-oriented crown geometry with oil-jet cooling provision and adequate knock/thermal margin.
- Exhaust system: short-path manifold and close-coupled catalyst to reduce catalyst light-off time.

5.2 In-Cylinder Flow and Combustion Design

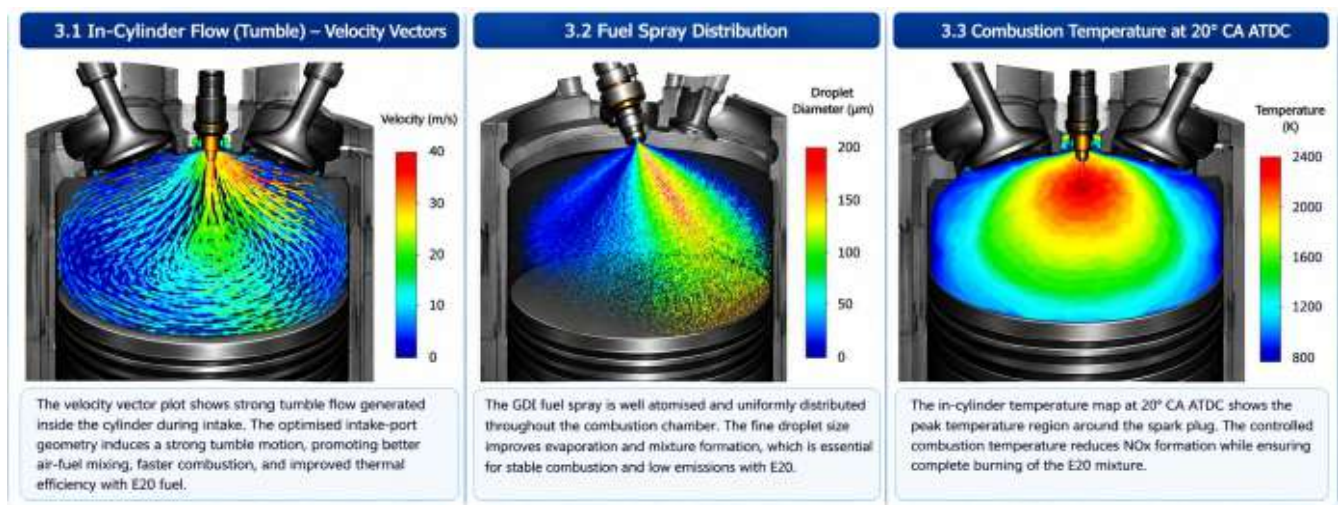


Figure 3. Conceptual in-cylinder flow, fuel-spray and combustion-temperature fields for the proposed E20 engine.

The proposed combustion chamber is designed to promote controlled tumble motion and improved fuel-air mixing. The injector arrangement is intended to minimize wall wetting and support more uniform mixture preparation. The conceptual temperature field illustrates the intended control of high-temperature regions during E20 combustion.

5.3 Piston Thermal-Management Design

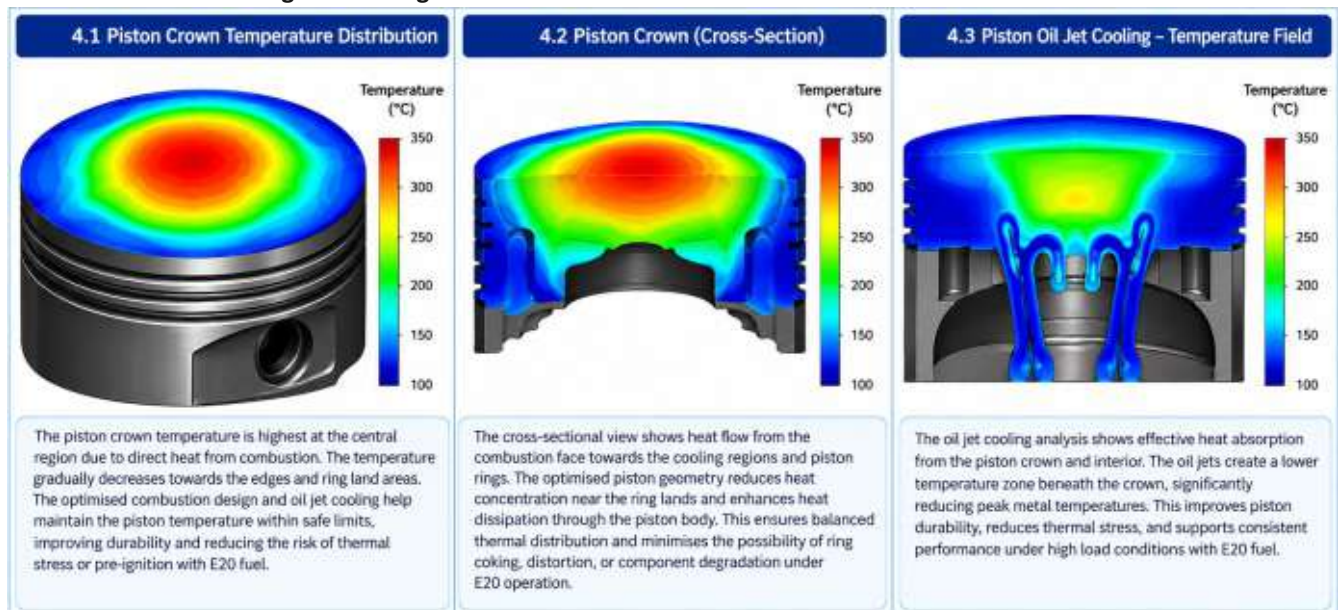


Figure 4. Proposed piston geometry and thermal-management arrangement with oil-jet cooling provision.

The proposed piston incorporates an E20-oriented crown geometry with provision for underside oil-jet cooling. The design aims to improve heat removal from the piston crown and reduce local thermal loading during high-load operation, thereby supporting piston and ring durability.

5.4 Cylinder-Head Thermal-Management Design

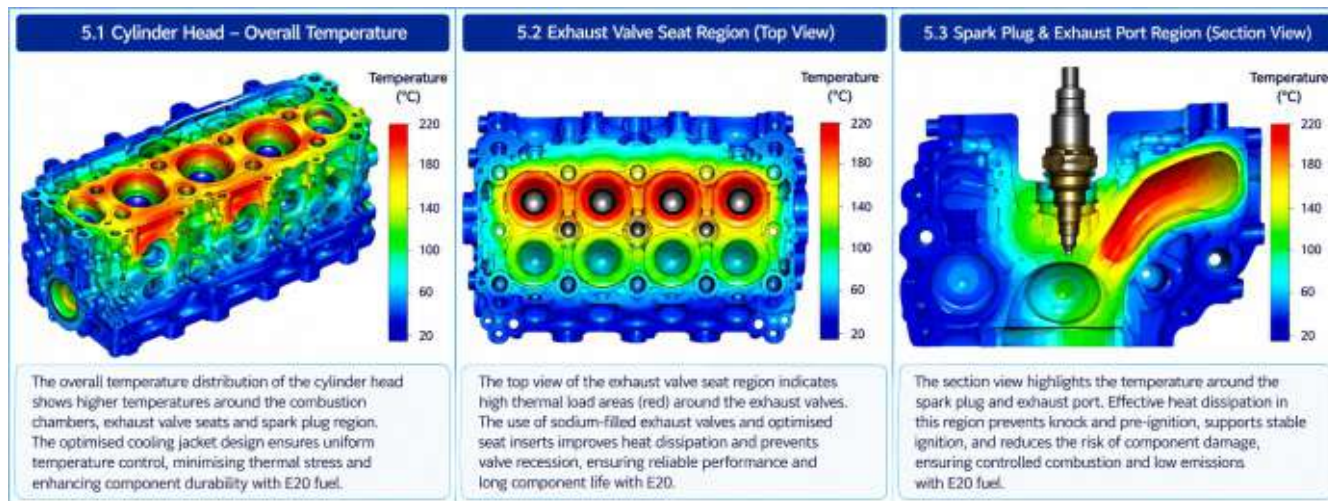


Figure 5. Conceptual cylinder-head thermal-management arrangement showing heat concentration around the combustion chamber and exhaust-valve region.

The cylinder-head design incorporates optimized cooling passages around the combustion chamber, spark-plug region and exhaust-valve zones. The objective is to achieve a more uniform temperature distribution and limit localized thermal loading while maintaining the temperature conditions required for stable combustion and effective emission control.

6. E20-Oriented Combustion Design

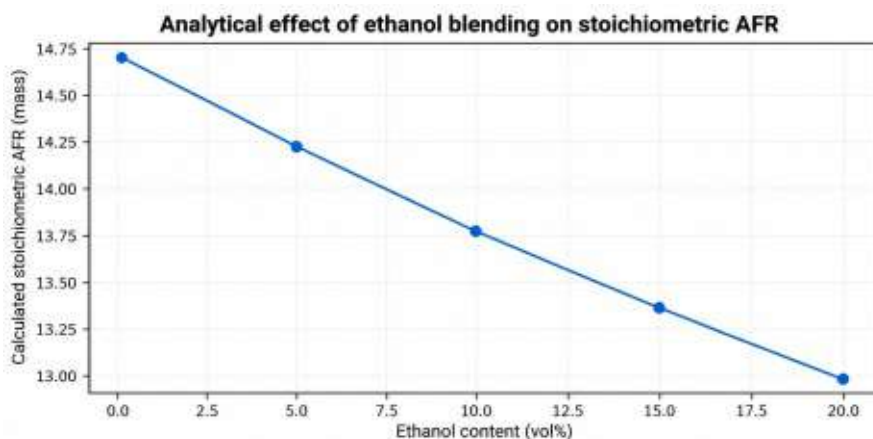
Ethanol has a higher-octane quality than conventional gasoline and a substantial latent heat of vaporisation. These characteristics can support higher knock resistance and charge cooling, creating an opportunity for efficiency improvement if the engine is calibrated to exploit them. At the same time, ethanol has a lower lower-heating value, which increases the fuel quantity required for a given energy output. [5]

6.1 Stoichiometric analysis

Using iso-octane as an idealized gasoline surrogate: $2\text{C}_8\text{H}_{18} + 25\text{O}_2 \rightarrow 16\text{CO}_2 + 18\text{H}_2\text{O}$

For ethanol: $\text{C}_2\text{H}_5\text{OH} + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 3\text{H}_2\text{O}$

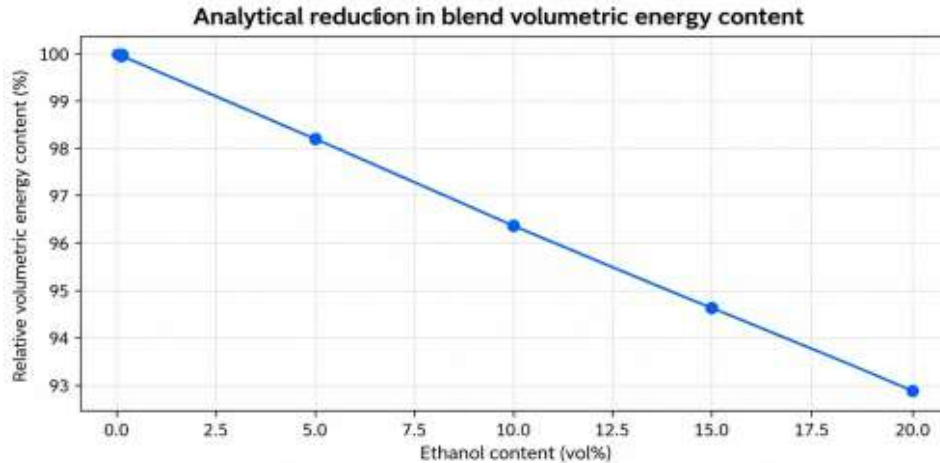
Because ethanol contains chemically bound oxygen, its stoichiometric air requirement is lower than that of a hydrocarbon gasoline surrogate. The exact AFR of a commercial E20 fuel depends on the base gasoline composition, density and fuel specification.



Graph 1. Analytical stoichiometric AFR trend. Assumptions: gasoline AFR 14.7:1, ethanol AFR 9.0:1, densities 0.745 and 0.789 kg/L. The figure is a modelled illustration, not an experimental result.

6.2 Energy-density consideration

The lower heating value of ethanol is substantially lower than that of gasoline on a mass basis and its volumetric energy density is also lower. A design that seeks to minimize the resulting fuel-economy penalty should therefore improve thermal efficiency and exploit ethanol's knock resistance rather than relying only on increased fuel delivery.



Graph 2. Analytical relative volumetric energy content of gasoline-ethanol blends. Representative values of 32.8 MJ/L for gasoline and 21.1 MJ/L for ethanol are used only for design illustration.

7. Fuel-System and Material Design

The fuel system is designed around high-pressure direct injections with multi-hole injectors, a high-pressure pump and ethanol-compatible wet materials. Material selection should be based on fuel-specific ageing tests rather than assuming a single polymer or elastomer is universally optimal.

- Validate injector seals, O-rings, hoses, pump seals and tank interfaces against E20 exposure and temperature cycling.
- Characterize mass change, swelling, hardness, tensile strength and leakage after accelerated ageing.
- Use fuel-pressure feedback to identify injector/pump degradation before drivability symptoms become severe.
- Control fuel-system water contamination through fuel-quality specifications and storage/handling practices.
- Design the rail and injector arrangement to minimize wall wetting and cold-start instability.

8. Adaptive Engine Control Strategy

The control system should estimate ethanol concentration using a dedicated fuel-composition sensor, model-based estimation from lambda/fuel trims, or a validated combination of available signals. The estimated fuel composition is then used to select or interpolate injection, ignition, valve-timing and cold-start strategies.

- Wideband lambda feedback for closed-loop mixture control.
- Knock sensing for ignition advance adaptation.
- Fuel-pressure sensing for injector and pump diagnostics.
- Coolant and intake-air temperature inputs for cold-start and transient calibration.
- Variable valve timing for load-dependent breathing and internal EGR control.
- Diagnostic limits for fuel-trim, misfire and catalyst-efficiency monitoring.

Proposed adaptive E20 engine control architecture

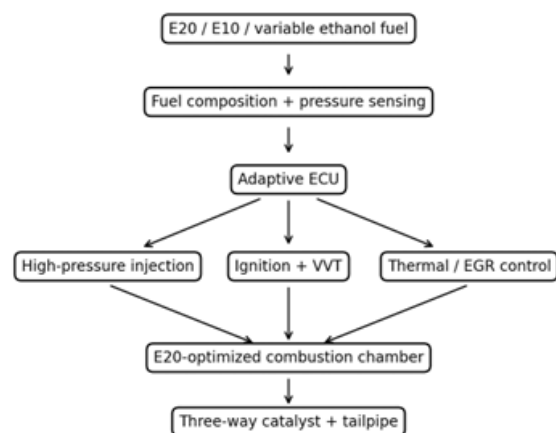


Figure 6. Proposed adaptive control architecture for E20-oriented engine operation.

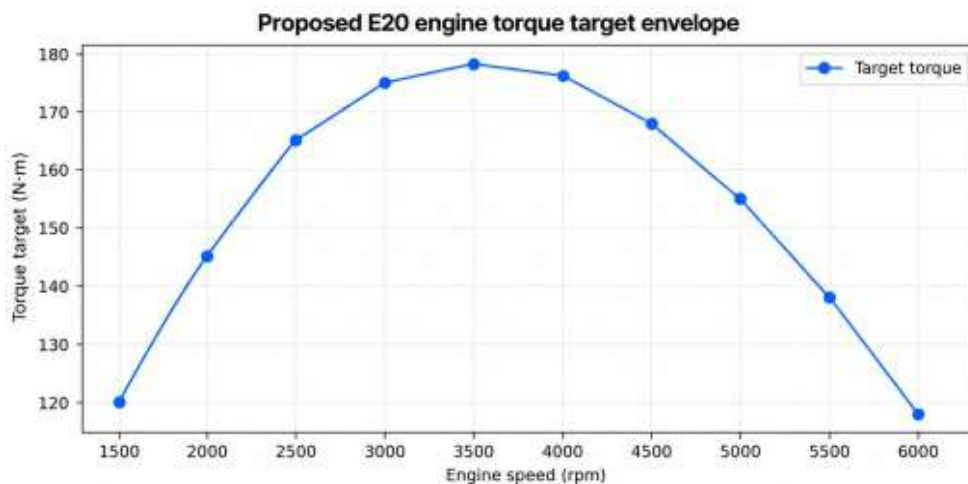
9. Thermal Management

Ethanol's charge-cooling effect can improve knock resistance, but cold-start vaporisation and catalyst light-off remain important. The proposed design therefore treats thermal management as an integrated subsystem.

- Optimized cylinder-head coolant passages to control local temperature gradients.
- Piston oil jets manage crown temperature at high load.
- Rapid catalyst warm-up strategy during cold start.
- Thermostat and coolant-flow control to reduce unnecessary thermal losses.
- Optional cooled EGR for part-load efficiency and NO_x control, subject to calibration.

10. Proposed Engine Performance Envelope

The following torque curve is a preliminary engineering target for a 1.5-L naturally aspirated passenger-car engine. It is not a measured or simulated result. The final curve must be generated from 1-D and 3-D modelling and subsequently verified on an engine dynamometer.



Graph 3. Preliminary torque target envelope for the proposed E20-oriented engine. Target values are illustrative design inputs only.

11. CFD and 1-D Simulation Methodology

The proposed design should be evaluated through coupled 1-D and 3-D modelling before hardware manufacture. 1-D simulation can establish the operating envelope and valve/fueling requirements, while 3-D CFD can resolve in-cylinder mixture formation and combustion behaviour.

- 1-D model: GT-Power, AVL BOOST, Ricardo WAVE or equivalent for air-path, combustion, friction, fuel consumption and performance prediction.
- 3-D CFD: CONVERGE, ANSYS Fluent, AVL FIRE or equivalent for intake tumble, spray penetration, mixture distribution and combustion.
- Thermal/structural FEA: cylinder head, piston crown, valves and exhaust manifold temperature/stress evaluation.
- Control model: hardware-in-the-loop or software-in-the-loop testing of ethanol estimation and adaptive calibration.
- Emission model: CO, HC and NO_x prediction followed by after-treatment modelling.

Primary CFD variables:

Parameter	Design variable	Performance indicator
Combustion chamber	Bowl geometry, plug position	Flame travel / burn duration
Intake port	Port angle and runner geometry	Tumble ratio
Injector	Hole count, spray angle, timing	Wall wetting / mixture uniformity
Ignition	Spark timing	CA50 / knock tendency
Compression ratio	11.5–12.0 design range	BTE / knock margin
EGR	Rate and temperature	NO _x / efficiency

12. Emission-Control Strategy

The engine should be designed as an emission-control system rather than treating the catalyst as a downstream add-on. Precise lambda control is central to three-way catalyst conversion. The proposed architecture therefore combines wideband oxygen sensing, close-coupled three-way catalysis, catalyst temperature monitoring, controlled EGR and EVAP management.

- Close-coupled three-way catalyst for rapid light-off.
- Wideband lambda sensor upstream of the catalyst.
- Downstream oxygen sensing for catalyst monitoring.
- EVAP canister and purge control designed for the selected fuel-vapour characteristics.
- Misfire detection to protect the catalyst from excessive unburned fuel loading.
- OBD-compliant diagnostic logic for fuel-trim, lambda and catalyst performance.

ARAI's current in-service framework highlights the importance of considering differences in fuels, ambient conditions, road speeds and urban/highway driving split when assessing real-world vehicle performance. [6] These factors should therefore be included in the validation programme for the proposed engine.

13. Validation and Experimental Program

Subsystem	Design Variable	Primary Validation
Combustion	CR, Chamber, Tumble	CFD + dyno
Fuel	Rail pressure, injector	Flow + durability
Thermal	Coolant passages, piston jets	FEA + thermal test
Control	Lambda, Ignition, Ethanol Estima	HIL + dyno
Emissions	Catalyst, EGR, EVAR	BS-VI test protocol
Durability	Materials + sealing	Accelerated ageing

Proposed design-verification matrix for the E20-oriented engine.

Stage 1 – material and component screening under controlled E0/E10/E20 exposure.

Stage 2 – 1-D engine simulation and calibration optimization.

Stage 3 – 3-D CFD of intake, spray, combustion and thermal fields.

Stage 4 – single-cylinder or full-engine bench validation.

Stage 5 – dynamometer testing over steady-state and transient operating points.

Stage 6 – emission testing using applicable Indian certification procedures.

Stage 7 – accelerated durability and field validation under representative Indian ambient conditions.

14. Problem–Solution Matrix

E20-related design issue	Engineering mechanism	Proposed design response	Validation
Lower volumetric energy	Greater fuel quantity for equal energy	Higher efficiency + optimized combustion	BSFC / BTE testing
Higher octane quality	Greater knock resistance potential	Validated higher CR + ignition optimization	Knock/combustion analysis
Charge cooling	Lower charge temperature	Combustion-chamber and ignition optimization	CFD + dyno
Fuel composition variation	Stoichiometric AFR changes	Fuel sensing + adaptive lambda control	HIL + dyno
Cold-start behaviour	Fuel vaporisation/calibration sensitivity	Dedicated cold-start strategy	Cold-start emissions
Material exposure	Fuel-system ageing	Validated fuel-contact materials	Accelerated ageing
Emission control	Lambda/catalyst sensitivity	Wideband lambda + TWC + OBD	Emission certification test

15. Expected Engineering Outcomes

The proposed architecture is expected to provide a basis for reducing the practical fuel-economy penalty associated with E20 through improved thermal efficiency and use of ethanol's knock resistance. It is also intended to reduce the need for reactive retrofit interventions by incorporating fuel compatibility, adaptive control and emission-control requirements at the design stage.

