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Emission Controls Manufacturers Association (ECMA) is the only premier body in India having association of 19 global emission control systems manufacturers, dedicated to achieving clean air and sustainable mobility solutions through the promotion and development of emission control technologies.

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ECMA is also engaged to provide expert guidance and inputs to policymakers on emission control strategies and technologies while framing new emission norms for example, ECMA members are actively participating in various BS-7 panels formed by SCOE / AISC.

ECMA fosters the exchange of knowledge among stakeholders on the latest advancements in emission reduction technologies and suitable solutions for alternative fuels and sustainable powertrain options; through conferences, workshops, webinars, etc.

ECMA continues to be a driving force in India's transition towards cleaner and more sustainable transportation solutions. ECMA's Flagship Event – ECT conferences provides a strong platform to the stakeholders to deliberate on emerging trends, challenges, and innovations in emission control.

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- We are Committed Collaboratively to Lead India towards Cleaner Air.

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- We will work with the Industry, Government, Regulators, Oil companies and Public at large to be a credible source of knowledge on emission control.
- We will strive to increase awareness of the need and to provide relevant technical solution for emission control.
- We will achieve this through assimilation of technologies for emission control providing and disseminating knowledge; enabling legislation, implementation and test procedures.

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Comparison of Particulate Emissions from Different Categories of Diesel and Otto Engines and Vehicles

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Abstract

Based on the Brazilian vehicles' average certification values, it can be seen that there has been an increase in particulate matter emissions from gasoline and flexfuel cars, due to the introduction of direct fuel injection Otto engines (GDI). This effect was compared to the particulate emission reduction strategies for heavy duty diesel engines, already underway in Brazil since 1986 and with great effectiveness, in order to assess the need for a specific approach for light duty Otto cycle engines.

This study compares the technological standards applied to light and heavy-duty engines, for a strategic assessment of the vehicle particulate emissions control, but since these emissions are expressed in different ways for those vehicle categories, a new analysis method was developed specifically for this purpose.

This is an easy and efficient method, based on energy demand, which converts the emission factors into a common base, more associated with the engine's workload and, consequently, more representative of the activities performed by all vehicles in their fleet, regardless of knowing the usage statistics of each one. The concept is based on converting the apparently non-comparable emission factors, measured in g/km for light-duty vehicles and in g/kWh for heavy-duty vehicles, to a standardized unit in grams of PM per kilogram of fuel burned (or per Mol of Carbon, for more accurate comparisons with oxygenated fuels), which allows the comparison of the "environmental efficiency" of different types of machines.

The comparison made on this new basis allows the identification of whether the technological advances in engines and gas after-treatment systems applied to heavy-duty vehicles already exceed the quality of the current technologies applied to light-duty vehicles, and will indicate the real need to prioritize the latter in the control of particulate matter. If this is the case, the replacement of Otto engines with MPFI indirect injection with the new GDI engines will need to be re-evaluated, so that this market trend can be made viable by applying resources that reduce PM emissions. Such a strategy potentializes the application of ceramic filters in exhaust systems, which is the best alternative, as it provides the most advanced environmental results, with the additional benefit of also reducing the number of particles (NP).

This calculation process is being studied to be applied to the entire history of the particulate emissions control in Brazil, taking into account the average emission factors of each technology and the MPFI/GDI market proportions, in order to effectively compare the downward trend in PM emissions from heavy-duty diesel vehicles, with the new upward trend in light-duty gasoline and flex-fuel engines, in order to precisely define the strategy for its correction.

This same analysis technique was extended to other engines, such as generator sets, and indicated the need to equip them with state-of-the-art technologies, in the EURO VI standard if possible, so that the emissions induced by electric vehicles, under the "well-to-wheel" concept, are compatible with those of traditional vehicles with internal combustion engines, in cities that depend on the electricity supply produced by diesel thermoelectric plants.