- Targeted improvement in thermal efficiency relative to a conventional gasoline engine of comparable architecture.
- Stable lambda control across E0–E20 operation.
- Improved knock margin through combustion and calibration optimization.
- Controlled cold-start and transient operation.
- Validated durability of fuel-contact components.
- BS-VI-oriented emission-control performance after calibration and testing.

These are development objectives rather than experimentally demonstrated outcomes. Quantitative claims should be added only after the proposed simulation, and testing program has produced reproducible data.

16. Manufacturing and Cost Considerations

For production feasibility, the proposed architecture should prioritize components already common to modern passenger-car engines: aluminum cylinder heads and blocks, high-pressure GDI systems, variable valve timing, wideband oxygen sensing and close-coupled three-way catalysis. The principal incremental development effort is expected to be concentrated in calibration, fuel-composition estimation, material validation, combustion optimization and thermal management rather than in entirely new engine hardware.

A modular approach could allow an existing four-cylinder engine family to adopt E20-specific combustion and control packages while preserving manufacturing commonality. This could reduce the cost of transitioning from an E10-oriented architecture to E20-optimized architecture.

17. Limitations

This paper is a design proposal and does not claim original engine dynamometer, CFD or durability results. The 3D figure is a conceptual visualization. Preliminary numerical curves are design targets or analytical illustrations. Actual compression ratio, injector pressure, chamber geometry, valve timing, torque, BSFC and emissions must be established through validated simulation and experimental testing.

The proposed engine is also not intended to imply that all existing engines require replacement. The concept addresses future or redesigned four-wheeler powertrains and complements, rather than replaces, the in-use E20 compatibility assessment programmes being conducted by Indian automotive research institutions.

18. Conclusion

E20 should increasingly be treated as an engine-design input rather than solely as a fuel-compatibility challenge. This paper proposes a 1.5-L four-cylinder spark-ignition engine architecture that integrates E20-oriented combustion geometry, high-pressure fuel injection, validated fuel-system materials, thermal management, adaptive electronic control and emission after-treatment.

The central design principle is to use ethanol's higher-octane quality and charge-cooling characteristics to support efficient combustion while compensating for its lower volumetric energy density through improved thermal efficiency and adaptive fuel control. The proposed 3D architecture provides a practical foundation for CAD development, CFD analysis and prototype manufacture.

The next research stage should convert the conceptual architecture into a parameterized CAD model, perform 1-D and 3-D simulation, and experimentally validate torque, BSFC, combustion stability, emissions, fuel-system durability and cold-start behaviour. Such a programme would provide the quantitative evidence required to determine whether the proposed architecture can deliver a measurable advantage over conventional E20-calibrated engines in Indian four-wheeler applications.

References

- [1] Government of India, Ministry of Petroleum & Natural Gas, "Government Highlights Safety, Performance and National Benefits of Ethanol-Blended Petrol," Press Information Bureau, 23 July 2026.
- [2] Automotive Research Association of India (ARAI), Alternate Fuels Centre, "Assessment of E20 Fuel on In-Use 2W and 4W Vehicles: Consortium Project—ARAI_SIAM_OMC."
- [3] Tyagarajan, S., Pise, C., Kavekar, P., and Agarwal, N., "Development of Flex Fuel Engine for Indian Market," SAE Technical Paper 2026-26-0117, Symposium on International Automotive Technology, 2026. DOI: 10.4271/2026-26-0117.
- [4] Chansauria, P. and Mandloi, R.K., "Effects of Ethanol Blends on Performance of Spark Ignition Engine—A Review," Materials Today: Proceedings, Vol. 5, 2018, pp. 4066–4077. DOI: 10.1016/j.matpr.2017.11.668.
- [5] Turner, J.W.G., et al., "Ethanol blends in spark ignition engines: RON, octane-added value, cooling effect, compression ratio, and potential engine efficiency gain," Applied Energy, 2017.
- [6] Automotive Research Association of India (ARAI), "Conformity of Production, ISC & IUPR (BS-VI OBD Compliance)," In-Service Conformity requirements and operating-condition considerations.
- [7] Automotive Research Association of India (ARAI), "Alternate Fuels Centre," engine and vehicle durability, material compatibility and emission evaluation programmes.
- [8] Indian Oil / Government of India, Ethanol Blended Petrol Programme and applicable fuel-quality specifications for E20 petrol.
- [9] Society of Automotive Engineers (SAE), technical literature on ethanol-gasoline blends, spark-ignition combustion and flex-fuel engine development.
- [10] Heywood, J.B., Internal Combustion Engine Fundamentals, 2nd ed., McGraw-Hill Education, 2018.



India's EV Journey: Progress, Challenges and the Road Ahead

Sanjeev Chugh
Gen Lotus

India's mobility sector is undergoing a structural transition in which electric vehicles have moved from a niche technology into a material part of new-vehicle sales. This update assesses India's EV journey using the latest government programme status, incentives and policy direction. The focus remains on practical, affordable and sustainable electrification, while recognising India's energy mix, infrastructure constraints, supply-chain exposure, employment transition and diverse vehicle-use patterns.

The policy direction has become broader than vehicle purchase incentives alone: demand support is being combined with charging infrastructure, domestic manufacturing, battery-cell capacity, critical-mineral and rare-earth supply chains, recycling, public transport electrification and testing capability. This integrated approach is important because EV adoption depends on the complete ecosystem rather than vehicle subsidies alone.

The question is therefore not simply how fast India can electrify vehicles, but how effectively it can build a competitive EV ecosystem—covering vehicles, batteries, charging, power supply, materials, manufacturing, skills and circularity—while keeping mobility affordable and reliable.



India's EV Adoption Status – Where Do We Stand?

India's EV market crossed approximately 2.3 million annual EV sales in 2025. Two- and three-wheelers remain the principal volume segments, while electric passenger cars are expanding from a lower base and EV Buses are growing esp. thru State Transport Bodies . Government programme data show continued strong momentum into 2026: by 22 July 2026, PM E-DRIVE had supported 26.54 lakh EVs against a demand-incentive target of 28.16 lakh vehicles, while FAME-II had supported 16.72 lakh EVs by 30 June 2026.

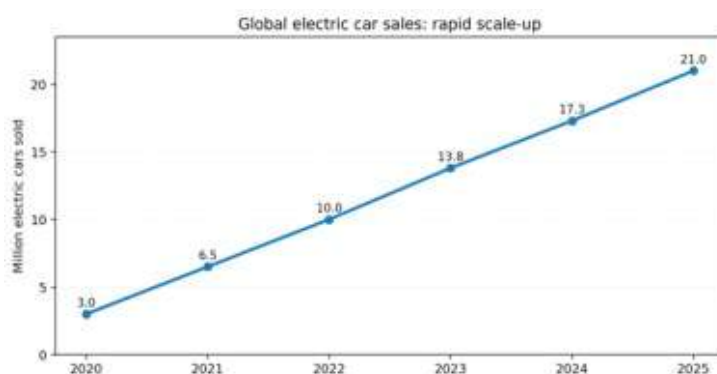


Figure 1. Global electric-car sales have moved from early adoption to mass-market scale. Source: IEA Global EV Outlook 2026; values shown are rounded/derived from IEA-reported annual series

These programme figures are scheme-supported vehicles and should not be treated as total national EV registrations.

Segment-wise EV Adoption

Segment	Adoption Status
Two-Wheelers	Fastest growing
Three-Wheelers	Among world's highest penetration
Passenger Cars	Emerging
Commercial Vehicles	Early growth phase
Buses	Policy-driven deployment

The Positive Story

1. Rapid Market Growth

EV sales have increased nearly fifteen-fold since FY20, indicating that consumer acceptance is steadily improving.

2. Improved Economics

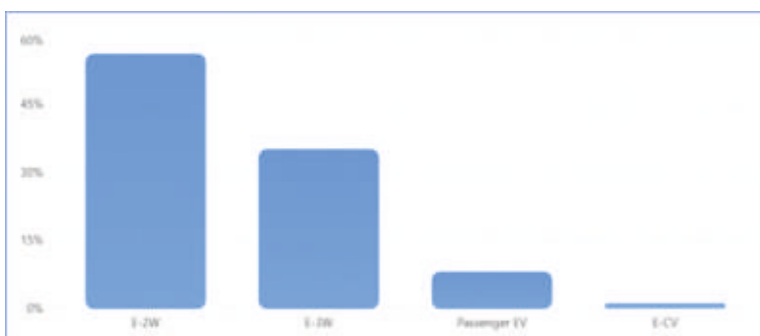
Rising fuel prices, declining battery costs, and lower operating expenses are improving the total cost of ownership proposition for EVs.

Government policy support is now structured around multiple levers rather than a single subsidy programme.

Government initiatives have created a strong foundation for long-term growth.

Key central interventions relevant to EVs include:

- PM E-DRIVE — demand incentives, e-buses, e-trucks, e-ambulances, public charging and testing-agency upgrades
- PARIVARTAN Scheme — initiative designed to replace >2lac BSIV or earlier trucks and buses with cleaner BSVI or electric vehicles.
- PLI-Auto — advanced automotive products, including zero-emission vehicles and components
- PLI-ACC — domestic advanced-chemistry-cell manufacturing capacity
- SPMEPCI — manufacturing of electric passenger cars in India
- REPM manufacturing scheme, critical-mineral recycling support and battery-waste EPR



IND 2025 - Approximate share of EV sales by vehicle segment
Source: Industry reports and Vahan-based market analyses.

4. Growing Charging Infrastructure



Figure 2. Real-world fast-charging plaza illustrating the infrastructure required for longer-distance EV use.

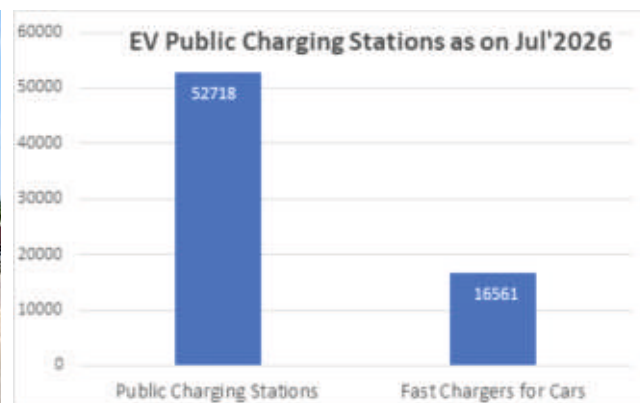


Figure 3. India public charging-point expansion required under the IEA STEPS outlook.
Source: IEA Global EV Outlook 2025, Electric vehicle charging.

Public charging infrastructure has expanded substantially. As reported by the Ministry of Heavy Industries in July 2026, the BHEL portal recorded 52,718 public charging stations, including 16,561 public charging stations equipped with fast EV chargers for cars. In parallel, PM E-DRIVE had ₹2,000 crore allocated for EV public charging stations; by 1 July 2026, ₹689 crore had been approved for deployment of 6,562 chargers to three oil marketing companies and nine states. The key next challenge is therefore not only charger count, but geographic coverage, uptime, interoperability, grid readiness and commercially sustainable utilisation.

The Challenges We Must Acknowledge

1. Charging Infrastructure: From Quantity to Reliability

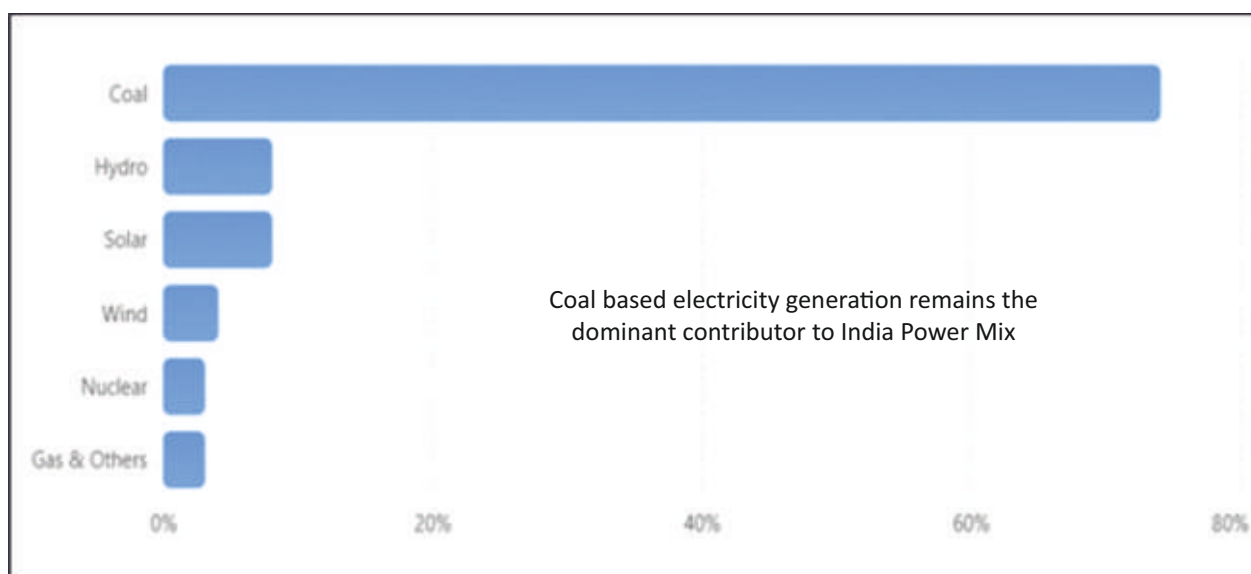
The national network is growing, but the next phase requires higher utilisation, reliable uptime, faster inter-city coverage and better interoperability. Government policy now explicitly supports public charging through capital support under PM E-DRIVE and through the Ministry of Power's charging-infrastructure framework.

The July 2026 government position recorded 52,718 public charging stations, of which 16,561 were equipped with fast EV chargers for cars. PM E-DRIVE had also approved 6,562 chargers under its charging-infrastructure component by 1 July 2026, while FAME-II had 9,583 EV public charging stations installed by 1 July 2026. These figures use different programme/portal definitions and should not be simply added.

2. Grid and Energy Mix

A significant portion of India's electricity continues to come from thermal generation.

Therefore, while EVs eliminate tailpipe emissions, the overall environmental benefit depends upon increasing renewable energy penetration.



Source: Central Electricity Authority (CEA), Govt. of India – Values in %age rounded off.

3. Range Anxiety

Particularly relevant for:

- Inter-city passenger vehicles
- Commercial fleets
- Heavy-duty transport

4. Supply Chain Dependence — From Imported Oil to a Broader Mineral and Technology Basket

India remains dependent on imports for:

- Lithium
- Critical minerals
- Advanced battery materials



Figure 4. Long-distance fast charging can reduce range anxiety when coverage, reliability and payment interoperability are adequate.

India's policy response is increasingly moving upstream: domestic ACC cell manufacturing, automotive-component localisation, critical-mineral recycling and rare-earth permanent-magnet manufacturing are being supported. The strategic issue is therefore shifting from only reducing crude-oil dependence to building diversified, resilient and circular supply chains for cells, cathode/anode materials, graphite, lithium, nickel, cobalt, rare-earth magnets, power electronics and other critical components.

5. Employment and Industrial Transition

EVs can reduce mechanical complexity and change the mix of jobs across manufacturing, maintenance and the supply chain. At the same time, government-supported manufacturing programmes are creating new investment and employment: PLI-Auto reported ₹44,326 crore cumulative investment and 67,820 jobs as of 31 March 2026. The policy challenge is to ensure that workforce reskilling keeps pace with the shift toward batteries, power electronics, software, charging and advanced manufacturing.

6. Well-to-Wheel Emissions: The Real Comparison

Environment protection thru Emission control has been one of the main objective of EV promotion.

For countries like IND, balanced assessment requires evaluating emissions from fuel production through vehicle operation.

Indicative Well to Wheel CO2 Emissions

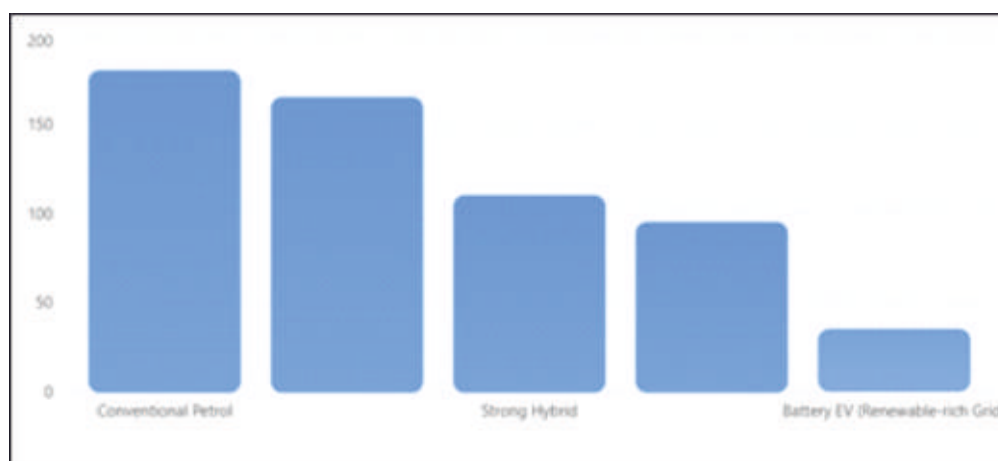
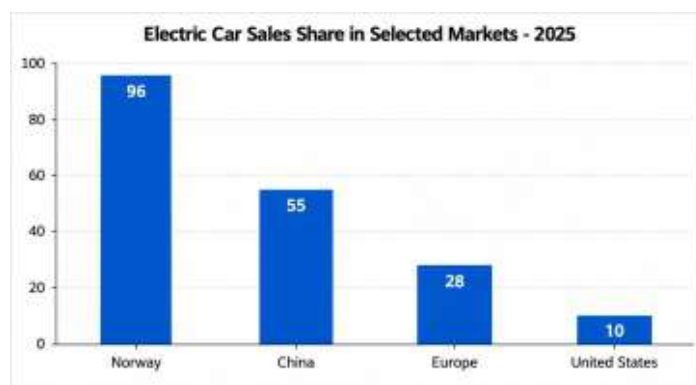


Figure 5. Selected 2025 electric-car sales shares illustrate different adoption pathways. Illustrative comparison across propulsions technologies

Global Lessons India can learn



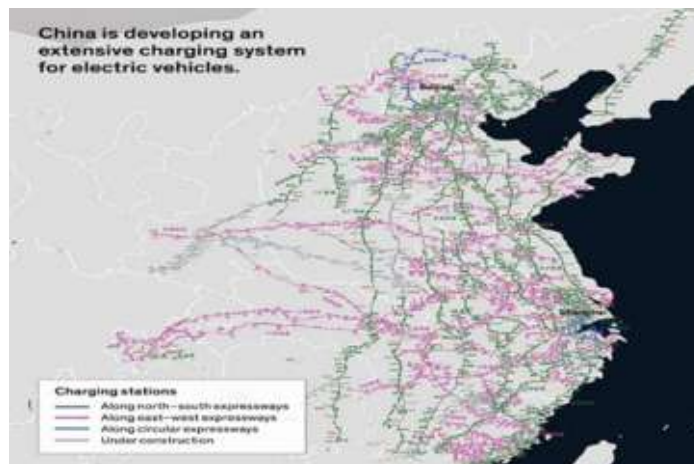
Norway: Infrastructure



Norway demonstrates the value of charging convenience, predictable policy and a mature electricity/vehicle ecosystem.

- i. Charging is convenient
- ii. Incentives are stable
- iii. Policy remains consistent

China: Ecosystem Development



China's experience is relevant particularly for scale and supply-chain depth: local manufacturing, battery ecosystems, large domestic demand and integration between vehicles, cells and components. India's PLI-Auto, PLI-ACC and related localisation measures are intended to build comparable ecosystem depth, although the Indian market structure is different.

- i. Local manufacturing
- ii. Battery ecosystem development
- iii. Scale economies
- iv. Supply chain localization

United States: Charging and Private-Sector Innovation



Figure 6. - Public private charging infrastructure is a recurring feature of the US experience.
Visual: author/library image; illustrative charging-infrastructure scene.

The US experience highlights fast-charging corridors, technology innovation, private investment and public-private partnerships. India's PM E-DRIVE charging component and Ministry of Power guidelines similarly seek to combine public support with private deployment.

- Fast charging corridors
- Technology innovation
- Public-private partnerships

IND Government Direction & Incentive Landscape

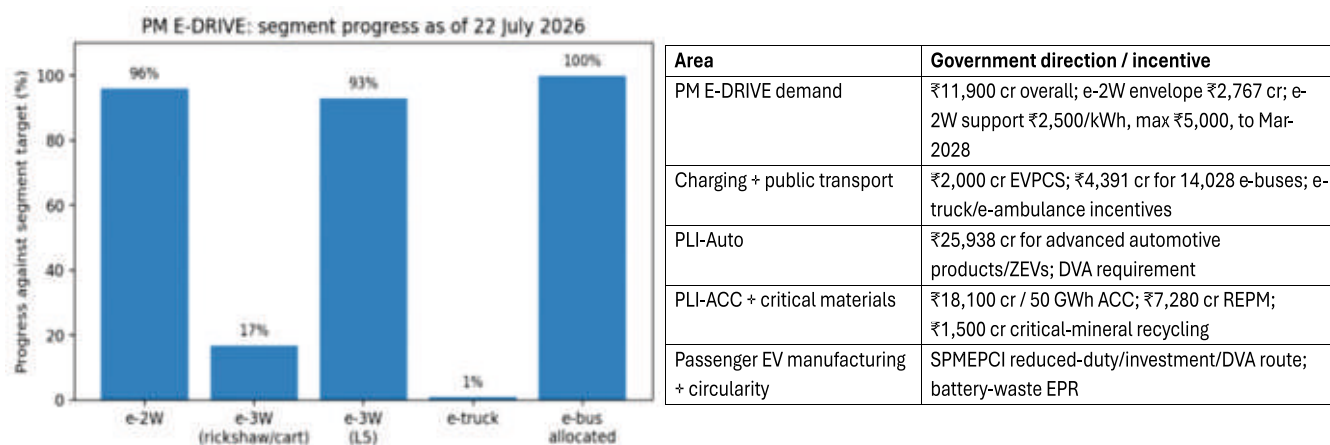


Figure 7. PM E-DRIVE segment progress against scheme targets

Source: Ministry of Heavy Industries, Ministry of Power, PIB and Government notifications; cut-off date for this report: 31 August 2026. Developments notified after this date are excluded.

1. Demand incentives — PM E-DRIVE

PM E-DRIVE now has an amended overall outlay of ₹11,900 crore and runs to 31 March 2028. The 10 August 2026 amendment increased the e-2W support envelope to 45,79,120 vehicles with ₹2,767 crore allocated; the incentive for 1 April 2025–31 March 2028 remains ₹2,500/kWh capped at ₹5,000 per vehicle, subject also to the 15% ex-factory-price ceiling. The e-3W LS segment had already closed on 26 December 2025 after reaching its target. Other supported areas include e-rickshaws/e-carts, e-trucks, e-ambulances, e-buses and charging infrastructure.

2. Public charging infrastructure

₹2,000 crore is allocated under PM E-DRIVE for EV public charging. By July 2026, government reporting showed 6,562 chargers approved under the PM E-DRIVE charging component, while 52,718 public charging stations were reported nationally on the BHEL portal. Ministry of Power guidelines also provide a framework for interoperable charging, grid connections and tariff principles.

3. Public transport, trucks and special-use EVs

PM E-DRIVE provides ₹4,391 crore for 14,028 e-buses, and includes incentives for e-trucks and e-ambulances. By 22 July 2026, 14,000 e-buses had been allocated and 55 e-trucks had been sold under the scheme. This indicates a policy emphasis on high-utilisation/public-service segments in addition to private vehicles.

4. Manufacturing and localisation

PLI-Auto has a ₹25,938 crore outlay and focuses on advanced automotive products including ZEVs. As of 31 March 2026, cumulative investment was ₹44,326 crore, employment 67,820 and incentives disbursed ₹2,386.36 crore. By 16 July 2026, 18 applicants had received DVA certificates for 154 products/variants.

5. Battery cells, magnets and critical materials

PLI-ACC carries ₹18,100 crore for 50 GWh of ACC capacity; four awarded projects represented 40 GWh as reported in July 2026, with no PLI-ACC incentive claimed at that point. A separate ₹7,280 crore REPM scheme targets 6,000 MTPA of integrated sintered NdFeB permanent-magnet capacity; 20 bids were received and technical bids opened on 13 August 2026. A ₹1,500 crore critical-mineral recycling incentive scheme and battery-waste EPR strengthen the circular-supply-chain direction.

6. Electric passenger-car manufacturing

SPMEPCI was notified in 2025 to attract fresh investment in electric passenger-car manufacturing. Approved applicants can access a reduced 15% customs duty for qualifying imported CBUs subject to scheme conditions, alongside minimum investment and domestic-value-addition requirements. The application window closed in October 2025; MHI's 2025-26 annual report recorded that no applications were received during that window. This remains an important policy instrument, but its actual manufacturing impact should be assessed separately from vehicle-demand incentives.

IND Action Proposed — 2026–2030 Priorities

- Policy & market design: retain predictable multi-year rules; periodically calibrate incentives to technology cost reduction; avoid creating avoidable demand distortions between segments; publish transparent progress dashboards.
- Infrastructure: move from charger-count targets toward uptime, utilisation and corridor coverage; prioritise highways, fleet hubs, workplaces, apartments and high-density urban areas; strengthen grid connection planning and interoperability.
- Energy: pair EV growth with renewable generation, managed charging, storage and time-of-use tariffs; develop pilots for smart charging / V2G where grid conditions justify them.
- Industry & supply chain: accelerate cell / material localisation, rare-earth magnet capacity, power electronics and recycling; develop second-life battery pathways and resilient sourcing of critical minerals.
- Consumers & fleets: focus incentives where utilisation and TCO justify electrification; expand transparent TCO tools; improve battery-health information, warranty clarity and used-EV confidence.
- Skills, testing & safety: reskill ICE workforce; expand EV/battery/charger testing capacity; maintain strong thermal, electrical, software and functional-safety practices as architectures evolve.

Charging • Public transport • Manufacturing • Energy transition

Conclusion :

India's EV journey has moved into a more mature ecosystem-building phase. By August 2026, government support extends beyond purchase incentives to charging infrastructure, e-buses, e-trucks and e-ambulances, advanced automotive manufacturing, battery-cell capacity, rare-earth magnets, recycling and testing capability.

The evidence also shows that policy support is not uniform across segments: e-2W support has been extended to March 2028 with a revised incentive structure; the e-3W L5 demand-incentive window had already closed; passenger EVs are supported more through manufacturing and broader tax/policy measures than through PM E-DRIVE purchase subsidy; and charging deployment is moving from sanctioning toward actual commissioning and utilisation.

The next stage should therefore be measured not only by EV sales, but by ecosystem outcomes: reliable charging, domestic value addition, battery and critical-material resilience, renewable-energy integration, skilled employment, recycling and competitive total cost of ownership.

A pragmatic, data-driven and technology-aware strategy can allow India to expand electrification while addressing affordability, energy security, industrial competitiveness and environmental performance.

The objective is not electrification for its own sake; it is a durable mobility ecosystem in which the right electric solutions are deployed where they deliver clear economic, environmental and energy-security value.

IMAGE & DATA CREDITS

Visual/data update (August 2026): this version refreshes the report to the end-August 2026 policy and programme position, including the 10 August 2026 PM E-DRIVE amendment, July 2026 EV/charging progress, PLI-Auto/ACC status, REPM initiative and critical-mineral recycling direction. Charts are based on the cited government/IEA datasets and are intended as analytical illustrations.

Data Sources:

- Ministry of Heavy Industries (Government of India) — PM E-DRIVE notifications, dashboard and parliamentary replies through August 2026
- Ministry of Power / Bureau of Energy Efficiency — EV charging infrastructure guidelines and July 2026 charging-station data
- Ministry of Mines / PIB — critical-mineral recycling measures
- Ministry of Environment, Forest & Climate Change — Battery Waste Management / EPR framework
- NITI Aayog
- Vahan / BHEL charging data as cited by Government of India
- International Energy Agency (IEA), Global EV Outlook 2026
- ICCT and other industry sources where specifically identified
- MHI Annual Report 2025-26 and PIB releases on PLI-Auto, PLI-ACC and REPM

Note: State EV policies and incentives vary by jurisdiction and are not exhaustively catalogued in this national-level report.

Image Credits:

- Government of India / PIB
- Ministry of Petroleum & Natural Gas / IndianOil Corporation Ltd.
- Publicly available corporate media resources in the source draft
- Author/library illustrative photographs
- Author-created charts and graphics

Graphs and illustrations compiled by the author from publicly available datasets and industry references.

COPYRIGHT & DISCLAIMER

© 2026 Sanjeev Chugh. All rights reserved.

This article reflects the personal views and professional assessment of the author based on publicly available information, industry reports, government publications, and market analyses. The content is intended for knowledge sharing and discussion purposes only.

Data, statistics, programme status and charts are indicative and may vary with subsequent government dashboard updates, reporting cut-offs and source methodology. This edition intentionally uses 31 August 2026 as the policy/data cut-off; later notifications are not incorporated.

No part of this publication may be reproduced, distributed, or republished without appropriate acknowledgement of the author

The advertisement features the DINEX logo at the top left. The main title is "Full Aftertreatment and Pipe Technology Systems". The central image shows a complex aftertreatment system with various components labeled: "E-heater integration", "Pipe Cleaning", "Pipe Forming", "Thermal insulation", "1st AdBlue®/ DEF dosing unit (heated)", "Close coupled pipe mixer", "DiFlex™", "Insulated clamps/slip joint", "Corrosion and Heat Protection", "Pipe bending", "Low thermal mass metal parts", and "Dinex EATS". To the right, two bullet points highlight "Thermal & Emission Optimization Technologies" and "Pipe Design, Safety & Protection Technologies". On the left, two boxes provide contact information for DINEX India (Chennai) and DINEX India (Chennai). At the bottom, there is a row of images showing a white truck, a yellow excavator, and a white generator. The background is a light blue sky with a green field at the bottom.

dinex

Full Aftertreatment and Pipe Technology Systems

- Thermal & Emission Optimization Technologies
- Pipe Design, Safety & Protection Technologies

India (Chennai)
Dinex Emission Solutions India Pvt. Ltd.
Plot 1, Phase 5, 8th Ave,
Mahindra World City, Chengalpattu,
Tamil Nadu 603004

India (Chennai)
Dinex Emission Solutions India Pvt. Ltd.
Plot 2, Global Industrial Park
Sanaswadi, Pune, Maharashtra 412208

info@dinex.in **Dinex.org**

Strategy for Controlling Aldehyde Emissions in Brazil: Limits and Measurement Methods

Gabriel M. Branco e Fábio C. Branco

Bruno L. Hennemann; Maristhela P. A.

Marin; Érica F. S. Tirelli; Gabriela Leite

Edson Paixão; Miguel Zoca

EnvironMentality

Instituto Mauá de Tecnologia

UMICORE

Background

The Motor Vehicle Air Pollution Control Program (PROCONVE) was implemented in Brazil in 1986, initially for light- and heavy-duty vehicles, and was later expanded to include motorcycles, agricultural machinery, and road construction equipment.

Early on, there was concern that this program would not hinder the development of ethanol-powered vehicles, which was also emerging in Brazil. However, concerns arose that the use of ethanol increases the formation of aldehydes, which would require specific control of this emission. Ethanol-fueled vehicles emitted between 100 mg/km and 160 mg/km of aldehydes (formic and acetic), with the latter predominating. In contrast, gasoline-fueled vehicles emitted only 30 mg/km.

At that time, there were no studies determining the maximum acceptable concentration of aldehydes in the atmosphere; there were studies on the toxicity of aldehydes focused on occupational health. However, these studies focus on exposures of only 8 hours per day for healthy adults, whereas atmospheric standards are set for more susceptible populations, including children and the elderly, who are exposed 24 hours a day. Furthermore, the technological knowledge needed to reduce aldehyde emissions from internal combustion engines was not yet available.

Given the lack of knowledge regarding these two key aspects, Brazil adopted a strategy of immediately setting an initial standard of 150 mg/km to prevent the emergence of technologies that might eventually increase these emissions, as would be the case with silver-based catalysts, and a standard of 30 mg/km to be met within five years. This gave industry time to develop control technology, and it enabled ethanol-powered vehicles to reduce aldehyde emissions to the same levels as those in gasoline-powered vehicles, which have been practiced worldwide and were not considered an environmental problem. This strategy was based on practical objectives that accelerated the process, eliminating the need for scientific knowledge to be developed prior to its implementation.

Over time, we have learned that controlling hydrocarbons through catalytic converters also reduces aldehyde emissions, and the natural evolution of these engine technologies has enabled even greater reductions, currently reaching a limit of 10 mg/km, with a target of 8 mg/km by 2031 for light-duty vehicles. Given this technological scenario, it would already be advisable to establish equivalent emission targets for aldehydes for motorcycles and diesel vehicles.

History

Traditionally, the control of organic compound emissions in gasoline and diesel vehicles has focused on total hydrocarbons, which are measured by flame ionization detectors (FID) and exhibit virtually the same response factor for any compound, except for those containing oxygen.

In the case of alcohol use, the organic compounds come to include large amounts of unburned ethanol and aldehydes, which requires independent measurements using specific methods to determine their respective emissions.

During the early stages of PROCONVE, only aldehydes were measured independently, but unburned ethanol emissions continued to be included in the total hydrocarbon measurement, without any correction of the reading, and were thus underestimated by about 50%. However, their environmental effects are less severe, so one effect tends to offset the other.

With the advent of flex-fuel vehicles, specific regulations for NMHC (non-methane hydrocarbons) were adopted for light-duty vehicles, excluding methane and ethanol from these emissions. This procedure led manufacturers to modify cold-start devices by replacing gasoline injection with ethanol in an abusive manner, because the unburned portion of ethanol was no longer considered an organic pollutant. This fact forced the adoption of the NMOG (Non-Methane Organic Gases) concept, which encompasses all organic compounds weighted by their respective photochemical reactivity in the atmosphere. This concept requires detailed speciation of many organic compounds, which greatly complicates and increases the cost of quantification processes, presenting significant operational challenges in sampling and measurement procedures. It is therefore recommended only for research and for establishing reactivity standards to be used for certification.

However, a strategy based solely on THC measurements is simpler and more objective. It is fully justifiable during the intermediate phases of the program and is still used in Brazil for motorcycles.

The alcohol content of hydrated ethanol fuel must be between 95.1° and 96° GL, which results in a maximum limit of approximately 4.9% water by volume.

An important aspect of motorcycle emissions control relates to test cycles: the program was launched based on the European program, adopting the highly simplified ECE R40 cycle, which was later replaced by the WMTC (World Motorcycle Test Cycle) transient cycle, which more accurately reflects real-world traffic conditions and is much more effective.

In the case of evaporative emissions control in ethanol-fueled vehicles, these emissions are measured by the FID but corrected by the ethanol response factor, since no hydrocarbons are present in the same measurement.

Given these considerations, the history of the main measures to control emissions of organic compounds from light-duty vehicles and motorcycles, which use gasoline containing 32% ethanol (E32) or hydrated ethanol (E100), is summarized in Tables 1 and 2.

Table 1 – Organic emissions std. for Light Duty Vehicles – Test cycle FTP 75:

L1 1986	THC < 2,1 g/km and aldehydes reported; Exhaust THC encompasses Hydrocarbons and Ethanol without any correction
L1 1990	Evaporative 6g @ 1h+1h Cold and Hot Soak – (FID correction for ethanol);
L2 1992	Total aldehydes < 150mg/km
L3 1997	THC < 300mg/km Total aldehydes < 30 mg/km
L4 2003	Adopted the non-methane concept, subtracting unburned ethanol NMHC < 160 mg/km; Evaporative emission 2g @ 1h Cold and Hot Soak
L5 2009	NMHC < 50 mg/km Total aldehydes < 20 mg/km
L6 2012	Aldehydes < 15 mg/km
L7 2022	Eliminated ethanol subtraction and implemented exhaust NMOG Enhanced evaporative emission control < 0,5g/day @ 48h test + Hot Soak Refueling evaporative emission < 50mg/L (ORVR required)
L8 2025	Adopted corporate emission limits, NMOG+NOx < 50 mg/km progressively reduced to 30 for cars by 2031 NMOG+NOx < 140 mg/km progressively reduced to 30 for LDT by 2031 Total aldehydes < 15 mg/km progressively reduced to 8 for LDV by 2031

Table 2 – Organic emissions standards for Motorcycles:

M1 2003	Adopted ECE R40 driving cycle THC < 3,0 g/km
M2 2005	THC < 1,2 g/km (<150 cm ³) THC < 1,0 g/km (>150 cm ³)
M3 2009	THC < 800 mg/km (<150 cm ³) THC < 300 mg/km (>150 cm ³) (Start of production of flex-fuel motorcycles)
M4 2014	Adopted WMTC driving cycle THC < 800 mg/km (<130 km/h and moped) THC < 300m g/km (>130 km/h)
M4 2016	THC < 560 m g/km (<130 km/h) THC < 250m g/km (>130 km/h)
M5 2025	THC < 100 mg/km Total aldehydes < 20mg/km Evaporative emission < 1500 mg/test (UE 134/2014)

Considerations Regarding Methods for Measuring Organic Compounds

In gasoline and diesel engines, the quantification of organic compound emissions is performed by simply reading a flame ionization detector (FID) calibrated with propane, whose responses are very similar for most hydrocarbons present in the exhaust gas. When the fuel contains significant amounts of oxygenates, these compounds distort the FID's response, and its correction requires an independent measurement, since the proportion of these compounds in the total exhaust hydrocarbons is not known a priori. Only in the case of evaporative emission measurement, which consists exclusively of fuel and is free of combustion byproducts, is it possible to calibrate the FID with the fuel itself, as has been the practice in Brazil since 1990.

Aldehydes were the first organic compounds to be measured separately from the others. The methods used to determine organic compounds in exhaust gases involve different measurement principles, analytical characteristics, and limitations, all of which must be considered depending on the purpose of the analysis.

In the specific case of aldehydes, the method traditionally used to determine their concentration in vehicle emissions involves sampling exhaust gases in impingers or cartridges containing 2,4-dinitrophenylhydrazine (DNPH), followed by analysis of the resulting derivatives using high-performance liquid chromatography (HPLC).

In vehicle emissions testing, the procedure involves a standardized driving cycle, and samples are collected throughout the different phases of the test, stored, and subjected to derivatization and subsequent analysis, so that the result obtained corresponds to the integrated mass or average emission associated with the route or sampling period, rather than the instantaneous evolution of the emission.

However, a comparison of different techniques for determining ethanol, formaldehyde, and acetaldehyde in the emissions of a flex-fuel vehicle running on E85 showed that a gas chromatography system provided results approximately every five minutes, while the DNPH-HPLC method involved a sampling step followed by offline analysis.

The main advantage of DNPH derivatization is its ability to transform highly reactive carbonyl compounds with different physicochemical properties into derivatives suitable for chromatographic separation and quantification. In the comparative study of methods applied to vehicle emissions, the method based on DNPH cartridges and HPLC-UV had a detection limit of 0.1 mg per sample and a measurement uncertainty of 6.4% for formaldehyde and acetaldehyde.

The determination of aldehydes by DNPH derivatization is a well-established and widely used approach, and this procedure has been regulated in Brazil for the determination of aldehydes in vehicle certification.

However, for the design and development of vehicles and their emissions control systems, this method must be supplemented with instrumental techniques, such as Fourier Transform Infrared Spectroscopy (FTIR), capable of performing real-time measurements that allow for the identification of rapid variations associated, for example, with cold starts, changes in engine load and speed, and the operation of the aftertreatment system. Understanding how FTIR works is therefore important.

FTIR spectroscopy is based on the interaction of infrared radiation with the vibrational modes of molecules. In the mid-infrared region, approximately between 400 and 4000 cm^{-1} , certain frequencies of radiation are absorbed when they correspond to transitions between the molecule's vibrational levels. The intensity and position of these bands are characteristic of the chemical species and are related to their vibrational modes, allowing for both the identification and quantification of the compounds present in the sample. For a vibration to be observed in the infrared, it must be associated with a change in the molecule's dipole moment. Thus, molecules or species whose vibrations do not produce a dipole moment, such as N_2 , O_2 , and H_2 , do not exhibit infrared absorption bands and cannot be directly identified by FTIR.

The operating principle of FTIR is generally based on a Michelson interferometer. Radiation from the infrared source is split into two beams and directed toward a fixed mirror and a movable mirror. After being reflected, the beams are recombined, producing an interference pattern called an interferogram. This signal simultaneously contains information regarding the different frequencies of radiation and is subsequently converted, via a Fourier transform, into the absorption spectrum.

This configuration is particularly interesting because it allows for the simultaneous identification and measurement of various compounds across the entire spectral region, including aldehydes, methane, ethane, and unburned ethanol, contributing to the high data acquisition speed that is characteristic of FTIR instruments. In automotive applications, the use of multiple-reflection cells also allows the optical path length to be increased without requiring very large sample volumes, enabling the detection of low concentrations of species after dilution and providing a wide dynamic range.

In addition, the high signal acquisition frequency allows for real-time monitoring of rapid changes in gas composition under different engine operating conditions, including cold starts and transients, since short-duration events are attenuated or even undetected when using integrated sampling via the impinger collection method. In a comparison of different techniques for determining ethanol, formaldehyde, and acetaldehyde in the emissions of a flex-fuel vehicle running on E85, three FTIR systems were used. Depending on the equipment, the FTIR systems had acquisition rates of up to 5 spectra per second.

However, the use of FTIR presents challenges that must be considered. Quantification depends on the presence of suitable spectral regions and calibration models capable of distinguishing the compounds of interest in a complex matrix such as the exhaust gas. The overlap of absorption bands from different species, especially H₂O and CO₂, or even contaminants from the silicone tubing used in sampling, can hinder the determination of compounds present at low concentrations. Spectral resolution, the selection of frequencies used for quantification, the quality of the spectral libraries, and the calibration models are, therefore, key factors in obtaining reliable results⁵.

This limitation makes it especially important to select appropriate sampling conditions, to control the line and analysis cell temperatures, to characterize interferences, and to validate the quantitative model. In the intercomparison study conducted with E85, despite differences in techniques, sampling temperatures, and collection points, the determinations of ethanol, acetaldehyde, and formaldehyde showed good repeatability and reproducibility. The FTIR results for the complete driving test also showed values close to those obtained by conventional HPLC and GC methods¹.

In a conversation (2013) with European chemist Bertold Arlitt, an expert in FTIR, it was noted that, although FTIR can measure hydrocarbon compounds, it has sensitivity limitations when it comes to the low concentrations found in the exhaust gases of modern vehicles. The solution found was to integrate an FID analyzer into the FTIR system. This approach resolved the measurement instability for hydrocarbons, but not for aldehydes or unburned ethanol. For these compounds, a mathematical interpolation is used to achieve reliable values, which depend on the engine configuration and the fuel type. Therefore, this mathematical model must be validated on a case-by-case basis by comparing it with chromatographic measurements, preferably using the same engine and fuel, to be used as a relative measurement.

This fact prevents the use of FTIR as an official method for certification, where measurements must be absolute to be compared to emission limits. However, for research purposes and in the absence of such validation, well-known algorithms found in existing libraries are used as preliminary and less accurate references.

Thus, the DNPH-HPLC method offers a high degree of speciation for carbonyl compounds and has established itself as the most suitable method for verifying compliance with regulatory limits associated with standardized driving cycles in certification procedures.