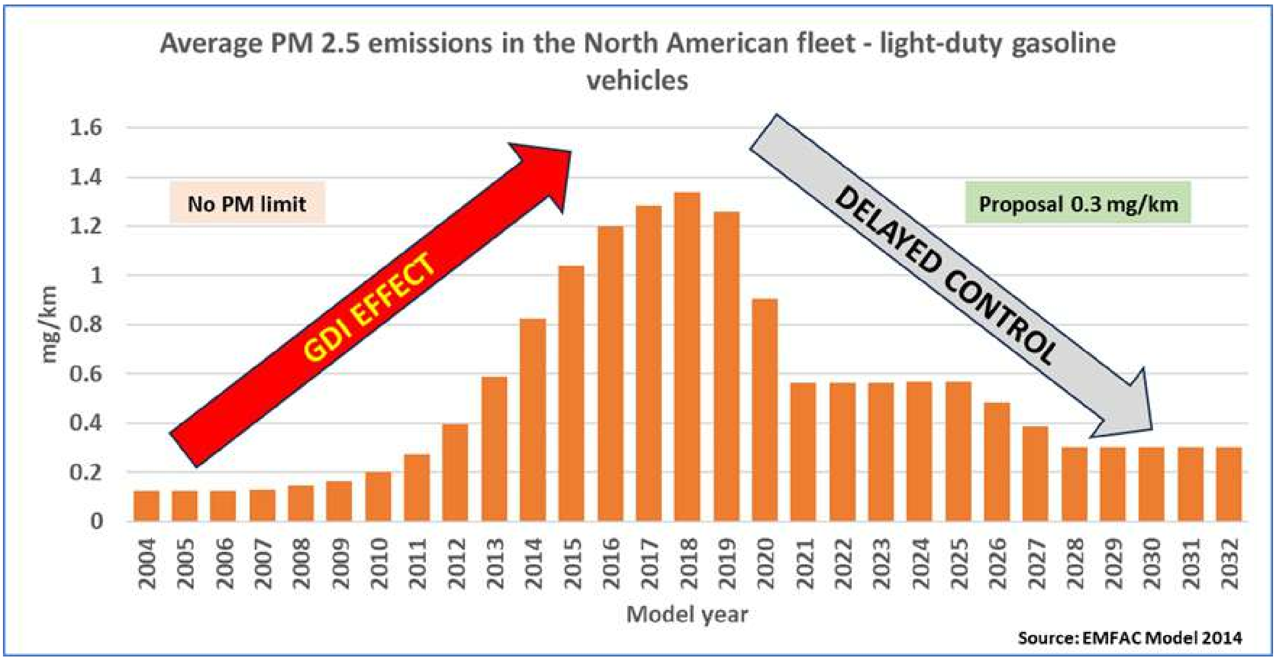
This analysis allows for a very comprehensive assessment, involving all vehicle and engine types in order to rebalance PM emission control strategies that are divorced from each other.