On the other hand, FTIR is best suited for the simultaneous determination of different compounds and the temporal monitoring of emissions to understand the influences of engine operating conditions and aftertreatment systems in vehicle development studies, always taking its measurements relatively to those obtained by HPLC on the same vehicle.

In other words, FTIR still requires demonstration of analytical performance, control of spectral and sampling interferences, and the establishment of calibration and validation procedures consistent with regulatory requirements⁶⁻⁷.

To further deepen our understanding of emissions of aldehydes, unburned ethanol, and other organic compounds, other methods offer important complementary characteristics.

Gas chromatography, in turn, offers distinct advantages. Chromatographic separation allows for the identification of volatile and semi-volatile compounds and can be combined with different detectors, such as FID and mass spectrometry, which, in this configuration, enable the direct measurement of compounds of interest in real time. Consequently, GC has potential for the analysis of carbonyl compounds and is particularly useful for ethanol and hydrocarbons, although the high cost of mass spectrometers is a drawback.

Among the GC-MS-compatible derivatization options, PFBHA (O - 2,3,4,5,6-pentafluorobenzyl-hydroxylamine) is widely cited for the determination of formaldehyde and acetaldehyde by headspace GC/MS, as described in the literature. More recent studies have also demonstrated the use of PFBHA in the capture and quantification of these aldehydes by GC-MS, highlighting the applicability of this approach to the analysis of carbonyl compounds.

In the intercomparison study, GC was used for ethanol and acetaldehyde, but it had a response time much longer than the FTIR systems used. Thus, chromatography remains particularly important when the identification and individual quantification of chemical species are priorities, while FTIR offers an operational advantage when the objective is to rapidly monitor the composition of a gas stream¹⁻⁷.

Studies combining FTIR and FID have shown that the simultaneous determination of ethanol, acetaldehyde, formaldehyde, and other compounds can improve the characterization of organic emissions and allow for their expression as NMOG₆.

Therefore, a comparison of methods should consider not only accuracy or the detection limit, but also the nature of the information obtained and the objectives of the measurement.

Environmental impacts resulting from emissions of organic compounds

Aldehyde emissions are of particular concern due to the toxicity of formaldehyde and acrolein, primarily. However, when

ethanol is used, acetaldehyde is the predominant compound. On the other hand, all these compounds exhibit high photochemical reactivity and require attention from the perspective of ozone formation. .

However, in flex-fuel engines running on E100, the emission of unburned ethanol itself also requires equal attention, not because of its low reactivity, but because it occurs in very significant quantities. Since ethanol evaporates only at temperatures of 78°C or higher, combustion efficiency is low during the first few seconds of engine operation, particularly during cold starts (20°C to 30°C). This requires a richer air-fuel mixture compared to a cold start with E22 gasoline, resulting in significant emissions of unburned ethanol. Once combustion has stabilized (usually after 1 minute of operation), ethanol emissions tend to zero. Furthermore, during catalyst warm-up, unburned ethanol can be decomposed into water and ethylene, which has high photochemical reactivity.

The identification and quantification of these compounds is carried out using highly sophisticated methods in accordance with the procedures recommended by the USEPA for characterizing these emissions as NMOG . However, this aspect should be taken into account when defining the emission standards to be certified, while taking care to keep procedures as simple as possible, such as sampling using impingers and chromatographic analysis for the determination of acetaldehyde and formaldehyde and ethanol , in a consistent manner with the technologies available for its control.

It is important to note that all organic compounds contribute to ozone formation. Therefore, emission standards must be set to achieve a balance between a vehicle's exhaust and evaporative emissions, as well as fuel supply and distribution evaporative emissions, in accordance with the "well-to-wheel" concept. . Analysis of this balance often reveals trade-offs that are important to understand when comparing the environmental impacts of gasoline- and ethanol-powered vehicles. In this case, the same low vapor pressure characteristic of ethanol that causes disadvantages in exhaust emissions during cold starts also represents a major advantage over gasoline in terms of evaporative emissions from all its sources .

Quantification of exhaust emissions and the magnitude of unburned ethanol

A study conducted in 2014 using a motorcycle equipped with a 150-cc flex -fuel engine was conducted to guide emissions regulations for the M5 phase of motorcycles. It indicated that the ECE R40 cycle is more stringent for total hydrocarbon (THC) emissions, as it is more representative of lighter usage conditions and short trips, when exhaust gas temperatures are lower. Conversely, the WMTC cycle better represents normal driving conditions, and its results should be considered more realistic for simulating everyday use and better suited for comparison with other vehicle types, given that NOx emissions in this cycle are four times higher than those measured in the ECE R40 cycle.

The results obtained in this study also show that, in the ECE R40 cycle, 20% of the measured THC corresponds to aldehydes and 40% to unburned ethanol, with the remaining 40% consisting of hydrocarbons properly speaking, whereas in the WMTC test cycle these proportions change to 30% and 70%, respectively, with negligible hydrocarbon emissions. It should be noted that emissions of unburned ethanol during the hot phases of the test are nearly zero in both driving cycles, while aldehyde emissions are reduced by about 80% compared to the cold phase. .

These findings point to the need for a more detailed approach to the emissions control strategy, quantifying the aldehydes and also the ethanol present in exhaust gases, using methods specifically designed for motorcycles, such as impinger sampling and chromatographic measurement, as employed in Brazil. However, treating these emissions as if they were THC simplifies the regulatory strategy and allows the program to be accelerated with good interim results, despite the inherent inaccuracy of the process.

A comparison of the average emissions of THC, aldehydes, and unburned ethanol from this motorcycle against typical values obtained from hundreds of light-duty vehicle models (LDVs), certified in accordance with PROCONVE's L6 standards, showed that the emission of organic compounds from motorcycle exhaust is significantly higher than that of cars, for which regulations have been evolving since the early 1990s.

The emissions of the organic compounds measured in that study, weighted by their respective photochemical reactivity, result in an ozone formation potential twice as high as that calculated for the LDV limits at that time, an argument that was used to define Phase M5 of Brazilian regulations, with similar standards to those for automobiles. Subsequent studies were conducted on light-duty vehicles, involving the identification of a greater number of organic compounds for the calculation of NMOG. These studies revealed the presence of ethylene during cold starts of engines fueled with E100 and demonstrated the need for a new phase of legislative improvements to finally correct this effect. This approach has not yet been applied to motorcycles in Brazil.

In this future phase, consideration is also being given to expanding the control of evaporative emissions from their various sources, and the possibility of using E90 (containing 10% gasoline), in place of E100, to improve cold-start performance and reduce NMOG emissions is being discussed.

Catalyst technology for controlling aldehydes and unburned ethanol

Given the high proportion of ethanol in Brazil's light-duty vehicle fuel matrix, whether in the form of hydrated ethanol (E100) or in gasoline blends containing between 22% and 32% ethanol by volume, emissions aftertreatment systems require specific catalytic formulations. Among the challenges associated with these applications, the control of aldehyde and unburned ethanol emissions stands out, particularly during cold starts.

From the perspective of automotive catalysis, aldehydes and ethanol exhibit oxidation mechanisms similar to those observed for hydrocarbons. However, optimizing conversion efficiency requires adjustments to the catalyst formulation, system sizing, and engine calibration for each vehicle platform. These activities have been carried out in Brazil along the same principles as those for gasoline engines, at local development centers using appropriate reference fuels.

The catalytic formulation can also be adjusted by substituting or optimizing certain active components, particularly platinum group metals (PGMs), with the aim of increasing the conversion efficiency of aldehydes, unburned ethanol, and the byproducts formed during their oxidation.

Contact information

gm.branco@gmail.com

fabio.branco4@gmail.com

maristhela.finep@maua.br

edson.paixao@am.umicore.com

References

- SUAREZ-BERTO, Ricardo; CLAIROTTE, Michael; ARLITT, Bertold; NAKATANI, Shigeru; HILL, Leslie; WINKLER, Klaus; KAARSBERG, Charlotte; KNAUF, Thorsten; ZIJLMANS, Rens; BOERTIEN, Henry; ASTORGA, Covadonga. Intercomparison of ethanol, formaldehyde and acetaldehyde measurements from a flex-fuel vehicle exhaust during the WLTC. *Fuel*, v. 203, p. 330–340, 2017. DOI: 10.1016/j.fuel.2017.04.131.
- SUN, Y.; TANG, H.; WANG, Y. Progress and challenges in quantifying carbonyl-metabolomic phenomes with LC-MS/MS. *Molecules*, v. 26, n. 20, p. 6147, 2021. DOI: 10.3390/molecules26206147.
- GUERRERO-PÉREZ, M. Olga; PATIENCE, Gregory S. Experimental methods in chemical engineering: Fourier transform infrared spectroscopy—FTIR. *Canadian Journal of Chemical Engineering*, v. 98, p. 25–33, 2019. DOI: 10.1002/cjce.23664
- ZARANTE, Paola Helena Barros; SODRÉ, José Ricardo. Comparison of aldehyde emissions simulation with FTIR measurements in the exhaust of a spark ignition engine fueled by ethanol. *Heat and Mass Transfer*, v. 54, p. 2079–2087, 2018. DOI: 10.1007/s00231-018-2295-5.
- GIECHASKIEL, Barouch; CLAIROTTE, Michaël. Fourier Transform Infrared (FTIR) Spectroscopy for Measurements of Vehicle Exhaust Emissions: A Review. *Applied Sciences*, Basel, v. 11, n. 16, p. 7416, 2021. DOI: 10.3390/app11167416.
- GIERCZAK, Christine A.; KRALK, Lora L.; MAUTI, Adolfo; HARWELL, Amy L.; MARICQ, M. Matti. Measuring NMHC and NMOG emissions from motor vehicles via FTIR spectroscopy. *Atmospheric Environment*, v. 150, p. 425–433, 2017. DOI: 10.1016/j.atmosenv.2016.11.038.
- ROY, Murari Mohan. HPLC analysis of aldehydes in automobile exhaust gas: comparison of exhaust odor and irritation in different types of gasoline and diesel engines. *Energy Conversion and Management*, v. 49, p. 1111–1118, 2008. DOI: 10.1016/j.enconman.2007.09.014.
- GAO, X.; ZHANG, X.; NIE, Y.; BAO, J.; LI, J.; GAO, R.; LI, Y.; WEI, W.; YAN, X.; YAN, Y.; et al. Analytical Methods for Atmospheric Carbonyl Compounds: A Review. *Atmosphere*, v. 16, n. 1, p. 107, 2025. DOI: 10.3390/atmos16010107.
- SUGAYA, N.; NAKAGAWA, T.; SAKURAI, K.; MORITA, M.; ONODERA, S. Analysis of aldehydes in water by head space-GC/MS. *Journal of Health Science*, v. 47, n. 1, p. 21–27, 2001. DOI: 10.1248/jhs.47.21.
- HALDER, S.; REED, E.; XIE, Z.; NANTZ, M. H.; FU, X.-A. Analysis of a broad range of volatile organic compounds in environmental air with dual-compartment micropreconcentrators. *Journal of Chromatography A*, v. 1756, 466071, 2025. DOI: 10.1016/j.chroma.2025.466071.
- Carter, W.P.L.- Updated Maximum Incremental Reactivity Scale and Hydrocarbon Bin Reactivities for Regulatory Applications - Prepared for California Air Resources Board - Revised January 28, 2010
- Branco, G.M.; Szwarc, A.; Branco, F.C.; Nigro, F.E.B. – Controle de emissão de compostos orgânicos com base no potencial de formação de ozônio – SIMEA 2013.
- ABNT NBR 12026: Veículos rodoviários automotores leves - Determinação de aldeídos e cetonas contidos no gás de escapamento, por cromatografia líquida - Método DNPH, 2021.
- ABNT NBR: 15598: Veículos rodoviários automotores leves - Determinação de etanol não queimado contido no gás de escapamento, por cromatografia gasosa - Método de ensaio, 2022.
- Branco, F.C.; Branco, G.M.; Blumrich, S.H. - PROCONVE Update to Match Technological Advances in Automotive Engines and Vehicle Emission Measurement Equipment – Congresso SAE Brasil 2026
- Szwarc, A.; Farah, E.L.; Branco, G.M. e Branco, F.C. - Redução da Emissão Evaporativa do Veículo em Movimento e no Reabastecimento de Combustível – XXII SIMEA Simpósio Internacional de Engenharia Automotiva – 2014.
- Szwarc, A.; Branco, G.M.; Cruz, J.A.; Romio, R.; Faggi, R. - Medição da Emissão de Aldeídos e Álcool não Queimado em Motocicletas Operando nos Ciclos WMTc e ECE R40 – XXII SIMEA - Simpósio Internacional de Engenharia Automotiva – 2014

In-Use Diesel Generator Emissions: Reading the NO_x-PM Signature and Identifying the Next Control Frontier

Ankit Trivedi

International Centre for Automotive Technology (ICAT) India

Abstract

Diesel generator sets remain important for standby and decentralised power, while a substantial in-use population continues to operate after certification under earlier emission stages. This article examines eight anonymised, field-procured diesel generator engines spanning 29.4-220 kW and model years 2004-2013. Following manufacturer-prescribed servicing and 20 hours of stabilisation, each engine was evaluated over the ISO 8178-4 D2 five-mode cycle. Baseline carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and particulate matter (PM) were compared with relevant historical type-approval information and CPCB-I/CPCB-II reference limits. A passive diesel oxidation catalyst plus partial-flow filter configuration was subsequently assessed to understand pollutant-specific retrofit response.

The data reveal a non-uniform in-use emission signature. CO and PM were generally controlled, but NO_x or HC+NO_x remained elevated in several samples. Three engines exceeded the 9.2 g/kWh CPCB-I NO_x benchmark, with the highest result at 13.16 g/kWh. Passive retrofit treatment produced large reductions in CO and HC and moderate, sample-dependent PM reduction, yet changed NO_x only marginally. These findings do not reduce the importance of PM control. Rather, they indicate that PM and NO_x require different technical responses. Established research confirms that NO_x control is possible through EGR- and SCR-based approaches under suitable conditions, but application to old engines is constrained by calibration, temperature, packaging, durability and cost. The article therefore retains the observed emission trend as its principal contribution and opens a limited technical dialogue on future in-use NO_x characterisation and frugal, duty-specific responses.

Keywords: diesel generator set; in-use emissions; NO_x; particulate matter; retrofit emission control device; DOC; partial-flow filter; ISO 8178 D2; legacy engines

1. Why in-use generator emissions deserve a second look

Type approval establishes the emission performance of a new engine family under prescribed conditions. It does not, by itself, describe the emission state of every unit after years of field operation. In-use generator engines experience diverse loading, maintenance quality, fuel history, thermal exposure and operating hours. Many standby sets also spend long periods at low load or operate intermittently, which can influence combustion and exhaust-after-treatment conditions.

India has progressively tightened emission standards for new generator engines. In parallel, the Retrofit Emission Control Device framework provides a route to reduce particulate emissions from eligible in-use sets. This is an important foundation. The present investigation asks a narrower question: what emission signature is observed when representative legacy engines are brought from the field and evaluated under a common laboratory cycle?

A PM-centred retrofit objective and a broader in-use emission assessment answer different questions. PM remains important because of its direct health relevance. At the same time, the World Health Organization addresses PM, ozone and nitrogen dioxide as separate key air pollutants, indicating the value of a multi-pollutant perspective in air-quality management. The present study therefore evaluates the measured behaviour of CO, HC, NO_x and PM without treating any one pollutant as a substitute for another.

2. Study design and boundaries

2.1 Selection of field-representative samples

Eight generator engines were procured from field use to cover a practical range of power ratings and model years. Commercial identities, model names and ownership history are intentionally withheld. Throughout the article, the units are identified only as Sample 1 to Sample 8. The sample set is exploratory and is not statistically representative of the entire national population.

Sample	Model year	Rated power (kW)
Sample 1	2012	220.0
Sample 2	2011	113.2
Sample 3	2007	93.3
Sample 4	2005	113.2
Sample 5	2004	77.2
Sample 6	2004	61.0
Sample 7	2011	29.4
Sample 8	2013	41.2

Table 1. Anonymised sample matrix used for the in-use assessment.

2.2 Preparation and measurement protocol

Each engine was serviced in accordance with the available manufacturer-prescribed procedure. It was mounted on an engine test cell, coupled to a dynamometer and operated for 20 hours to establish stable operation and confirm power capability. Emissions were measured over the ISO 8178-4 D2 five-mode steady-state cycle. CO, HC and NO_x were determined using gaseous emission analysers, while PM was measured gravimetrically through a particulate measurement system. Fuel flow, coolant condition and relevant operating parameters were monitored during testing.

The controlled laboratory cycle improves repeatability, but does not reproduce every field duty cycle. The results describe the condition of the tested engines over the prescribed D2 cycle and should not be interpreted as total annual mass emissions at their installation sites.

2.3 Retrofit configuration assessed

A passive configuration combining a diesel oxidation catalyst (DOC) and a partial-flow filter (PFF) was evaluated after baseline testing. The DOC primarily oxidises CO and unburned hydrocarbons, while the particulate element captures and oxidises a fraction of soot. Neither element is a dedicated lean-exhaust NO_x-reduction system. The exercise therefore separates pollutants that passive oxidation and filtration can address from pollutants requiring a different technical mechanism.

3. Baseline results: the emission signature is not uniform

Sample	CO	HC	NO _x	HC+NO _x	PM
Sample 1	0.39	0.41	9.54	9.95	0.1010
Sample 2	0.74	0.57	9.68	10.25	0.1620
Sample 3	0.60	0.66	13.16	13.82	0.0935
Sample 4	2.59	0.18	8.43	8.61	0.5294
Sample 5	0.71	0.52	7.18	7.70	0.1180
Sample 6	0.94	0.66	7.70	8.36	0.1340
Sample 7	0.89	0.34	9.01	9.35	0.1920
Sample 8	1.15	0.30	8.32	8.62	0.1440

Table 2. Baseline D2-cycle specific emissions (g/kWh).

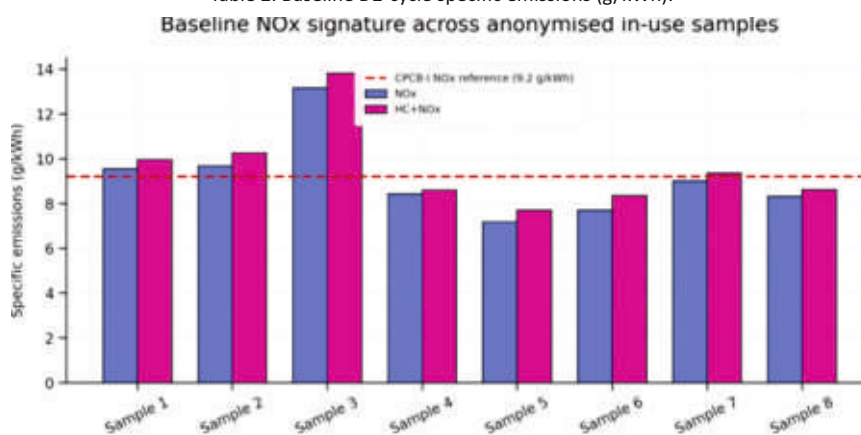


Figure 1. Baseline NO_x and HC+NO_x across anonymised in-use samples.

CO remained below 3.5 g/kWh in all eight samples. PM was below 0.30 g/kWh in seven samples, while Sample 4 recorded 0.5294 g/kWh. NOx behaved differently. Samples 1, 2 and 3 exceeded the 9.2 g/kWh CPCB-I benchmark, and Sample 7 approached it at 9.01 g/kWh. Sample 3 produced the highest NOx result at 13.16 g/kWh, approximately 43% above the benchmark. The results therefore show that comparatively moderate PM cannot be used to infer comparatively moderate NOx.

The measured divergence is consistent with the recognised NOx-soot trade-off in diesel combustion, but the present study does not establish a unique deterioration mechanism. Injection timing, pump calibration, governor response, injector condition, fuel properties, maintenance history and duty cycle are plausible influences. These parameters were not comprehensively measured and are therefore identified as hypotheses for follow-on investigation, not as demonstrated causes.

4. Passive retrofit results: strong oxidation, moderate filtration, minimal NOx change

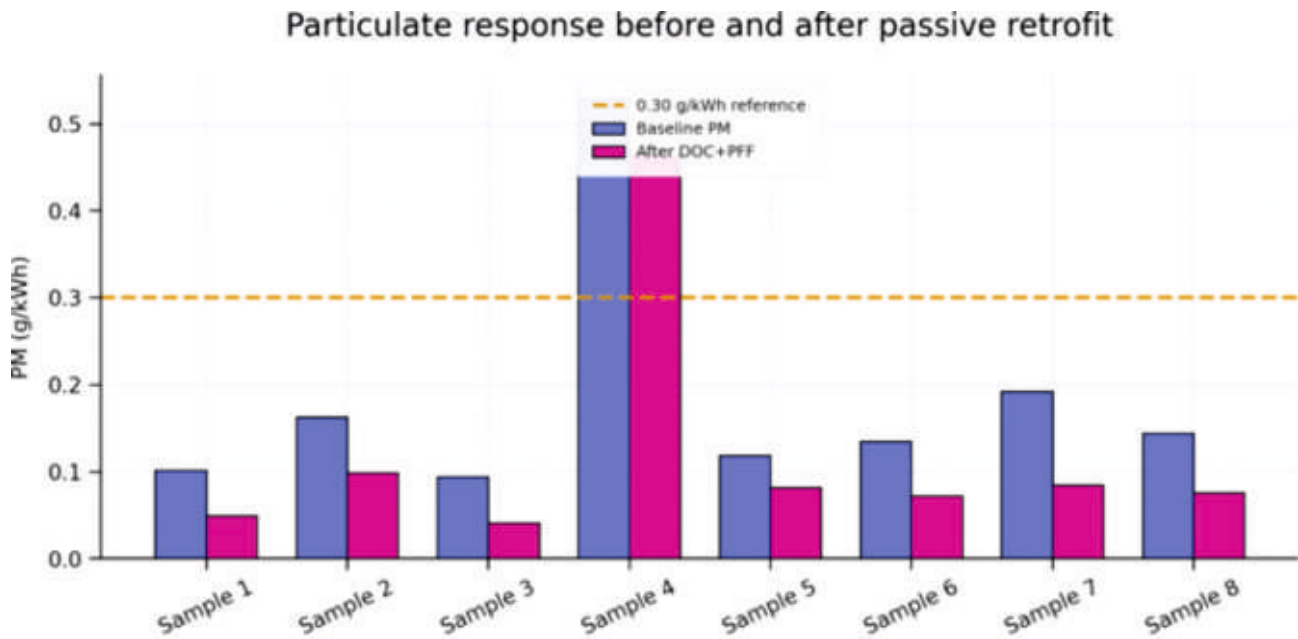


Figure 2. Baseline and post-retrofit PM emissions.

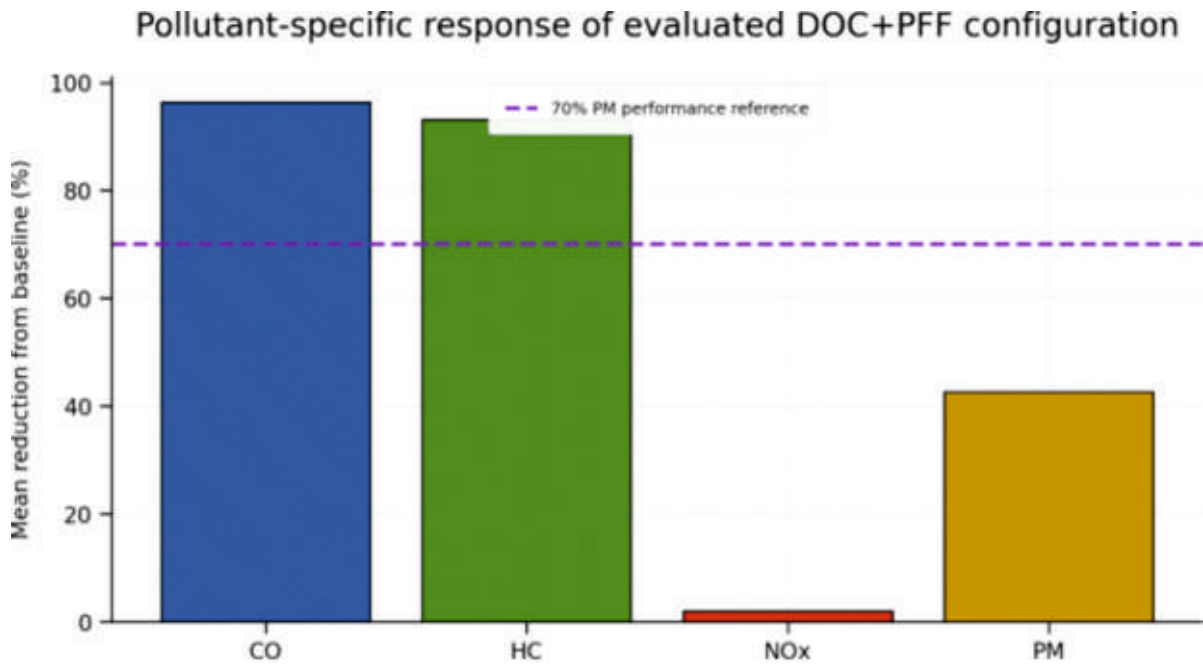


Figure 3. Mean pollutant-specific response of the evaluated DOC+PFF configuration.

Across the eight samples, the passive configuration reduced CO by 92.96-100% and HC by 86.67-97.56%. PM reduction varied from 12.16% to 56.25%. None of the tested sample-device combinations achieved 70% PM reduction in this experimental configuration. NOx changed by -1.67% to +4.03% reduction, averaging about 2%. In practical terms, NOx was carried through the passive system largely unchanged.

The result should not be generalised to every certified RECD technology or installation. Different systems may use different substrates, catalyst formulations, filtration strategies, regeneration controls and diagnostics. The finding instead illustrates a design principle: useful oxidation and particulate benefits can coexist with negligible NOx conversion because the respective control mechanisms are different.

5. Discussion: why NOx merits attention in future in-use studies

5.1 Air-quality relevance without diminishing particulate control

The discussion of NOx is complementary to, rather than in competition with, particulate control. PM2.5 has well-established health relevance and remains an essential control objective. The World Health Organization provides health-based air-quality guideline levels for PM2.5, PM10, ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide, treating these as distinct key pollutants rather than substitutes for one another.

NOx matters through both direct and secondary pathways. Nitrogen dioxide is itself included in the WHO air-quality guideline framework. In addition, ground-level ozone is formed through photochemical reactions involving NOx and volatile organic compounds in sunlight. The high HC reduction observed with the DOC is therefore a meaningful outcome because it reduces one class of ozone-forming precursors. However, the near-unchanged NOx result leaves the other major precursor largely unaffected.

The present data offer a technical signal rather than a population-wide conclusion. Seven samples recorded PM below 0.30 g/kWh, whereas three exceeded the 9.2 g/kWh NOx benchmark. This divergence demonstrates why PM performance alone cannot describe the complete in-use emission signature of an ageing diesel engine. It supports wider measurement and characterisation, but does not by itself establish the scale of a national NOx problem.

5.2 Relevance to stationary legacy engines

Stationary engines merit targeted consideration because emissions occur at identifiable fixed sites and may be released for sustained periods during outages or scheduled operation. The significance of an individual installation will depend on engine-out emissions, operating hours, load, stack arrangement, dispersion conditions and proximity of receptors. Consequently, a proportionate approach should begin with measurement and duty-cycle characterisation rather than a uniform technology prescription.

This is particularly important for the diverse legacy population. A lightly used emergency generator and a high-utilisation captive-power installation may have different cumulative emissions, exhaust-temperature profiles and practical capacity to support additional controls. Future in-use work should therefore distinguish applications by utilisation and thermal duty rather than treating all installed engines as one category.

5.3 Challenges in reducing NOx from old engines

NOx control in old engines is not analogous to fitting a passive oxidation catalyst. Many legacy generator engines use mechanical fuel systems and were not designed around integrated air-path control, electronic sensing, thermal management or exhaust after-treatment. Measures that reduce combustion temperature, such as EGR or injection-timing changes, can reduce NOx but may affect PM, CO, fuel consumption or exhaust temperature unless the engine is calibrated as a complete system.

Published SAE investigations demonstrate that EGR-based reduction is technically possible under controlled conditions. A low-pressure EGR and DPF retrofit reported more than 50% NOx reduction together with filtration efficiency above 99%. A separate generator-set investigation reported 75% NOx reduction at full load with 30% EGR, while also requiring an oxidation catalyst to control the accompanying increase in CO. A stationary-engine study reported up to 72% NO reduction at 25% EGR, together with increases in specific fuel consumption, CO and CO2. These results establish feasibility but also show why EGR cannot be treated as a universal bolt-on measure.

SCR-based retrofit has also demonstrated substantial potential. An SAE retrofit system combining catalysed particulate filtration, SCR and oxidation treatment achieved about 70% overall NOx reduction without communication with the engine CAN bus. Nevertheless, SCR performance depends on exhaust temperature, reductant dosing and catalyst integration. Standby or low-load duty may not consistently provide the thermal conditions required for reliable conversion. Packaging,

backpressure, reagent availability, deposit prevention, diagnostics, maintenance and ammonia-slip control further influence practical adoption.

5.4 Scope for a restrained and frugal technical dialogue

The evidence does not support recommending one NO_x-control technology for every old generator. It supports a sequence of questions. First, is the engine mechanically healthy and operating close to its intended calibration? Injector servicing, pump calibration, timing verification, air-path maintenance, cooling-system restoration and load validation use the existing service ecosystem and may correct avoidable deterioration at comparatively low cost. Their NO_x benefit must be measured rather than assumed.

Second, passive DOC and PFF or POC benefits should be retained where demonstrated. The large HC and CO reductions observed in this study and the partial PM benefit are meaningful even though NO_x remains unchanged. Third, advanced NO_x control should be examined selectively. Engine-specific EGR may merit evaluation where cooling margin, calibration support and particulate control are available. SCR may merit evaluation for larger or higher-utilisation installations with an adequate thermal window and professional operation. Where engine condition or duty is unsuitable, repower, replacement or operational measures may be more proportionate than a complex retrofit.

Accordingly, the article opens a dialogue rather than proposing a mandate. A useful next step would be a controlled demonstration programme that records engine condition, operating hours, load, exhaust-temperature distribution, baseline NO_x and PM, intervention cost, fuel or reagent penalty, maintenance requirement and measured durability. Such evidence would allow technical and economic suitability to be judged by duty class.

6. Limitations and future experimental work

The sample size is small and does not support population-wide prevalence estimates. Operating hours, maintenance quality and field-load history were not available uniformly. The D2 cycle provides a controlled comparison but cannot represent every installation. The study also did not measure combustion pressure, start of injection, injector flow, pump advance, EGR rate, detailed exhaust-temperature distribution, fuel composition or catalyst ageing.

Follow-on work should pair emissions with root-cause instrumentation. Useful experiments would include baseline testing before and after injector and pump calibration; direct measurement of injection timing and cylinder pressure; fuel-property analysis; cold-start and low-load thermal mapping; repeated testing after defined service intervals; and comparison of passive, EGR-based and SCR-based packages on selected duty classes. The purpose should be to test practical hypotheses, not presume the suitability of a technology.

7. Conclusions

1. The eight field-procured engines did not exhibit one uniform in-use emission pattern. CO and PM were generally controlled, while NO_x or HC+NO_x remained elevated in several samples.
2. Three samples exceeded the 9.2 g/kWh CPCB-I NO_x benchmark; the highest NO_x result was 13.16 g/kWh. One sample also showed distinctly high PM.
3. The evaluated DOC+PFF configuration strongly reduced CO and HC and reduced PM to varying degrees, but did not materially reduce NO_x.
4. The findings do not displace the importance of PM control. They show that PM and NO_x are distinct engineering and air-quality considerations, and that PM performance alone does not describe the complete in-use emission signature.
5. Published research demonstrates possible EGR- and SCR-based NO_x reductions under suitable conditions, but also identifies performance trade-offs and integration constraints for old engines.
6. The study does not recommend a particular NO_x-control technology or immediate regulatory intervention. It supports expanded in-use evidence, engine-condition restoration, selective demonstrations and a broader multi-pollutant perspective in future investigations.

The present study therefore opens a measured technical dialogue. The immediate opportunity is to preserve proven PM, HC and CO benefits while improving the characterisation of in-use NO_x. Any future response should be guided by verified emission benefit, engine suitability, duty cycle, affordability, durability and customer operability.

Acknowledgement and declaration

The article draws on an anonymised technical study commissioned in the public-interest context and testing undertaken at recognised automotive emission laboratories. Commercial identities have been removed. The discussion is technology-neutral and does not endorse or criticise any manufacturer, retrofit supplier or product. Interpretations beyond the measured results are presented as technical hypotheses and directions for further investigation.

References

- i. Central Pollution Control Board. System and Procedure for Emission Compliance Testing of Retrofit Emission Control Devices for Diesel Power Generating Set Engines up to Gross Mechanical Power 800 kW, CPCB-PCLS/12/2021-22, 2022.
- ii. International Organization for Standardization. ISO 8178-4: Reciprocating internal combustion engines - Exhaust emission measurement - Test cycles for different engine applications.
- iii. World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter, Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva, 2021.
- iv. United States Environmental Protection Agency. Ground-level Ozone Basics.
- v. Hohl, Y., Amstutz, A., Onder, C., Guzzella, L. and Mayer, A. Retrofit Kit to Reduce NO_x and PM Emissions from Diesel Engines Using Low-Pressure EGR and a DPF System. SAE Technical Paper 2008-01-0330. <https://doi.org/10.4271/2008-01-0330>.
- vi. Khalil, N., Levendis, Y.A. and Abrams, R.F. Reducing Diesel Particulate and NO_x Emissions via Filtration and Particle-Free Exhaust Gas Recirculation. SAE Technical Paper 950736. <https://doi.org/10.4271/950736>.
- vii. de Oliveira, A., Bernardes, A.P. and Ferreira, F. Reduction of a Diesel Engine NO Emissions Using the Exhaust Gas Recirculation Technique. SAE Technical Paper 2019-36-0067. <https://doi.org/10.4271/2019-36-0067>.
- viii. Servati, H. et al. A NO_x Reduction Solution for Retrofit Applications: A Simple Urea SCR Technology. SAE Technical Paper 2005-01-1857. <https://doi.org/10.4271/2005-01-1857>.
- ix. Conway, R. et al. Combined SCR and DPF Technology for Heavy Duty Diesel Retrofit. SAE Technical Paper 2005-01-1862. <https://doi.org/10.4271/2005-01-1862>.
- x. Wang, F. et al. Research on NO_x Emissions Testing and Optimization Strategies for Diesel Engines Under Low-Load Cycles. Atmosphere, 2025, 16(2), 190. <https://doi.org/10.3390/atmos16020190>.
- xi. Chen, Z. et al. Recent Advances in SCR Systems of Heavy-Duty Diesel Vehicles: Low-Temperature NO_x Reduction Technology and Combination of SCR with Remote OBD. Atmosphere, 2024, 15(8), 997. <https://doi.org/10.3390/atmos15080997>.



Accelerating Engine Efficiency through Integrated Technology Solutions

The Value Proposition: Optimize Combustion. Reduce Friction. Preserve Energy, Extend Durability & Improved Fuel Economy

Thalavai Venkatesan
Tenneco Clean Air India Pvt Ltd

Abstract

The automotive industry is undergoing a significant transformation driven by increasingly stringent emissions regulations, fuel economy mandates, and customer expectations for higher performance and durability. While substantial advances have been achieved through combustion optimization and electronic engine controls, further efficiency gains now require a holistic approach to powertrain design.

Tenneco's integrated portfolio of pistons, piston rings, bearings, valve train components, sealing systems, ignition and aftertreatment technologies provides a comprehensive engineering solution that addresses the key sources of efficiency loss throughout the engine. By simultaneously optimizing combustion, reducing friction, minimizing leakage, improving gas exchange, and enhancing durability, these technologies enable OEMs to maximize engine performance while meeting increasingly stringent emissions regulations.

In today's highly competitive automotive landscape, engine manufacturers face unprecedented challenges in achieving higher fuel efficiency, lower emissions, increased power density, and enhanced durability. While significant advancements continue to be made in combustion systems and engine controls, the greatest gains are increasingly being achieved through the integration of advanced powertrain components that work synergistically as a complete system.

Integrated Approach

Historically, engine efficiency improvements were often pursued through individual benefits from use of advanced technology Components. However, modern internal combustion engines operate in a highly interconnected environment where friction, combustion efficiency, thermal management, airflow, lubrication, and sealing all influence overall engine performance.

As emission standards continue to tighten and OEMs pursue aggressive fuel economy targets, incremental improvements from individual components are no longer sufficient. Instead, substantial gains are realized when powertrain technologies are engineered to operate as an integrated system. Tenneco's powertrain solutions exemplify this approach by addressing every critical interface within the engine architecture.

Introduction

Modern internal combustion engines operate within a highly interconnected ecosystem where every subsystem influences overall performance. Friction, combustion efficiency, thermal management, lubrication, sealing effectiveness, and airflow characteristics collectively determine fuel consumption, emissions output, and engine durability.

Historically, engine efficiency improvements were achieved through isolated component enhancements. However, as engines approach practical efficiency limits, incremental gains from individual technologies deliver diminishing returns. The next generation of performance improvements demands integrated engineering solutions that optimize interactions across the entire powertrain.

Sources of Efficiency Loss in Modern Engines

Engine efficiency losses originate from five primary areas:

1. Combustion Inefficiency

Incomplete fuel combustion reduces thermal efficiency and increases harmful emissions.

2. Mechanical Friction

Friction between moving components such as pistons, rings, bearings, and valve train assemblies converts useful energy into heat.

3. Blow-By and Leakage

Leakage of combustion gases past piston rings reduces cylinder pressure and wastes energy.

4. Inefficient Gas Exchange

Restrictions in air intake and exhaust valve operation limit volumetric efficiency and combustion effectiveness.

5. Component Wear

Progressive wear degrades sealing, increases friction, and reduces long-term engine performance.

Addressing these losses requires technologies that function together rather than independently.

Integrated Powertrain Technologies

1. Advanced Piston Technology

Pistons represent the heart of the combustion chamber. Advanced piston designs contribute to:

- Enhanced combustion chamber geometry
- Improved thermal management.
- Reduced reciprocating mass.
- Lower mechanical losses (Friction, weight, and NVH)

Modern lightweight materials and optimized crown designs improve combustion efficiency while reducing inertia, contributing to improved fuel economy and performance.



DuraBowl®



Benefits

- Improved thermal efficiency.
- Reduced fuel consumption
- Enhanced power density
- Better durability under high loads

2. Low-Friction Piston Ring Technologies

Piston rings perform a critical balancing act between effective sealing and friction reduction.

Advanced ring coatings and optimized geometries help:

- Reduce friction losses
- Minimize oil consumption
- Improve cylinder sealing
- Lower blow-by emissions

Even small reductions in ring friction can translate into measurable fuel economy benefits across the engine lifecycle.

TENNECO

TENNECO CLEAN AIR INDIA LIMITED



PASSENGER VEHICLES



COMMERCIAL TRUCKS



OFF-HIGHWAY VEHICLES



DRIVING INDIA TOWARDS **CLEANER TOMORROW**

Advanced Exhaust & Aftertreatment Technology

Tenneco Clean Air designs and manufactures emissions control solutions that help vehicle manufacturers address emissions, fuel economy and acoustic performance.

Emission Control

- Full Aftertreatment System with one stop solution

Thermal Management

- Cold Start Thermal Unit
- EHeater

Acoustic Performance

- Active & Passive valve
- Smart Sound Cold-End Systems

WHY TENNECO CLEAN AIR



GLOBAL ENGINEERING

Advanced technology portfolio designed for evolving emissions standards.



SYSTEM INTEGRATION

From thermal management to aftertreatment engineered as complete systems.



APPLICATION BREADTH

Solutions spanning light vehicle, commercial truck and off-highway markets.



ENGINEERED EFFICIENCY

Technologies developed to support emissions control, fuel economy and acoustic performance.

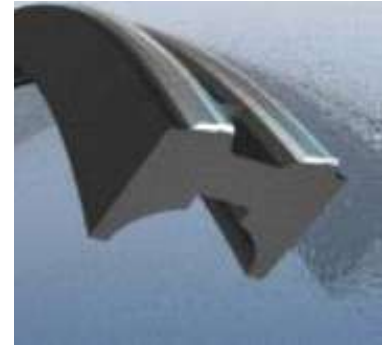
INNOVATION | PERFORMANCE | SUSTAINABILITY

LET'S CONNECT

Sandeep Chaukhande | Director – Sales

Email: SChaukhande@Tenneco.com

Mobile: +91 98226 07055



Benefits

- Reduced Friction
- Improved sealing efficiency (Better Blowby and LOC)
- Lower emissions
- Extended engine life

3. Advanced Bearing Solutions

Bearings support rotating assemblies while minimizing resistance.

Modern bearing technologies feature:

- Improved material compositions
- Enhanced fatigue resistance
- Optimized surface finishes
- Superior lubrication characteristics

High-performance bearings reduce energy losses while maintaining durability under increasingly demanding operating conditions.



Technology :-

- Enhance Fatigue strength (120 Mpa)
- Friction reduction (25%)
- High wear resistance (50x lesser)



Technology :-

- Same performance as coated bearings at lower cost (15% less)
- Enhance Fatigue strength (120 Mpa)
- Weight reduction (10%)



Benefits

- Reduced parasitic losses
- Improved reliability
- Greater load-carrying capacity
- Enhanced fuel efficiency

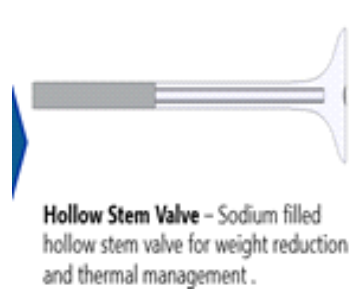
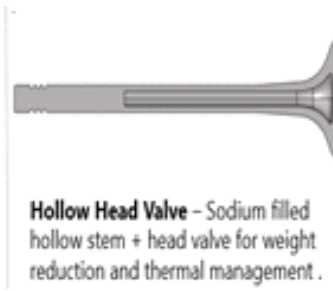
4. Valve Train Optimization

Valve train systems directly influence airflow management and combustion performance.

Precision-engineered valve train components help:

- Improve airflow efficiency
- Reduce valve train friction
- Enable higher operating speeds
- Improve combustion stability

Efficient gas exchange supports greater cylinder filling and improved combustion quality.



Mirror Finishing Top Head TOH with mirror finishing to improve thermal management and New Valve material development.

Benefits

- Enhanced volumetric efficiency
- Improved power output
- Lower mechanical losses
- Reduced emissions

5. Advanced Sealing Systems

Effective sealing is essential to maintain pressure, lubrication integrity, and thermal control.

Tenneco sealing technologies help:

- Prevent combustion gas leakage
- Maintain lubrication effectiveness
- Improve thermal management
- Protect critical engine components



Benefits

- Reduced fluid losses
- Enhanced engine reliability
- Improved emissions control
- Longer service life

6. Ignition Technologies

Combustion quality depends heavily on ignition performance.

Advanced ignition systems enable:

- Faster flame propagation
- More complete combustion
- Improved cold-start performance
- Reduced emissions generation

Enhanced ignition efficiency translates directly into improved fuel utilization and cleaner engine operation.