Background

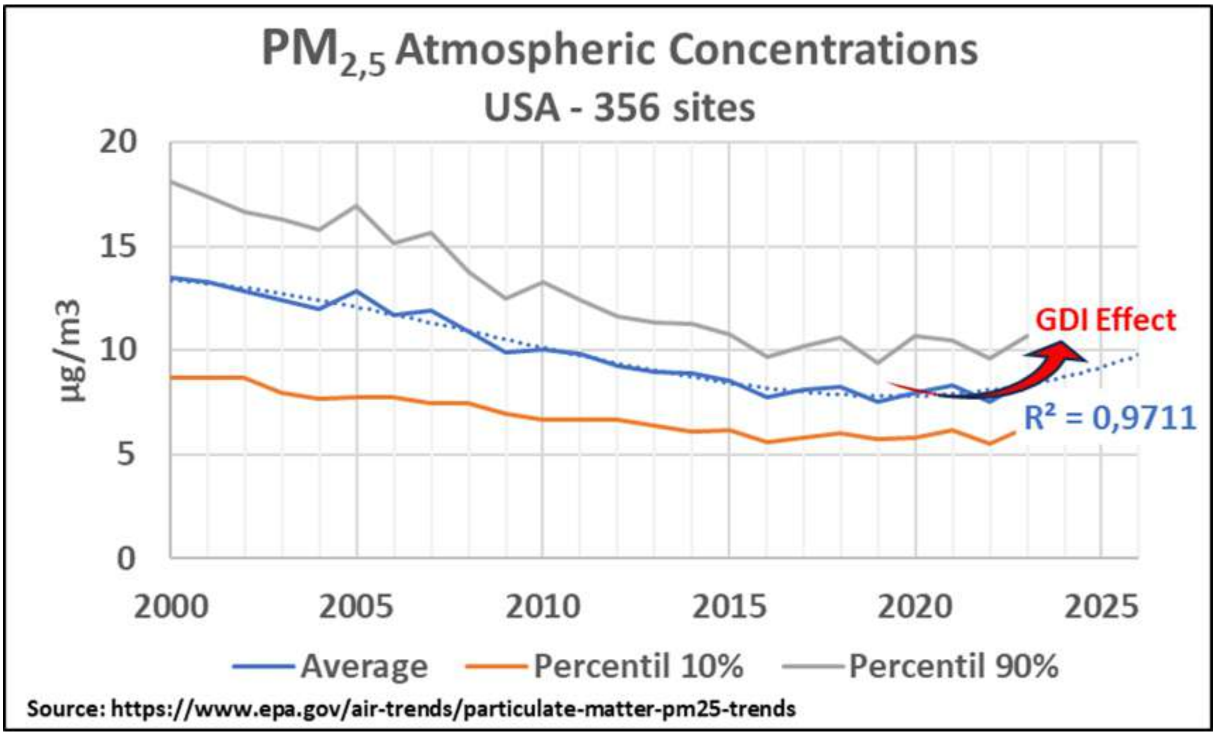
Traditionally, spark-ignition Otto cycle engines have low particulate emissions, even without control devices, because the air-fuel mixture is prepared before it enters the combustion chamber, resulting in a high degree of homogeneity and more complete combustion. This fact significantly differentiates them from diesel engines, in which fuel is injected under high pressure directly into the combustion chamber, forming a spray whose droplets become nuclei for the particulate matter formation, whose emission is naturally high.

However, this fuel injection system offers performance and energy efficiency advantages, and has also been applied to Otto cycle engines, which significantly increases their particulate matter emissions.

In the United States, the introduction of gasoline direct injection (GDI) engines in 2008 increased cars' average particulate matter emissions by about 10 times, leading the country's environmental legislation to set a limit of 0.3 mg/km. Forecasts modeled by its environmental agency in 2014 indicated that this process would take two decades to bring average PM emissions back to acceptable levels, as shown in Figure 1



This effect was confirmed in 2023 in emissions surveys conducted by remote sensing for the TRUE Initiative Program, which showed a decline in PM emissions from 2005 to 2015 models and an abrupt reversal of this trend, which was completely lost with the growth observed up to the 2020 model years. This same trend is also detected in the analysis of atmospheric concentrations of PM2.5 in various US regions, which already show a reversal of the decline in this pollutant that had been observed since 2010, with growth resuming from 2020 at the national level, which has already led the annual average to exceed the US standard of 9μg/m3 in several regions, as shown in Figure 2, obtained from EPA data.