Pre- Chamber Spark Plug



Benefits

- Better fuel economy
- Lower emissions
- Improved drivability
- Enhanced combustion stability

The Synergy of Integration

The true value of advanced powertrain technology emerges when multiple systems are engineered to work together.

For example:

- Low-friction piston rings reduce mechanical losses.
- Advanced bearings further decrease energy consumption.
- Optimized valve train systems improve airflow.
- Improved ignition systems enhance combustion efficiency.
- Effective sealing systems preserve compression and lubrication.

The combined impact exceeds the sum of individual improvements because gains in one subsystem reinforce performance in another.

This integrated engineering philosophy enables manufacturers to unlock efficiencies that would be difficult to achieve through standalone component optimization.

Supporting Future Emissions and Efficiency Targets

Global emissions regulations continue to become more stringent. Simultaneously, OEMs face increasing pressure to improve:

- Fuel economy
- Carbon dioxide reduction
- Engine downsizing effectiveness
- Power density
- Durability requirements

Meeting these objectives requires a comprehensive approach to powertrain efficiency that addresses every major source of energy loss within the engine architecture. Tenneco's integrated technology portfolio provides OEMs with a pathway to achieve these goals while maintaining performance and reliability.

Integration of Clean Air Technologies for Future Emission Standards

1. Beyond Engine Efficiency: The Role of Aftertreatment Systems

While engine efficiency improvements reduce fuel consumption and carbon emissions, compliance with future emission regulations increasingly depends on advanced exhaust aftertreatment technologies. Modern Clean Air systems must simultaneously address nitrogen oxide (NOx) reduction, fuel efficiency, packaging constraints, durability, and real-world driving emission compliance. These requirements have transformed aftertreatment system (ATS) development from a component-focused activity into a system-level engineering challenge.

Figure 5 illustrates the evolution of mixer development from a simple fluid mixing device into a multifunctional subsystem supporting overall ATS performance.



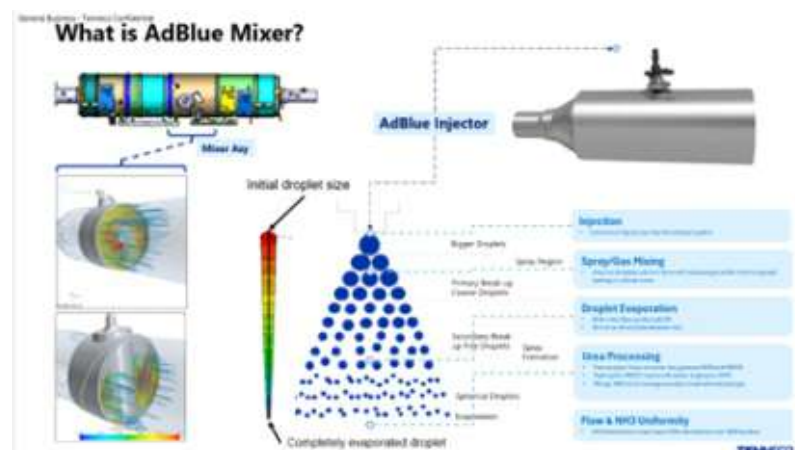
2. AdBlue Mixer as a Critical ATS Enabling Technology

The AdBlue mixer serves as the interface between reductant dosing and Selective Catalytic Reduction (SCR) catalyst performance. Its function extends beyond generating turbulence within exhaust gases.

The mixer is responsible for:

- AdBlue spray atomization
- Exhaust gas mixing
- Droplet evaporation
- Urea thermolysis and hydrolysis
- Ammonia distribution across the SCR catalyst face

Effective mixer design directly influences NOx conversion efficiency, catalyst utilization, deposit formation risk, and overall ATS pressure loss.



3. Future Emission Regulations Driving ATS Complexity

Future BS VII, Euro VII, and Real Driving Emission (RDE) regulations introduce significantly tighter limits on NOx emissions under a broader operating window.

As a result, next-generation aftertreatment systems increasingly incorporate:

- Close-coupled catalyst systems
- Dual dosing arrangements
- Electrically heated catalysts
- Compact packaging architectures
- Enhanced SCR catalyst utilization targets

The development process must therefore simultaneously optimize emissions performance, system pressure drop, packaging constraints, and thermal management

4. Simulation-Led ATS Development Methodology

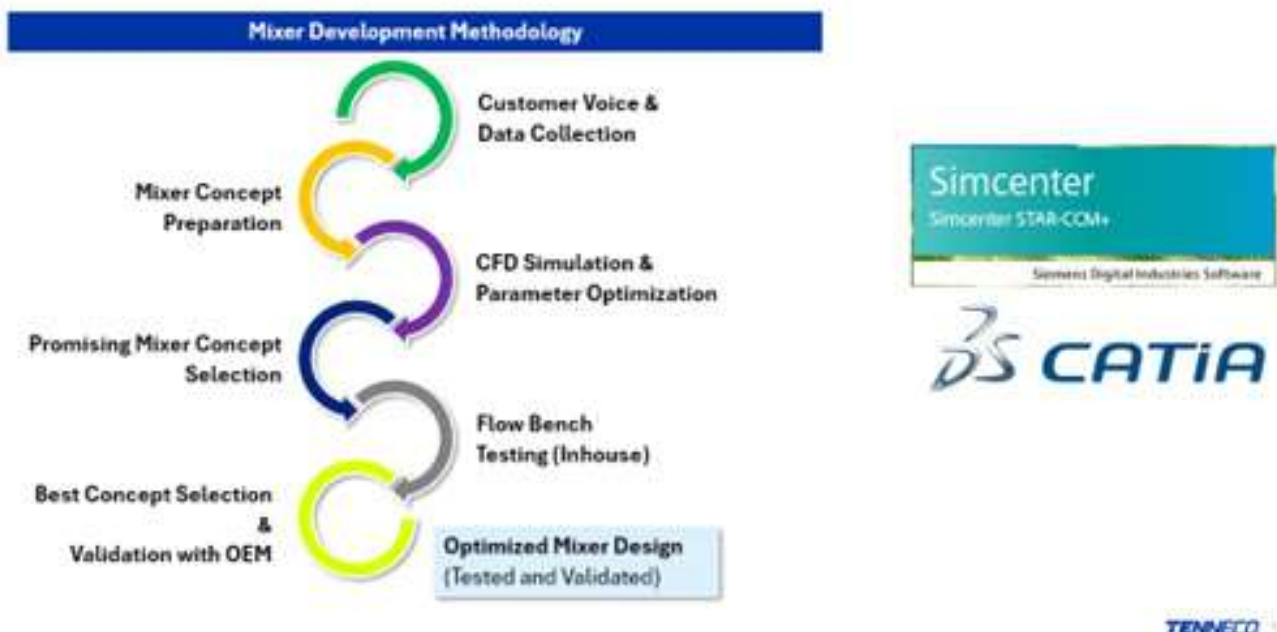
To address the growing complexity of emission systems, Tenneco has developed a simulation-led, field-informed methodology for mixer optimization. The development approach includes:

1. Customer and operating-data collection
2. Mixer concept preparation
3. CFD-based parameter optimization
4. Flow-bench validation
5. Concept selection
6. OEM validation and system integration

This process enables rapid exploration of the design space while maintaining correlation between simulation and physical testing.

General Business - Tenneco Confidential

Case Study: NextGen Double Swirl Mixer



5. SCR Optimization Through Improved NH₃ Uniformity

One of the most significant contributions of advanced mixer technology is increased ammonia distribution uniformity at the SCR inlet.

Improved NH₃ Uniformity Index (UI):

- Enhances catalyst-face utilization
- Improves NO_x conversion efficiency
- Creates opportunities for catalyst-volume optimization Contributes to overall system cost reduction



Table 4. Key Requirements for Future ATS Mixer Development

Requirement Category	Key Objectives
Performance	NH ₃ Uniformity, NO _x Conversion, Low-Temperature Operation
Integration	Packaging, Serviceability, Injector Compatibility
Robustness	Thermal Durability, Deposit Management, High Dosing Capability
System Efficiency	Pressure Drop Reduction, Catalyst Optimization
Regulatory Compliance	RDE, ISC, Future NO _x Limits
Field Validation	Real Driving Conditions, Expanded Operating Window

Case Study: Gen2 Double Swirl Mixer

A case study involving a Next-Generation Double Swirl (Gen2 DS) mixer demonstrated the effectiveness of the integrated development methodology.

The final validated design achieved:

- NH₃ Uniformity Index greater than 0.99 across evaluated operating points
- 35% reduction in mixer backpressure
- Very low wall impingement
- No deposits observed during evaluation conditions
- Compatibility with multiple injector configurations
- Serviceable design within existing ATS packaging limits

These improvements support improved SCR utilization, fuel efficiency, DEF consumption optimization, and platform commonization.

Conclusion

The future of powertrain development requires simultaneous optimization of engine efficiency and emissions performance. Advanced engine technologies, including pistons, piston rings, bearings, valve train systems, sealing systems, and ignition technologies, must increasingly work in conjunction with sophisticated Clean Air solutions such as SCR aftertreatment systems and advanced AdBlue mixer technologies.

The integration of Tenneco's Powertrain and Clean Air portfolios creates a comprehensive engineering framework that addresses the complete energy-conversion pathway, from combustion efficiency within the cylinder to emissions reduction within the exhaust stream. Through synchronized optimization of combustion, friction reduction, sealing performance, catalyst utilization, ammonia distribution, and aftertreatment effectiveness, OEMs can achieve the dual objectives of maximum engine efficiency and compliance with future global emission standards.



E20 Fuel Compatibility in Pre-E20-Ready Vehicles: Risks and Mitigation

Dr Sarmistha Nandy

Consultant- Energy Transition & Industrial Decarbonization; India, UAE

Abstract

India's transition toward E20 petrol is an important component of its energy-security and decarbonisation strategy. The transition also requires systematic assessment of the heterogeneous in-use vehicle fleet, particularly vehicles developed before widespread E20-oriented calibration and component validation. This paper presents a technical risk-assessment framework for pre-2023 vehicles without assuming that vehicle age alone determines incompatibility. Four principal pathways are examined: altered stoichiometric fuel demand and energy density, fuel-system material compatibility, water-assisted phase stability and corrosion, and the ability of electronic fuel-control systems to compensate for changed fuel properties. Analytical calculations are used to illustrate the direction and magnitude of stoichiometric and energy-density changes, while published material and fuel-phase studies are used to establish the evidence base. A practical problem-solution framework is proposed covering vehicle identification, fuel-quality verification, material inspection, fuel-pump/injector diagnostics, ECU monitoring and controlled durability testing. The paper concludes that a risk-based compatibility programme is preferable to a blanket classification of all pre-2023 vehicles as E20-incompatible.

Keywords: *E20 fuel; ethanol-blended petrol; pre-2023 vehicles; fuel-system compatibility; elastomer degradation; phase stability; corrosion; stoichiometric air-fuel ratio; ECU calibration; emission control.*

1. Introduction

India's ethanol-blended petrol programme has progressed from lower ethanol concentrations toward E20, creating a new fuel environment for both newly validated vehicles and vehicles already operating in the field. The engineering challenge is not adequately represented by a simple division between 'old' and 'new' vehicles. Fuel compatibility is a system property determined by material formulation, fuel quality, temperature, water exposure, component ageing, injector and pump capacity, and electronic control strategy.

The Automotive Research Association of India (ARAI) identifies E20 assessment of in-use two-wheelers and four-wheelers as including tailpipe emissions, fuel economy, durability and material-compatibility evaluation. This is important because it establishes the need to evaluate the in-use fleet rather than treating E20 solely as a new-vehicle certification issue. [1]

Published studies also demonstrate that ethanol-containing fuels can interact differently with elastomers and polymers used in fuel systems. A 2014 Indian study examined NBR, HNBR, neoprene, PVC/NBR, Nylon-66 and polyoxymethylene after controlled exposure to E5 and E10. [2] Other controlled studies have evaluated elastomer behaviour across broader ethanol concentrations and have shown that swelling and hardness response is strongly material dependent. [3,4]

Accordingly, the objective of this paper is to establish a technically defensible framework for identifying possible E20 compatibility risks in pre-2023 vehicles and to define mitigation measures that can be implemented without assuming that every older vehicle will experience failure.

2. Objectives and Research Questions

- Quantify, using a transparent analytical model, how increasing ethanol content changes stoichiometric AFR and blend energy density.
- Identify the principal fuel-system material, water/phase-stability, corrosion and fuel-control pathways that may influence in-use vehicle behaviour.
- Separate fuel-related mechanisms from failures caused by ageing, contamination or inadequate maintenance.
- Develop a practical diagnostic flow from reported symptoms to fuel, component and ECU verification.
- Recommend a risk-based framework for regulators, OEMs, service organisations and vehicle owners.

3. Methodology

3.1 Literature and regulatory review

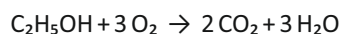
The manuscript uses literature-review and analytical-modelling methodology. Published material-compatibility studies, fuel-phase studies and Indian vehicle-testing information were used to identify mechanisms. No laboratory experiment is claimed as part of the present manuscript.

3.2 Stoichiometric analysis

Iso-octane is used as a simplified gasoline surrogate. Complete combustion is represented by



For ethanol:



Ethanol contains oxygen within its molecular structure, so the stoichiometric air requirement is lower than that of a hydrocarbon gasoline surrogate. For E20, the nominal volumetric composition is 20% ethanol and 80% gasoline. Because actual gasoline composition and density vary, the exact E20 stoichiometric AFR is formulation dependent.

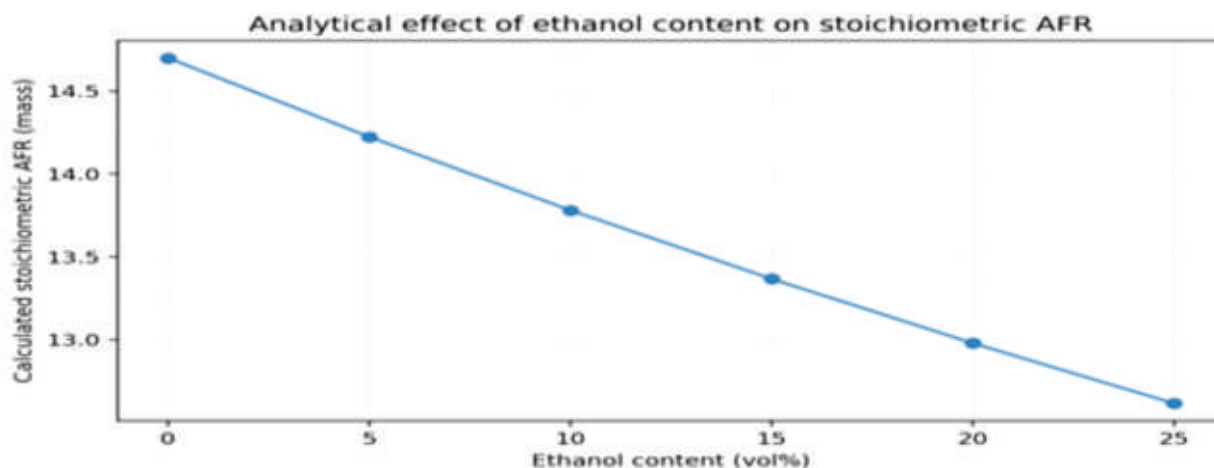


Figure 1. Calculated trend in stoichiometric AFR with ethanol content.

Model assumptions: gasoline AFR 14.7:1, ethanol AFR 9.0:1, densities 0.745 and 0.789 kg/L. Values are analytical illustrations, not vehicle measurements.

3.3 Energy-density analysis

Ethanol has a lower lower-heating value than conventional gasoline. Using representative assumptions of 44.0 MJ/kg for gasoline and 26.8 MJ/kg for ethanol, the blend LHV decreases as ethanol content increases. This does not mean that engine power must decrease because an electronically controlled engine can increase fuel delivery; it does mean that fuel quantity and calibration margin become relevant.

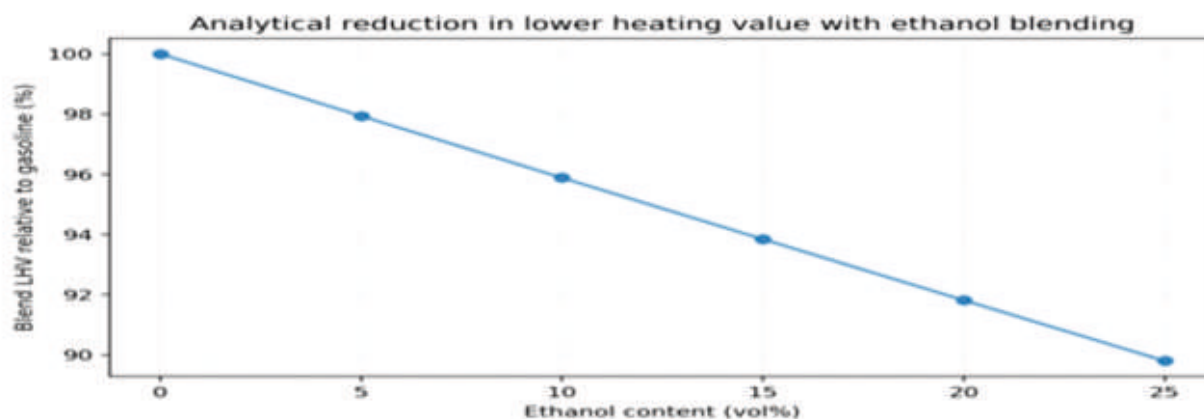


Figure 2. Calculated blend lower-heating-value index relative to the gasoline reference.

Model assumptions are stated above; the figure is not experimental vehicle data.

4. Principal E20 Compatibility Pathways

4.1 Elastomer and polymer interaction

Fuel hoses, seals, O-rings, gaskets and other components may contain NBR, HNBR, FKM, fluorosilicone and other formulations. Ethanol-containing fuels can alter volume, hardness and mechanical properties through solvent interaction and extraction or absorption of low-molecular-weight constituents. The effect is not uniform across materials. A study covering six elastomer families found substantial differences in swelling behaviour, with fluorocarbon materials generally showing lower swelling than several conventional elastomers. [3]

An Indian study on E5 and E10 reported measurable changes in physical and mechanical properties after 500 hours at $55 \pm 2^\circ\text{C}$ and demonstrated that compatibility depends on the specific material rather than ethanol percentage alone. [2] A later study directly compared E0, E10, E12, E15 and E20 exposure of NBR/PVC and epichlorohydrin materials using a six-week elevated-temperature protocol, reinforcing the need for component-specific assessment. [4]

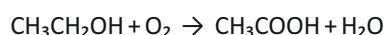
4.2 Water absorption and phase stability

Ethanol has a strong affinity for water. Water ingress can occur through condensation, storage problems, dispensing equipment or other contamination pathways. Experimental work on gasoline-ethanol-water systems has shown that water tolerance and phase behaviour depend on temperature, ethanol concentration and the amount of water present. [5]

Phase separation can generate an ethanol-rich aqueous phase and a gasoline-rich phase with altered composition. The resulting fuel may produce drivability problems if a substantial quantity of the aqueous phase reaches the engine. A fixed universal water threshold should therefore not be used for every E20 formulation.

4.3 Corrosion pathway

Corrosion in ethanol-containing fuel systems should be treated as a multi-factor electrochemical process involving water, oxygen, fuel chemistry, ionic contaminants, material composition and exposure time. A simplified ethanol-oxidation pathway can be written as



This reaction is useful for illustrating a possible source of organic acidity, but it should not be interpreted as the sole or dominant corrosion mechanism in every vehicle. Corrosion-product generation and component degradation require material- and fuel-specific evidence.

4.4 Fuel-pump and injector pathway

Fuel pumps and injectors remain continuously exposed to the fuel environment. Potential issues include seal degradation, flow-rate changes, pressure instability, leakage or deposit-related injector restriction. These symptoms are not unique to ethanol and can also result from normal ageing or contaminated fuel. Diagnostic attribution should therefore compare pressure, flow and injector performance with manufacturer specifications.

5. Engine-Control and Combustion Implications

The lower stoichiometric AFR of E20 means that a greater fuel quantity is required for a given air mass at the same target equivalence ratio. Closed-loop lambda control can compensate when adequate fuel-trim authority is available. The risk is therefore a calibration-margin problem rather than an automatic lean-burn condition.

Conditions requiring particular attention include cold start, rapid acceleration, high-load operation, fuel-pressure variation, injector saturation and the transition between open- and closed-loop control. Ethanol's high octane quality and high latent heat of vaporisation also mean that combustion response cannot be reduced to a simple statement that E20 always raises temperature or causes knock. Engine calibration, compression ratio, load and ignition timing must be considered together.

6. Problem-to-Solution Framework

Proposed E20 compatibility risk-assessment pathway

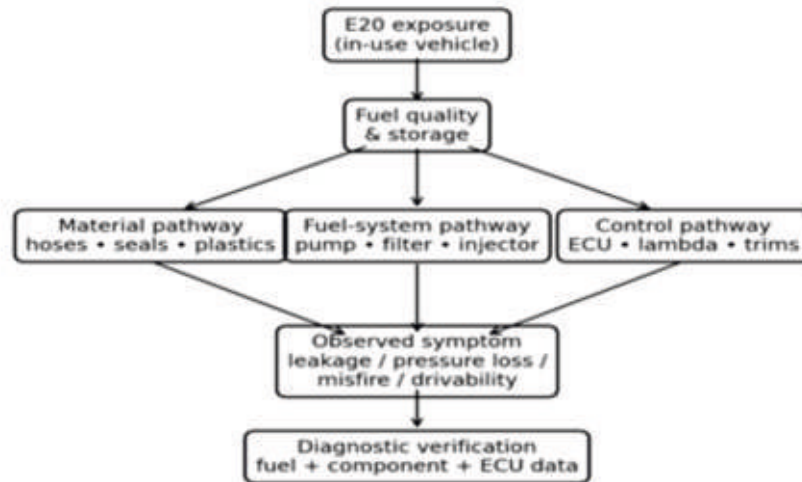


Figure 3. Proposed diagnostic pathway linking E20 exposure to fuel quality, materials, fuel delivery and electronic control.