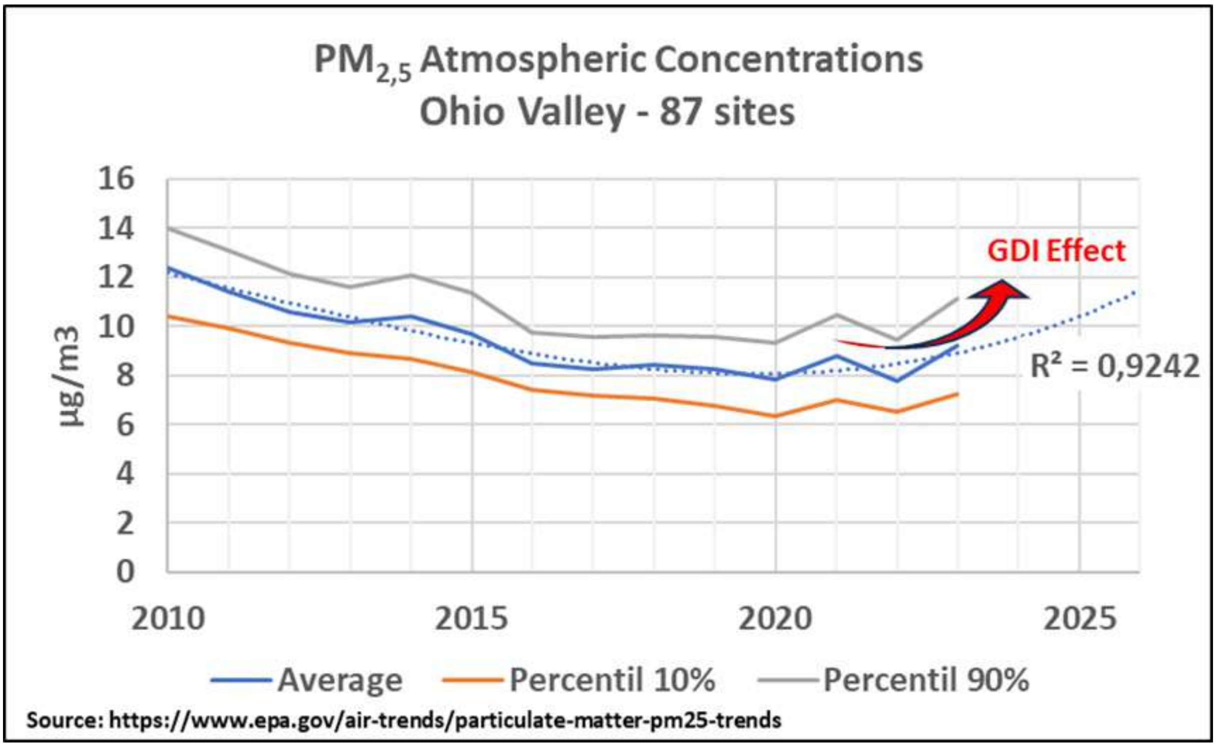


Figure 2: Annual atmospheric averages of PM2.5 in the United States

In both diesel and Otto GDI engines, the most effective technology for meeting the strictest MP emission limits is based on filtering exhaust gases and burning the soot accumulated in the filter, using the temperature of the gases themselves. These are ceramic filters that, in addition to reducing particulate mass, also reduce the number of particles present in the exhaust gases by up to 500 times, depending on the filter's technological generation.

This aspect is particularly important because the reduction in PM emissions, based on techniques associated with the combustion process to promote better particle burning, as in the case of oxidation catalysts, comes at the expense of particle size reduction, but maintains the same number of particles per cubic meter of exhaust gas. It is worth noting that, during the in-engine combustion process, soot particles form with diameters of around 0.1 μm (PM0.1), which are much smaller than particles known as PM2.5, i.e., with diameters of up to 2.5 μm. With this tiny diameter, MP0.1 has much higher toxicity, since submicron particles penetrate deeper into the lungs and can only be eliminated by the bloodstream, enhancing the absorption of foreign materials into the tissues, which cause more serious diseases, instead of being expelled by nasal mucus.

The formation of particulate matter in internal combustion engines

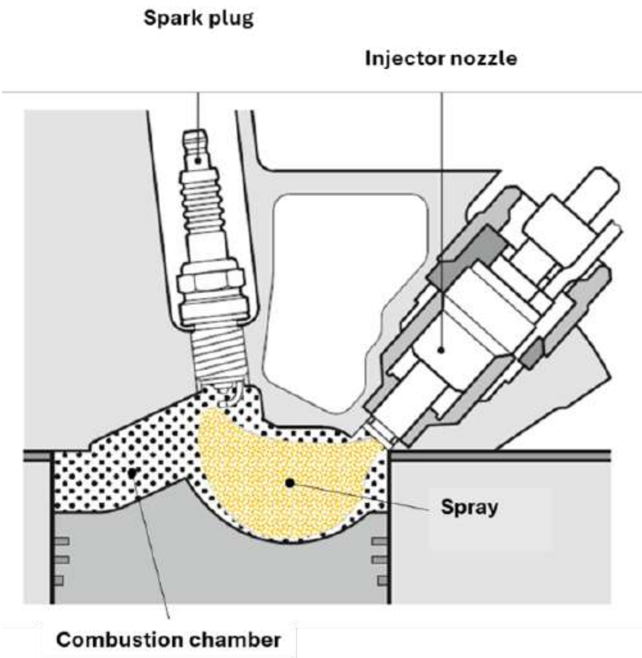
In diesel engines, fuel is sprayed directly into the combustion chamber, forming a heterogeneous mixture of air and liquid, whose droplets absorb heat and gasify, producing a cloud of vapor around them, mixed with air in decreasing concentrations as it moves away from the droplet. Combustion occurs in this vapor area, heating the droplet and producing a pyrolyzed carbon core that constitutes the particulate matter, as shown in Figure 3. In other words, each droplet is burned on the outside and "cooked" on the inside, leaving a carbon core from the heavier fractions of the fuel. This process leads to the higher formation of soot, known as typical for Diesel engines, which can be greatly reduced by increasing the fuel injection pressure, aiming to improve its pulverization, and complemented by exhaust gas filtration in the most modern engines.

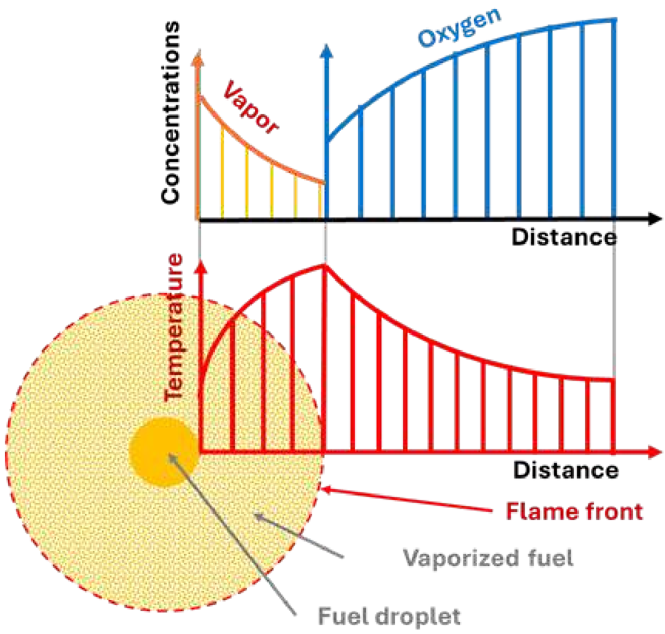
In spark ignition engines, Otto cycle with indirect injection (Multi Port Fuel Injection - MPFI), the fuel is mixed with air outside the combustion chamber, under better conditions to produce a more homogeneous mixture, with a great part of it being vaporized beforehand. Therefore, the particulate matter emissions from this type of engine are naturally much lower.

However, direct fuel injection into the combustion chamber has also recently been applied to Otto engines (GDI) to improve torque and fuel consumption, similar to diesel engines, which also makes them similar in terms of particulate matter formation, albeit to a lesser extent because the fuels used are more volatile, among other characteristics of this design.

For this reason, the introduction of GDI models on the market raises the average particulate emissions of light-duty gasoline vehicles, traditionally close to 1 mg/km, to 3 mg/km or more. This fact was observed in the US market in the first decade of the 2000's and is now being repeated in Brazil, significantly raising the average for Otto engines from 2021 onwards, including flex-fuel vehicles.

This process is controlled mainly by increasing the injection pressure to produce smaller droplets and by the geometry of the engine components, up to a certain point when gas filtration is necessary to meet more stringent limits.