The proposed framework begins with the vehicle and fuel history rather than assuming causation. If a symptom appears after E20 refuelling, the fuel should first be checked for ethanol content, water, particulate contamination and other quality indicators. Component inspection should then cover hoses, seals, filters, pump assemblies and injector performance. Finally, ECU data such as short- and long-term fuel trims, lambda response, misfire counts and fuel pressure should be reviewed.

 Risk pathway	 Trigger / condition	 Potential outcome	 Recommended control
 Material compatibility	Prolonged E20 exposure; temperature; susceptible elastomer formulation	Swelling, hardening, shrinkage or leakage of fuel-system components	Validate material compatibility; replace unsuitable components with validated fuel-compatible materials
 Water & phase stability	Water ingress, condensation, storage or dispensing contamination	Fuel-phase instability, drivability problems and possible misfire	Fuel-quality monitoring, proper storage and control of water contamination
 Corrosion	Water, oxygen, contaminants and susceptible metallic components	Corrosion, surface degradation and deposits	Material validation, fuel-quality control and periodic component inspection
 Fuel delivery	Ageing or degradation of pump/injector components; limited flow margin	Reduced pressure/flow, fuel-trim deviation or poor fuel delivery	Fuel-pressure, flow-rate and injector-performance verification
 Electronic control	Limited fuel-trim or calibration authority	Mixture-control deviation during specific operating conditions	OBD/fuel-trim diagnostics and model-specific calibration validation
 Cold-start operation	Low temperature and altered fuel-vapour characteristics	Hard starting, unstable combustion and increased cold-start emissions	Cold-start validation and appropriate ECU calibration
 Transient/high-load operation	Rapid load change or limited injector capacity	Temporary mixture deviation, hesitation or misfire	Transient dynamometer testing and fuel-system capacity verification
 EVAP system	Fuel-vapour exposure, seal/permeation behaviour	Increased evaporative or permeation emissions	EVAP-system inspection, permeability assessment and purge-system verification
 After-treatment	Sustained mixture deviation or misfire	Reduced catalyst conversion efficiency or catalyst thermal stress	Lambda, misfire and catalyst-performance monitoring
 Fuel-quality variation	Water, contaminants or off-specification fuel	Drivability problems and accelerated component degradation	Retail fuel-quality surveillance and fuel traceability

Table 1: Risk matrix summarising principal pathways and corresponding engineering controls.

8. Recommended Mitigation Measures

- Vehicle-specific compatibility classification should replace a blanket assumption that all pre-2023 vehicles are incompatible with E20.
- Service centers should inspect fuel hoses, seals, filters, fuel pressure and injector performance when E20-related complaints occur.
- Replacement components should have documented compatibility with the intended ethanol concentration and temperature range.
- Fuel-quality surveillance should include water contamination and storage/dispensing conditions because off-specification or contaminated fuel can create symptoms that may be incorrectly attributed to ethanol itself.

- ECU recalibration should be considered only after diagnostic evidence demonstrates inadequate fuel-control margin; a simple universal injector-duration increase is not an adequate engineering solution.
- Regulators should encourage a national field-failure database recording vehicle model, mileage, fuel source, fuel quality, component affected and diagnostic evidence.

9. Experimental Programme Proposed for Future Validation

The present paper is designed as an analytical review and framework. To convert the framework into a full experimental programme, the following tests are recommended.

- Material ageing: E0/E10/E20 immersion tests of NBR, HNBR, FKM and other representative fuel-system materials at controlled temperature, measuring mass, volume, hardness, tensile strength and elongation.
- Fuel-system durability: accelerated pump and injector testing with pressure, delivery rate, current draw, injector flow, leakage and spray-pattern measurements.
- Corrosion testing: exposure of representative metallic coupons to controlled fuel-water environments followed by mass-loss and surface-characterisation analysis.
- Vehicle dynamometer testing: comparison of representative pre-2023 vehicles using specification-compliant fuels under steady-state, transient, cold-start and high-load conditions.
- Field monitoring: longitudinal observation of representative vehicle models under Indian climate and driving conditions.

10. Research Gap and Contribution

Existing Indian work has already examined E20 in-use vehicle performance, including tailpipe emissions, fuel economy, durability and material compatibility. The remaining practical gap is the integration of these dimensions into a field-oriented diagnostic framework for vehicles that have accumulated mileage under changing fuel conditions. This manuscript contributes an integrated framework linking fuel properties, component condition, electronic fuel-control margin, evaporative emissions and tailpipe emission-control performance. The proposed framework is intended to support model-specific investigation rather than to classify every pre-2023 vehicle as E20-incompatible.

11. Emission-Control Implications of E20

E20 compatibility is directly relevant to emission control because the fuel system, combustion system and after-treatment system operate as one integrated chain. In spark-ignition engines, the three-way catalyst (TWC) achieves high conversion efficiency only when the exhaust mixture is held close to stoichiometric conditions. Ethanol's oxygen content and different physical properties change fuel delivery requirements, which makes accurate fuel metering and closed-loop lambda control more important, particularly during cold start and transient operation. Figure X shows the two pathways through which E20 affects tailpipe and evaporative emissions.

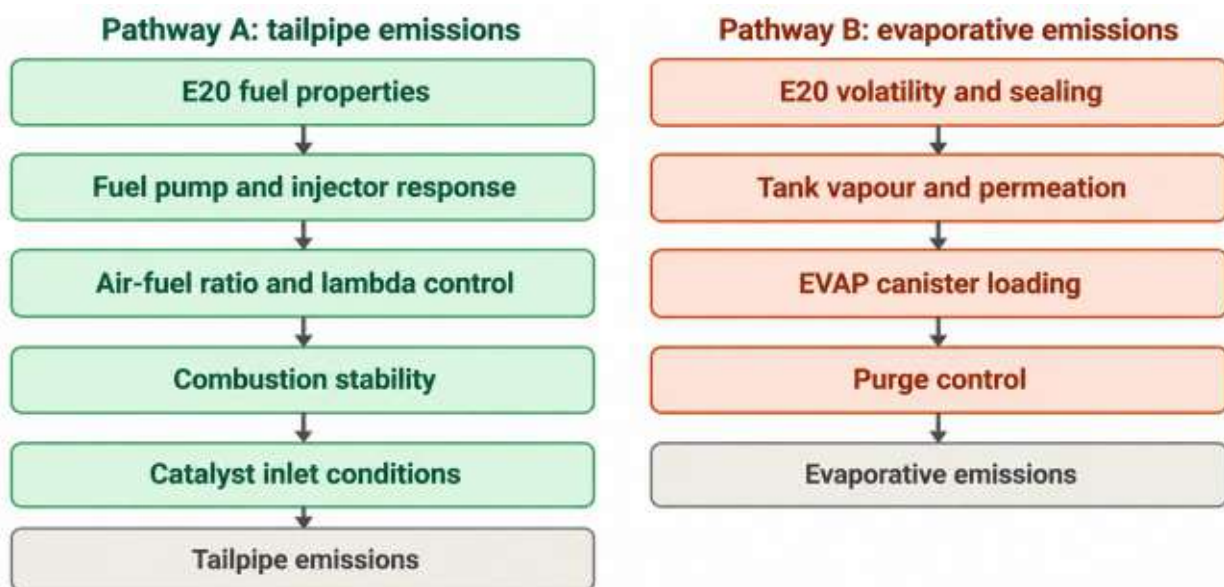


Figure 4. Emission-control pathways linking E20 fuel properties to (A) tailpipe emissions and (B) evaporative emissions in spark-ignition vehicles.

The evaporative pathway is especially relevant to pre-2023 vehicles, because ethanol blending alters vapour pressure behaviour and can increase permeation through elastomers and polymers not designed for higher ethanol content. ECMA technical material identifies evaporative emissions, EVAP systems, sensors and thermal management as key emission-control technologies, which supports treating both pathways as central to an assessment of E20 in the existing fleet.

12. Analytical Fuel-Delivery Requirement

For a fixed air mass and a target equivalence ratio, the lower stoichiometric AFR of ethanol-containing fuel implies a higher fuel mass requirement. The following analytical illustration expresses the theoretical fuel requirement relative to the gasoline reference. It is intended to show the direction of the engineering effect and is not a measured injector-duty-cycle result

13. Problem–Solution Framework for ECMA Application

The recommended approach is to move from anecdotal attribution to evidence-based diagnosis. When an E20-related complaint is received, the first step should be to establish fuel quality and vehicle history. The second step should identify whether the symptom originates from fuel-system material degradation, pressure/flow limitations, electronic control or evaporative-emission components. Only after these checks should a retrofit or calibration intervention be considered.

This approach is consistent with ECMA's broader position that vehicle technology, fuel quality and inspection/maintenance should be considered together when addressing emissions. It also avoids unnecessary replacement of components that are already suitable for E20.

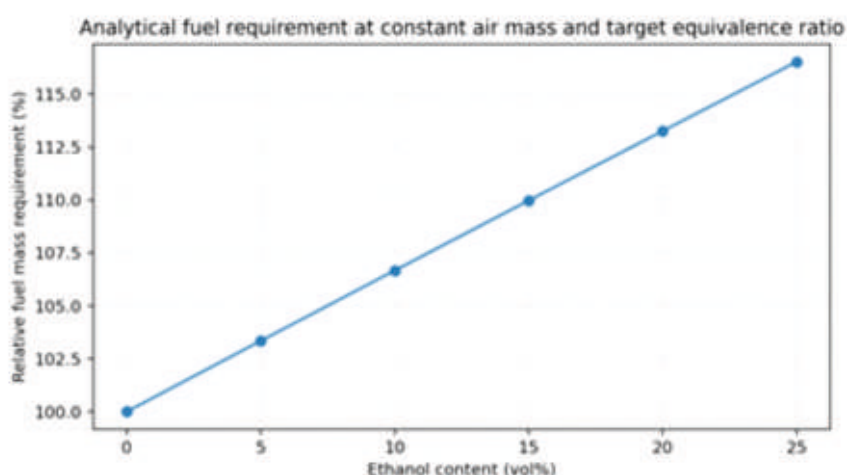


Figure 5. Analytical relative fuel requirement based on the modelled stoichiometric AFR. Gasoline AFR = 14.7:1 and ethanol AFR = 9.0:1. The curve is a theoretical illustration, not a vehicle measurement.

14. Recommended Validation Matrix

Test	Fuel	Vehicle/component	Primary measurement	Decision
Material immersion	E0 / E10 / E20	Hose / seal / elastomer	Volume, hardness, tensile properties	Compatibility class
Fuel-pump durability	E10 / E20	Pump module	Pressure, flow, current	Pump margin
Injector test	E10 / E20	Injector	Flow, spray, leakage	Delivery margin
Dynamometer	E10 / E20	Representative vehicle	Lambda, CO, HC, NOx, FE	Emission/drivability response
Evaporative test	E10 / E20	Fuel tank + EVAP	Diurnal loss, purge response	EVAP margin
Field monitoring	Commercial E20	In-use fleet	Fuel, faults, mileage, emissions	Real-world evidence

15. Conclusion

The engineering issue associated with E20 in the pre-2023 fleet should be framed as a compatibility-margin and emission-control question rather than as a universal failure mechanism. Ethanol changes fuel stoichiometry, energy density, material exposure and water sensitivity, while vehicle control systems determine how effectively those changes are accommodated. The most defensible regulatory response is therefore a model-specific, evidence-based framework combining fuel-quality surveillance, material compatibility assessment, fuel-system diagnostics, lambda/fuel-trim monitoring and emission-control validation.

For ECMA, the principal opportunity is to establish a common technical protocol that can connect E20 fuel quality with in-use vehicle emissions and component durability. Such a protocol would help distinguish fuel-related failures from ordinary ageing and contamination; support validated retrofit decisions and provide regulators with field evidence for future emission-control policy.

16. Discussion

The available evidence supports a nuanced position. Ethanol-blended gasoline can alter the physical and chemical environment experienced by fuel-system materials, but the magnitude of the effect varies substantially with material formulation and test conditions. Published work demonstrates both the potential for swelling and property change and the improved resistance of selected fluorocarbon materials. [2–4]

Water is another important variable. Experimental phase-equilibrium studies show that ethanol-gasoline systems can undergo water-induced phase separation, while the exact tolerance depends on composition and temperature. [5] Therefore, fuel-quality control is an essential part of any E20 compatibility policy.

For vehicle control systems, the key issue is the available correction range. An older ECU with closed-loop lambda feedback may compensate adequately under many conditions, while the same vehicle may have less margin during transient or high-load operation. This makes model-specific testing and diagnostics more useful than a simple manufacturing-year threshold.

ARAI's stated in-use E20 assessment program, which includes BS III, BS IV and BS VI two- and four-wheelers, durability and material compatibility, provides a suitable institutional basis for expanding evidence on the existing fleet. [1]

17. Limitations

This paper does not claim original laboratory or dynamometer measurements. The numerical graphs are analytical illustrations based on stated assumptions. Actual E20 behaviour depends on gasoline composition, ethanol purity, water content, additive package, vehicle calibration, component formulation, mileage, maintenance and environmental conditions. The framework should therefore be validated through controlled vehicle and component testing before being converted into mandatory retrofit requirements.

18. Policy Recommendations

- Establish a national E20 compatibility and field-performance database for in-use vehicles.
- Use manufacturer/model-specific compatibility information rather than manufacturing year alone.
- Create a standard diagnostic protocol for complaints associated with E20 use.
- Strengthen surveillance of water and other fuel contaminants at storage and retail stages.
- Require clear ethanol-compatibility information for aftermarket fuel-system components.
- Support independent durability and material testing through accredited automotive laboratories.
- Use field evidence to distinguish genuine E20 effects from normal ageing and contaminated/off-specification fuel.

19. Summary of Technical Findings

E20 represents an important step in India's ethanol-blending and energy-transition program, but its long-term implementation requires evidence-based management of the heterogeneous in-use fleet. The principal compatibility considerations include fuel-system materials, water-associated phase stability, corrosion, fuel-delivery capacity and electronic-control margin.

The available evidence does not justify classifying every pre-2023 vehicle as inherently incompatible with E20. Instead, a risk-based framework should identify vehicles and components with limited compatibility margins and provide targeted inspection, validated replacement, fuel-quality management and diagnostic support.

The proposed framework provides a practical pathway for regulators and the automotive service ecosystem to move from anecdotal E20 complaints toward measurable evidence. Future laboratory, dynamometer and field studies can use this framework to establish model-specific durability limits and validated mitigation measures for Indian operating conditions.

20. Declarations

Conflict of Interest: The author declares no known financial or commercial conflict of interest associated with this technical manuscript.

Funding: No external funding was received specifically for preparation of this manuscript.

Data Availability: The calculations underlying Figures 1 and 2 are reproducible from the assumptions stated in the captions. The literature-derived evidence is identified in the reference list. No proprietary experimental vehicle dataset is claimed.

Submission Integrity Note

All analytical figures in this manuscript are explicitly identified as modelled illustrations. No laboratory, dynamometer or field result is presented as an original measurement unless independently generated and documented by the author. The manuscript should be checked against the final ECMA submission template and reference style before submission.

References

- [1] Automotive Research Association of India (ARAI). Alternate Fuels Centre: Assessment of E20 Fuel on In-Use 2W and 4W Vehicles; material compatibility, durability, emissions and fuel-economy evaluation.
- [2] Dhaliwal, J.S., Negi, M.S., Kapur, G.S., et al. Compatibility Studies on Elastomers and Polymers with Ethanol Blended Gasoline. *Journal of Fuels*, 2014, Article 429608.
- [3] Compatibility of elastomers with test fuels of gasoline blended with ethanol. *Sealing Technology*, 2012, Issue 12, pp. 7–12. DOI: 10.1016/S1350-4789(12)70516-0.
- [4] Experimental Study on Elastomer Compatibility with Ethanol-Gasoline Blends. SAE/transport research literature, including E0, E10, E12, E15 and E20 exposure of NBR/PVC and epichlorohydrin materials.
- [5] Mueller, S.A., Anderson, J.E., Wallington, T.J., Hammond, R.M. A Classroom Demonstration of Water-Induced Phase Separation of Alcohol–Gasoline Biofuel Blends. *Journal of Chemical Education*, 2009, 86(9), 1045. DOI: 10.1021/ed086p1045.
- [6] Water Tolerance and Ethanol Concentration in Ethanol-Gasoline Fuels at Three Temperatures. *Energy & Fuels*, 2004. DOI: 10.1021/ef034040a.
- [7] Swelling of Vulcanized Rubber by Ethanol Blended Gasoline. *Journal of the Society of Rubber Science and Technology*, 2011, 84(6), 182–188.
- [8] Material Compatibility of Elastomers and Plastics in Gasoline-Ethanol-Methanol Blends. SAE Technical Paper 2023-01-0336.



Engineering Clean Mobility Advancements for BS-VII

(Conference Theme of ECT 2026)

Neelkanth Marathe

Emission Control Manufacturers Association (ECMA)

India's mobility requirements are evolving rapidly. Increasing urbanisation, economic growth, rising vehicle ownership, expanding logistics activity and growing demand for personal mobility are creating a transportation ecosystem that is both diverse and dynamic. At the same time, air-quality concerns, climate objectives, energy-security considerations and resource constraints are requiring the automotive industry to continuously improve environmental performance.

India has already travelled a considerable distance in tightening vehicle-emission requirements. The transition from earlier Bharat Stage regulations to BS-VI represented a major technological step for the industry. It brought significant improvements in engine and after-treatment technologies, fuel quality, electronic controls, diagnostics and emission measurement. The next stage of evolution will need to build on these achievements.

The concept of forthcoming emission regulation - BS-VII should, therefore, be considered in the context of a broader transition—from emission compliance to clean mobility performance. The transition towards BS-VII represents an important opportunity for the Indian automotive industry to move beyond conventional emission compliance and pursue a broader objective of clean, efficient, durable and sustainable mobility. Future emission regulations are expected to place increasing emphasis not only on laboratory certification, but also on real-world emission performance, durability, wider operating conditions, in-use compliance and the ability of vehicles to maintain their environmental performance throughout their useful life.

Engineering clean mobility for BS-VII, therefore, requires a holistic approach. The objective cannot be achieved by focusing on a single component, subsystem or emission-control device. It requires coordinated optimisation of the complete vehicle system—including powertrain, fuel, combustion, emission-control systems, thermal management, controls, diagnostics, vehicle operation and maintenance. At the same time, the engineering approach must recognise the very diverse Indian mobility landscape, ranging from two-wheelers and three-wheelers to passenger cars, light commercial vehicles, buses and heavy-duty vehicles, together with conventional, hybrid, gaseous-fuel and emerging powertrain technologies.

It is essential to examine major engineering challenges and opportunities that can shape the next generation of clean mobility in India. The central proposition is that BS-VII should be viewed not simply as another regulatory step, but as an opportunity to establish a framework for real-world, lifetime and technology-neutral clean mobility. The engineering objective should emerge clearly as vehicles must remain clean not only when tested, but also when driven by customers, on Indian roads, under Indian climatic and operating conditions, throughout their useful life.

BS-VII is expected to be viewed as an opportunity to integrate regulation, engineering, manufacturing, digitalisation, durability and sustainability into one clean-mobility framework. Future clean-mobility engineering is required to consider following aspects of broader engineering challenges:

- How clean is the vehicle during real-world operation?
- How quickly does it achieve effective emission control after starting?
- How does it perform under different loads and speeds?
- How does emission performance change with temperature and altitude?
- Does the vehicle remain clean as it ages?
- How effectively are emissions controlled during transient operation?
- Can the vehicle maintain its environmental performance over its useful life?
- Are the technologies compatible with Indian fuels and operating conditions?
- Can the required performance be achieved at an acceptable cost?

From Emission Compliance to Clean Mobility

The development philosophy of future vehicle-emission technology should consider the vehicle as an integrated environmental-performance system rather than as an isolated single entity emission-control system, and is expected to follow some of the following stages -

- First stage – focus on reducing emissions from the engine itself through improved combustion, fuel systems and engine controls.
- Second stage - introduce increasingly sophisticated emission-control systems to further reduce pollutants after combustion.
- Third stage - strengthen electronic controls, diagnostics and monitoring systems, with increasing attention to real-world operation.
- Fourth stage - focus widely on the complete environmental performance of the vehicle over its useful life.

A technically advanced emission-control system cannot deliver its intended benefit if it does not reach the appropriate operating condition. Similarly, excellent engine calibration cannot compensate indefinitely for inadequate durability or poor system integration. Therefore, the objective of BS-VII engineering should be to optimise the complete system rather than individual technologies in isolation.

What Should BS-VII Engineering Aim to Achieve?

A vehicle that is exceptionally clean under laboratory conditions but experiences significant degradation in actual use does not fully achieve the objective of clean mobility. With this background, while the final regulatory framework will determine specific requirements on new regulations, the engineering philosophy for BS-VII can be considered around five interconnected broad objectives-

- Real-world cleanliness: Vehicles should demonstrate low emissions under representative operating conditions rather than only under narrow laboratory conditions.
- Lifetime performance: Emission performance should remain effective throughout the vehicle's useful life.
- Technology neutrality: The environmental objective should be clearly defined while allowing different technological pathways to achieve it.
- Indian-condition robustness: Technologies should be engineered for India's climatic, traffic, road, fuel and operating conditions.
- Sustainable affordability: Environmental improvement must ultimately translate into deployable solutions across relevant vehicle segments and customer groups.

A technology that provides excellent environmental performance but cannot be economically deployed at scale may face limitations in its contribution to fleet-wide emission reduction.