The evolution of particulate matter emission control in Brazil

Since the beginning of PROCONVE – National Motor Vehicle Air Pollution Control Program, soot emissions from heavy-duty diesel engines have been reduced from 1,500 mg/kWh in the 80's, when diesel fuel was of low quality and contained 10,000 ppm of sulfur, to less than 30 mg/kWh in 2012 with the introduction of phase P7, when Brazil could count on ultra-low sulfur fuel (10 ppm). This process drastically reduced PM emissions, both in the formation of sulfates and by enabling advanced fuel injection technologies in diesel engines.

In 2023, phase P8 (EURO VI standards) consolidated new technologies, reducing PM emissions even further and enabling compliance with the limit of 10 mg/kWh, with the additional requirement of compliance with the limit of 6 x 1011 particles per kWh of engine-generated mechanical energy, which has been achieved through the use of ceramic filters. Table 1, based on historical data from PROCONVE, illustrates this evolution in the emission control of particulate matter in Brazilian heavy-duty engines.

Table 1 - Typical emissions and particulate matter limits for heavy-duty vehicles

HDV Phase	PM mg/kWh	Notes
Pre PROCONVE	1500	Old typical data, converted to equivalent values in the ETC test
P3 - 1996	1100	
P4 - 2000	250	
P5 - 2005	160	Limit - Introduced S500 diesel oil
P6 - 2009	30	Phase canceled due to unavailability of S50 diesel oil
P7 - 2012	30	Limit - Introduced S10 diesel oil
P8 - 2023	10	Mass limit in addition to the limit of 6×10^{11} part/kWh

At the same time, certified particulate matter emissions from gasoline, ethanol, and flex-fuel vehicles remained consistently at 1 mg/km until 2021, when the average began to rise, reaching 3 mg/km for gasoline vehicles in 2023, according to average certification data for vehicles with MPFI and GDI engines published by CETESB. It is important to note that light-duty diesel commercial vehicles had much higher values in 2011, but have already reached the level of 1 mg/km since 2023.

Therefore, the same behavior observed in the United States with the introduction of GDI engines has been intensifying in Brazil in recent years, although CETESB has not specified the proportions between the two. In Brazil, there is still a mitigating factor when these engines (MPFI and GDI) use hydrated ethanol, but even in this case, they emit particulates between 1 and 2 mg/km, still below the corporate limits required in phase L8, which are currently 4 mg/km and will be 3 mg/km from 2029 onwards. These limits for phase L8 are lenient and allow for an increase in average PM emissions in the coming years, permitting values above these limits for a particular model to be compensated for by another model from the same manufacturer.

Table 2 - Typical particulate matter emissions from light-duty vehicles [IV]

PM Emission Averages - mg/km							
Calendar Year	Passenger Vehicles			Commercial Vehicles			
	Flex -Ethanol	Gasohol	*Flex* -Gasohol	Diesel	*Flex* -Ethanol	Gasohol	*Flex* -Gasohol
1997 a 2011	1,1	1,1	1,1	65	1,1	1,1	1,1
2011 a 2021	1,1	1,1	1,1	13,6	1,1	1,1	1,1
2022 (L7)	1,6	1,3	3,0	2,0	1,6	2,3	3,0
2023	2,4	1,3	2,9	1,1	1,0	1,7	3,5
2024	1,7	1,2	2,4	0,7	1,0	1,8	3,5
2022-24 Ave.	1,9	1,3	2,8	1,2	1,2	1,9	3,3

GDI EFFECT

Source: CETESB certification data, 2024

Technological comparisons between vehicles of different categories

CETESB provides society with the best information on vehicle activity, publishing annually the average values of certified emission factors for each vehicle category and model year so that society, the scientific community, and public administrators can learn about, evaluate, and propose public policies for maintaining environmental quality.

Although it is the most comprehensive publicly available data source, several categories do not present all data in some phases of PROCONVE. However, similar categories can be grouped together to provide an overview of the program's evolution. Thus, the statistical significance is not uniform for all cases, but it accurately describes the history of typical values, especially in terms of their progressiveness and the technological evolution of the Brazilian fleet.