Real-World Emissions: The Next Engineering Frontier

One of the most important developments in emission-control engineering is the growing importance of real-world operation. Vehicles operate under highly variable conditions. Urban traffic may involve frequent acceleration, deceleration, idling and low-speed operation. Highways involve relatively stable high-speed operation. Hilly areas introduce changes in load and altitude. Hot climatic conditions influence thermal behaviour. Cold conditions influence warm-up and fuel behaviour. Commercial vehicles may experience substantial variation in payload. Buses can experience repeated stop-and-go operation. Two-wheelers may operate extensively in congested urban environments. Therefore, the emission-control system must function effectively across a broad operating envelope. Therefore, there is a growing emphasis on -

- representative driving conditions
- transient operation
- cold-start performance
- thermal behaviour
- load variation
- altitude

- ambient temperature
- vehicle ageing
- maintenance condition
- real-world driving behaviour

The engineering challenge is consequently shifting from designing a system that performs well at a particular test point to designing one that maintains effective emission control across a wide operating map. This requires a closer integration between vehicle development, testing, simulation, calibration and field validation.

The Importance of the Complete Vehicle System

Future engineering should not be considered solely an engine or after-treatment development, however, vehicle is required to be considered as an integrated system.

Changes in one subsystem can influence another. For example, changes in powertrain operating strategy can affect exhaust temperature. Changes in exhaust conditions can influence emission-control performance. Changes in vehicle energy management can influence the operating temperature of emission-control systems. The introduction of hybridisation creates new opportunities but also introduces new engineering interactions between engine operation, electric assistance, regenerative braking and emission-control-system temperature.

Cold Start and Low-Temperature Operation

Cold-start emissions remain an important engineering consideration. Emission-control systems generally require appropriate operating conditions before achieving their intended effectiveness. Immediately after engine start, the exhaust system may not yet have reached its effective operating condition. This creates a particular challenge for vehicles operating in congested urban environments, where a significant proportion of journeys may be short. The engineering response therefore needs to focus on reducing the time between engine start and effective emission control. It involves the interaction between:

- engine operating strategy
- exhaust-system configuration
- thermal management
- control strategy
- vehicle operating conditions
- ambient environment

The same principle applies to hybrid vehicles. Frequent engine shutdown and restart can change the thermal state of the emission-control system. Therefore, hybrid energy management and emission management must be coordinated.

Future clean-mobility engineering should increasingly consider thermal state as an integral part of vehicle control.

Two-Wheelers: A Distinct Engineering Challenge

Two-wheelers represent a particularly important part of India's mobility ecosystem.

Their engineering characteristics are different from those of passenger cars and commercial vehicles. They are generally compact, cost-sensitive and subject to significant urban use. Their emission-control systems must operate within constrained packaging and thermal environments. For BS-VII, the broad engineering priorities for two-wheelers are likely to include:

- rapid emission-control effectiveness after start
- effective control of gaseous emissions
- control of particulate emissions where applicable
- evaporative-emission management
- low exhaust-system pressure loss
- thermal and vibration durability
- compact packaging

- reliable sensing and diagnostics
- fuel compatibility
- cost-effective solutions

The appropriate approach is to define the environmental objective and then develop segment-appropriate engineering solutions.

Three-Wheelers and Urban Mobility

Three-wheelers perform an important role in passenger and goods transportation in India, particularly in urban and semi-urban areas. Their duty cycles can involve:

- frequent stops
- low average speeds
- high utilisation
- substantial idling
- variable loads
- intensive urban operation

These characteristics create particular requirements for emission-control performance.

For gaseous-fuelled vehicles, fuel-system integrity and control of relevant gaseous emissions become important considerations. The BS-VII engineering approach for three-wheelers may emphasise on:

- real-world urban performance
- robust emission control at low loads and speeds
- durability under intensive utilisation
- reliable diagnostics
- fuel-system integrity
- maintainability
- overall lifecycle cost
- competition with other powertrain technologies

Passenger Cars

Passenger cars provide an increasingly diverse technology landscape in India. Conventional internal-combustion vehicles, hybrids, plug-in hybrids and battery-electric vehicles can all form part of the broader mobility ecosystem.

For combustion-powered passenger vehicles, future emission-control engineering will need to address:

- cold-start performance
- real-world emissions
- particulate control
- evaporative emissions
- transient operation
- high-load operation
- flexible-fuel operation
- fuel economy / CO₂ emission
- durability
- diagnostics.

For hybrid vehicles, the challenge becomes more integrated. The engine may operate intermittently rather than continuously. Therefore, maintaining effective emission-control-system conditions during repeated engine starts and stops becomes an important engineering consideration. Hybridisation consequently creates an opportunity to combine efficiency improvement with low emissions, provided that energy management and emission management are engineered together.

Commercial Vehicles

Light and medium commercial vehicles operate under highly variable conditions. Payload, road gradient, traffic conditions, driving style and operating schedule can all significantly influence powertrain behaviour. This makes real-world engineering particularly important. Future commercial-vehicle development is expected to consider:

- payload-sensitive operation
- transient response
- low-temperature emission control
- regeneration or maintenance requirements where applicable
- robust diagnostics
- long operating hours
- flexible-fuel operation
- fuel economy
- durability
- total cost of ownership

For commercial customers, environmental performance must coexist with productivity.

An emission-control solution should, therefore, be evaluated not only on its technical capability but also on its effect on vehicle uptime, fuel consumption, maintenance and operating cost.

Heavy-Duty Vehicles and Buses

Heavy-duty vehicles present a different challenge because of their high annual mileage, high loads and long operating life. A small change in emission performance per kilometre can have significant cumulative environmental consequences over the vehicle's lifetime. The engineering priorities therefore are expected to include:

- low emissions over a wide load range
- stable performance at low and high exhaust temperatures
- effective control during transient operation
- durability over extended mileage
- reliable diagnostics
- robust thermal management
- effective particulate control
- management of gaseous pollutants
- high system availability
- flexible fuel opportunity

Buses deserve particular attention. City buses often operate under low-speed, stop-and-go conditions and may experience frequent idling and auxiliary loads. Intercity buses, in contrast, may operate for long periods at relatively high loads. Therefore, even within the heavy-duty category, a single engineering approach may not be optimal for every duty cycle. Therefore, the importance of duty-cycle-specific optimisation is required to be recognised in the forthcoming emission regulations.

Alternative Fuels and Clean Mobility

The future mobility landscape is unlikely to be defined by a single fuel or powertrain.

India has access to a broad energy ecosystem that includes liquid fuels, gaseous fuels, bio-derived fuels and electricity. Compressed natural gas, liquefied natural gas, biogas-derived fuels, biomethane, hydrogen and other emerging energy carriers may have different applications depending on vehicle category, infrastructure and economics.

The environmental performance of each pathway should be assessed systematically.

For gaseous fuels, for example, the engineering focus may include:

- combustion efficiency
- gaseous emissions
- fuel-system integrity
- methane management where relevant
- thermal behaviour
- durability

Hydrogen-based combustion pathways can potentially reduce carbon-containing exhaust pollutants, but combustion-related nitrogen-oxide formation remains an engineering consideration.

The broader principle could be that fuel choice and emission-control engineering should be considered together.

Electrification and Clean Mobility

Electrification is an important element of the clean-mobility transition. Battery-electric vehicles eliminate tailpipe emissions during operation and can contribute significantly to urban air-quality improvement. Although clean mobility is a broader concept than tailpipe emissions alone, future clean-mobility framework should increasingly consider lifecycle environmental performance as an holistic view. The overall environmental assessment can include:

- electricity generation
- battery manufacturing
- material sourcing
- vehicle manufacturing
- battery durability
- recycling
- tyre emissions
- brake-related emissions
- end-of-life management

Different powertrain technologies may have different strengths in different applications. The engineering objective should be to achieve the required environmental outcome using appropriate solutions for the relevant duty cycle.

Thermal Management: A Cross-Cutting Engineering Priority

Thermal management is likely to become increasingly important as emission requirements become more demanding. Emission-control effectiveness depends strongly on operating conditions. At the vehicle level, thermal management encompasses:

- engine thermal behaviour
- exhaust-system temperature
- heat transfer
- insulation
- cooling
- heating
- hybrid operating strategy
- control-system coordination

The objective is not simply to increase temperature. The engineering requirement is to maintain the appropriate thermal environment for effective emission control while minimising fuel or energy penalties. This creates a multidisciplinary optimisation problem. Thermal management will, therefore, increasingly connect powertrain engineering, exhaust-system engineering, vehicle controls and energy management.

Sensors, Controls and Diagnostics

Modern emission-control systems depend heavily on sensing and electronic control.

As emission requirements become more demanding, the importance of accurate and durable measurement will increase. The information should be used to maintain the system within its intended operating range. Diagnostics will also become increasingly important. A future vehicle should be capable of identifying abnormal operating conditions and degradation that could affect environmental performance.

This creates an important transition from passive emission control to actively managed emission performance.

Durability: From Compliance at Start of Life to Lifetime Cleanliness

A major engineering challenge is ensuring that emission performance does not deteriorate excessively with vehicle age. Emission-control systems experience:

- thermal cycling
- vibration
- contamination
- chemical exposure
- mechanical stress
- repeated start-stop operation
- long-term material ageing

The vehicle therefore needs to be engineered not only for initial compliance but also for sustained environmental performance. These demands require focused attention to:

- component durability
- system ageing
- control-system adaptation
- diagnostics
- maintenance
- replacement strategy
- end-of-life performance

The concept of lifetime cleanliness is becoming a central engineering principle, emphasising on how clean does the vehicle remain throughout its useful life rather than how clean the new vehicle is.

Indian Operating Conditions

India presents a particularly diverse operating environment. Vehicles may encounter varied operating conditions specially across the length and breadth of Indian territory. These conditions must be incorporated into engineering validation:

- very high ambient temperatures
- low winter temperatures in northern regions
- high humidity
- monsoon conditions
- dust
- traffic congestion
- high-altitude operation

- poor road surfaces
- variable payloads
- frequent idling
- different driving patterns

A technology that performs well in a controlled environment may behave differently when exposed to prolonged congestion, high ambient temperature or repeated thermal cycling. Therefore, Indian validation is progressively moving towards a wider range of representative operating conditions. This is going to strengthen the confidence that BS-VII vehicles, for example, will provide the enhanced intended environmental benefit in actual use.

Fuel Quality and Compatibility

Fuel characteristics have a direct influence on vehicle performance and emissions. India is also undergoing an important transition in fuel composition, including increasing use of bio-derived components and higher ethanol blends in appropriate applications. Future vehicles therefore need to be engineered for the fuels that they are expected to encounter over their useful life considering:

- fuel-system compatibility
- combustion behaviour
- material compatibility
- evaporative emissions
- lubricant interaction
- emission-control-system compatibility
- long-term durability

Digitalisation and Intelligent Engineering

Digital engineering is becoming an increasingly important enabler of clean mobility.

Simulation and virtual development can reduce development time while allowing engineers to evaluate a much larger range of operating conditions. Artificial intelligence and machine learning are emerging as additional engineering tools. Their application should be viewed as an enabler rather than a replacement for fundamental engineering. The most valuable applications are likely to arise where data-driven methods are combined with established physical models and engineering knowledge. This combination can provide a more robust basis for future emission-control development. The combination of digitalisation and advanced intelligent engineering will open a new chapter of achieving a robust basis for future emission-control development.

Technology-Neutral Approach

The future mobility landscape is likely to contain multiple powertrain pathways.

Internal-combustion engines, hybrids, battery-electric vehicles, gaseous fuels and emerging technologies may coexist for different applications and duty cycles. The environmental objective should therefore be clearly defined while allowing engineering solutions to evolve. A technology-neutral approach does not mean treating every technology as identical. Rather, it means establishing the required environmental outcome and evaluating technologies according to their ability to deliver that outcome under the relevant operating conditions. This approach encourages innovation and avoids prematurely limiting engineering pathways.

Beyond Tailpipe Emissions

Clean mobility is increasingly becoming broader than conventional exhaust emissions. This broader perspective can encourage more sustainable vehicle engineering. For example, lightweighting can improve energy efficiency, but material selection and recyclability also matter. Similarly, electrification can reduce tailpipe emissions, while battery material use and recycling become important lifecycle considerations.

Clean mobility therefore needs to be viewed as a system-level environmental objective.

Future environmental assessment may include:

- exhaust emissions
- evaporative emissions
- particulate emissions
- tyre-related emissions
- brake-related emissions
- energy consumption
- greenhouse-gas emissions
- resource utilisation
- end-of-life considerations

Engineering Collaboration

The increasing complexity of forthcoming BS-VII indicates that probably no single organisation will be able to address all challenges independently. Therefore, successful development will require a collaborative approach between:

- vehicle manufacturers
- component manufacturers
- emission-control specialists
- fuel suppliers
- testing agencies
- research institutions
- academia
- regulatory authorities
- customers

Industry and component associations can play an important role by creating platforms for technical dialogue. Knowledge sharing at the system level can accelerate development while allowing individual organisations to retain their proprietary intellectual property. Industry collaboration should focus on common engineering challenges, test methodologies, operating conditions and environmental objectives, rather than disclosure of proprietary designs or technologies.

A Framework for BS-VII Engineering

A practical engineering framework for future clean mobility can be represented through following steps, providing a pathway from regulatory requirement to real-world environmental benefit:

Step 1: Define the environmental objective - Establish clear objectives for real-world and lifetime environmental performance.

Step 2: Understand Indian operating conditions - Develop representative operating and environmental envelopes for different vehicle segments.

Step 3: Characterise the complete vehicle - Understand the interaction between fuel, powertrain, emission-control system, controls and vehicle operation.

Step 4: Identify system-level engineering priorities - Focus development resources on the conditions that have the greatest influence on real-world emissions.

Step 5: Optimise the complete system - Avoid optimising individual components at the expense of overall vehicle performance.

Step 6: Validate across the operating envelope - Use laboratory, simulation, proving-ground and real-world data.

Step 7: Validate durability - Confirm that environmental performance remains effective over the intended useful life.

Step 8: Assess lifecycle sustainability - Consider energy, materials, manufacturing, operation, maintenance and end-of-life.

Segment-Specific Priorities

Although the overall clean-mobility objective should be common, engineering priorities are likely to vary by vehicle segment. The broad principle underlines that one environmental objective may not depend upon one technology solution.

Vehicle segment	Indicative broad BS-VII priorities
Two-wheelers	Cold start, real-world urban emissions, particulate control, evaporative emissions, compactness, durability
Three-wheelers	Low-speed operation, high utilisation, gaseous emissions, durability, diagnostics
Passenger cars	Real-world emissions, cold start, particulate control, hybrid integration, evaporative emissions
Hybrid vehicles	Engine start-stop management, thermal management, energy/emission coordination
Light commercial vehicles	Load variation, transient operation, durability, real-world emission control
Heavy-duty vehicles	Lifetime emissions, low-temperature operation, high-load operation, durability
City buses	Low-speed operation, frequent stops, thermal management, high utilisation
Intercity buses	High mileage, high-load operation, durability and lifecycle performance
Gaseous-fuel vehicles	Fuel-system integrity, combustion optimisation, relevant gaseous emissions
Electric vehicles	Energy efficiency, battery durability, lifecycle impacts, tyre and brake emissions

The Road Ahead

The transition towards BS-VII should be viewed as a journey rather than a single regulatory event, which will require continuous interaction between regulation and engineering.

- The first priority should be establishing a common understanding of the desired environmental outcome.
- The second should be developing robust test and validation methodologies.
- The third should be understanding actual Indian operating conditions.
- The fourth should be supporting technology development across different vehicle segments.
- The fifth should be ensuring durability and lifetime performance.
- The sixth should be developing a cost-effective and locally sustainable supply chain.

Broad Engineering Priorities for BS-VII

1. Real-world emission performance - The vehicle should remain clean across representative operating conditions.
2. Faster achievement of effective emission control - Cold-start and low-temperature operation should receive greater engineering attention.
3. Lifetime environmental performance - Emission-control effectiveness should remain robust throughout useful life.
4. Integrated thermal management - Powertrain, exhaust and vehicle controls should be coordinated.
5. Advanced sensing and diagnostics - Reliable information should support effective emission management.
6. Segment-specific engineering - Solutions should reflect the actual duty cycles of different vehicle categories.
7. Fuel and powertrain compatibility - Vehicles should be designed for the evolving Indian fuel and energy ecosystem.
8. Real-world validation - Development should increasingly incorporate actual operating conditions.
9. Lifecycle sustainability - Environmental performance should extend beyond tailpipe emissions.
10. Affordability and scalability - Technologies should be capable of deployment at the scale required by India's mobility needs.

The Role of the Automotive Industry

The Indian automotive industry has demonstrated its ability to respond to increasingly stringent emission requirements. The leap-frogged transition to BS-VI demonstrated the importance of collaboration between vehicle manufacturers, suppliers, testing organisations and regulatory institutions. The next phase will require an even greater degree of integration and investments:

- engineering capability
- test infrastructure
- simulation
- real-world data
- durability development
- local manufacturing
- skilled manpower
- research and development

Clean-Mobility Ecosystem

Industry associations such as ECMA can contribute significantly to this transition by providing a platform for technical collaboration and knowledge exchange. The emission-control industry encompasses a wide range of capabilities, including system engineering, components, materials, sensors, controls, testing and validation. ECMA can facilitate dialogue around common challenges.

ECMA Conferences, such as ECT 2026, provide an opportunity for industry, government, research organisations and technical experts to discuss the future direction of emission-control engineering. The value of such forums lies not merely in presenting individual technologies, but also in developing a shared understanding of the engineering challenges ahead.

Conclusion

- The transition towards BS-VII represents an opportunity to redefine the meaning of vehicle-emission compliance.
- The future objective should be broader than achieving a laboratory number.
- It should be about delivering clean, durable, efficient and sustainable mobility under real operating conditions.
- This requires a shift from component-level thinking towards system-level engineering.
- Powertrain efficiency, emission control, thermal management, sensors, controls, diagnostics, durability, fuel compatibility and vehicle operation must increasingly be considered as interconnected elements.
- At the same time, the diversity of India's mobility landscape must be recognised.
- The engineering priorities of a two-wheeler are different from those of a passenger car. A city bus has different operating conditions from an intercity bus.
- A heavy-duty truck has different requirements from a three-wheeler.
- Hybrid and electric vehicles introduce new system interactions.
- Consequently, BS-VII should provide a common environmental objective while allowing segment-specific and technology-neutral engineering solutions.
- India also has an opportunity to develop its own clean-mobility engineering capabilities.
- The combination of a large domestic market, diverse operating conditions, strong automotive manufacturing capabilities and a growing engineering ecosystem provides a unique environment for innovation.
- The next generation of emission-control development should therefore focus not only on increasingly sophisticated technologies, but also on better system integration, better validation, better durability and better understanding of real-world vehicle operation.



MANGLA COR-TUBI PVT LTD

PRECISION | INNOVATION | RELIABILITY

Your Trusted Partner
for Advanced
Exhaust and After-
treatment Solutions



FROM CONCEPT TO END-TO-END SOLUTIONS

FOR COMMERCIAL & TRACTOR SEGMENTS



We design. We develop. We manufacture.

Delivering high-performance exhaust and after-treatment systems
with precision, performance and reliability – every step of the way.

1



DESIGN &
ENGINEERING



Advanced design & simulation
for optimal performance
and cost efficiency.

2



PROTOTYPE
DEVELOPMENT



Rapid prototyping to
validate design and
ensure perfect fit.

3



MASS PRODUCTION
WITH QUALITY ASSURANCE



High-volume manufacturing with
stringent quality standards and
global certifications.



END-TO-END
SOLUTIONS

From concept to
final product



STRINGENT
QUALITY STANDARDS

ISO certified processes
& global benchmarks



INNOVATION
DRIVEN

Future-ready
technologies



LONG-TERM
PARTNERSHIPS

Built on trust
and performance

VISIT US AT



www.manglacortubi.com



+91 9100090108



connect@manglacortubi.com

30/7, Sector-23,
Industrial Area Phase 1,
Aghwanpur, Haryana
121102

CONNECT

COLLABORATE

GROW





GLIMPSES OF ECT-2026 CONFERENCE, NEW DELHI



ECT-2026

17th International Conference

CONFERENCE THEME

ENGINEERING CLEAN MOBILITY ADVANCEMENT for BS-VII

ECT 2026 Conference theme, “**Engineering Clean Mobility Advancement for BS-VII,**” reflects India's next transformative step toward cleaner, smarter, and future-ready transportation. As India prepares for the next generation of emission regulations, BS-VII is expected to move beyond conventional tailpipe limits and emphasize real-world emissions, onboard monitoring, lifecycle sustainability, and broader mobility solutions.

The transition will require a significant evolution in engine technologies, emission control systems, fuel pathways, and integrated mobility strategies.

ECT 2026 Conference aims to serve as a strategic platform bringing together policymakers, industry leaders, researchers, academia, and technology experts to discuss pathways for engineering this transition. The conference will focus on innovations in advanced internal combustion engines, hybridization, hydrogen, biofuels, advanced after-treatment technologies, and digital monitoring systems that can support India's clean mobility journey. Emerging BS-VII discussions also point toward stronger real-world emission compliance and broader environmental considerations.

The theme recognizes that India's journey toward sustainable mobility must balance environmental objectives with affordability, energy security, industrial competitiveness, and inclusive growth. ECT 2026 Conference, therefore, seeks to shape a collaborative roadmap for engineering solutions that enable a cleaner, resilient, and low-carbon mobility future for India.



Mr S K Singh
President



Mr Prakash Sardesai
Vice President



Mr Neelkanth Marathe
Executive Director

Conference Organiser

Emission Controls Manufacturers Association (ECMA)

205, Chandra Bhawan, 67-68, Nehru Place, NEW DELHI – 110019 (India)
011-41606513; www.ecmaindia.in

Contact

Mr Neelkanth Marathe, Executive Director
neel.marathe@ecmaindia.com; 9975492651;

Mr Deepak Nigam, Manager
Deepak.nigam@ecmaindia.in; 9810931760;