Exhaust emissions and their respective limits set by PROCONVE are expressed in grams per kilowatt hour for heavy-duty vehicles and in grams per kilometer for light-duty vehicles and motorcycles, which makes it difficult to compare emission levels across all categories. These emissions measurement methods are associated with driving cycles characteristic of the engine loads encountered in everyday use of the various vehicle categories. Thus, heavy-duty engines are tested at higher loads than light-duty engines and motorcycles, each in its own way, but in the manner most representative of the actual use of the vehicle category for the determination of emissions and fuel consumption.

Consequently, the ratio between emission factors and fuel consumption under the same test load conditions, which corresponds to emissions per kg of fuel, is also representative of actual use. For this calculation, both are measured and expressed in the same units, either in g/km or g/kWh. It should be noted that this factor is much more stable than the first ones throughout the engine map, i.e., the average results of the test cycle are representative of a wide variety of operating conditions.

The factor obtained in g_pollutant/kg_fuel multiplied by the actual total consumption of a given vehicle category, whether in a fleet or in a region, results in a fairly accurate estimate of the total pollutant emissions of that fleet or region.

This technique circumvents the difficulty of comparing emissions from different types of vehicles and engines, categories, sizes, and applications, without the need to create traditional inventories, allowing for a comparison of their "environmental efficiency".

The same technique can be used for comparisons with remote sensing emissions monitoring, where measurements are expressed directly in g/mol of carbon, easily converted to g/kg of fuel burned.. Based on this technique, Figure 4 compares the certified average emissions as published by CETESB and converted to g/kg_fuel based on fuel consumption determined in the same certification tests.

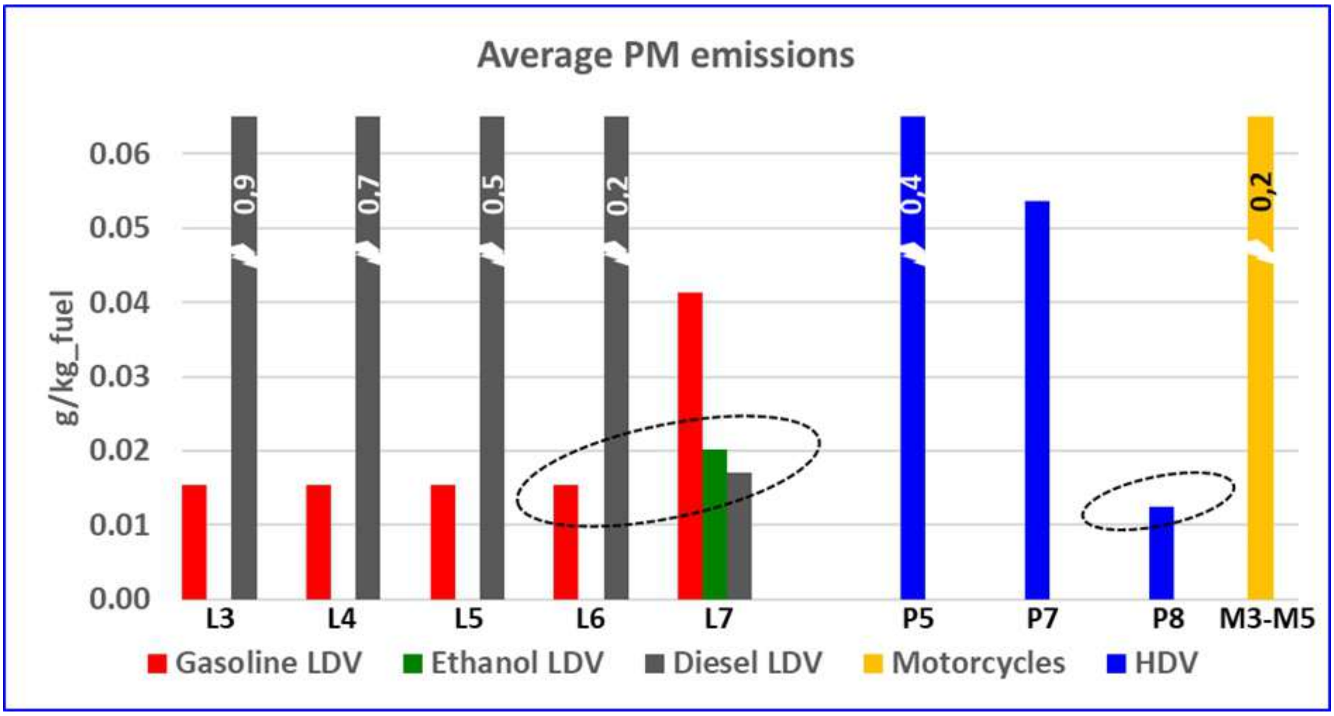


Figure 4 - Certified average emissions expressed in g/kg fuel

From these comparisons, some important findings can be drawn:

a) Light-duty vehicles with Otto cycle engines had the lowest particulate emissions up to phase L6 (data available only for gasoline vehicles, flex-fuel vehicles fueled with gasoline, and diesel vehicles);

b) Starting in phase L7, the significant market share of GDI engines increased PM emissions from gasoline and flex-fuel engines by more than 100%, reaching levels similar to those of heavy-duty engines in the penultimate phase of PROCONVE (P7);

c) Still in phase L7, the first data on flex-fuel vehicles fueled with ethanol appears, showing emissions still compatible with those of traditional gasoline vehicles (MPFI) in previous phases;

d) Since the early stages of the program, particulate emissions from both diesel light-duty and heavy-duty engines have been drastically reduced in stages L7 and P8 (95% to 99%), reaching levels compatible with those of traditional Otto engines (MPFI), which were considered satisfactory until then;

e) Motorcycles still have technologies that allow high PM emissions, at levels almost four times higher than those of the heavy-duty engines of the P7 phase.

Observations "a" and "b" suggest the immediate implementation of technologies that reduce PM emissions from light-duty vehicles with Otto cycle engines. However, observation "c" indicates that the use of ethanol represents a possibility for mitigating this problem.

Observation "d" leads to the conclusion that Brazil already has technological solutions and aftertreatment systems for reducing PM emissions from light duty diesel engines to the required levels, which can also be used for Otto GDI engines.

These facts, already evidenced by the results of new vehicle certifications, indicate the urgent need and feasibility to correct the distortions caused by GDI engines in controlling particulate matter emissions by motor vehicles in general.

It is important to note that, for a long time, Diesel vehicles had by far the highest levels of particulate matter emissions, until the introduction of phase P7 of PROCONVE in 2012, when this was reduced below the emission level of motorcycles, but still well above flex-fuel and gasoline vehicles. In 2023, emissions from heavy vehicles were reduced to ¼ of the P7 limit, equivalent to those of MPFI engine cars, virtually eliminating this problem. However, GDI engines are raising the averages for light-duty vehicles to levels comparable to those of P7 phase heavy-duty vehicles, now outdated. It should also be noted that light-duty diesel vehicles also had their PM levels drastically reduced, well below the established limits, due to the widespread use of ceramic filters, reaching levels of 1 mg/km, compatible with those of traditional gasoline and flex-fuel vehicles.

In technological terms, these figures show that Brazil already has sufficiently clean technologies to return light-duty vehicles with Otto engines, including GDIs, to low emission levels, with the advantage that filters also reduce the number of particles by a factor of 10 to 500 times below current levels, depending on the technology generation to be adopted and the substrate impregnation with catalytic material.

The first recommendation resulting from this analysis is to improve the data used here, based on specific measurements of PM mass and particle number (NP), distinguishing between GDI and MPFI vehicles running on ethanol and the current E30 gasoline, so that a detailed study can be carried out on the feasibility of applying the technologies considered to date and included in the CETESB certification database.

In addition, observation "e" indicates that motorcycle engines do not yet have technologies for stricter control of PM emissions. However, current international regulations for four-stroke engines have not yet prioritized PM control in this category, because these vehicles have limited space for control systems and their PFI engines already reduce this problem. Furthermore, most motorcycles have single-cylinder engines that produce strong mechanical and gas flow vibrations, which reduces the durability of ceramic substrates, hindering their application.

Comparison of environmental impacts

Traditional analyses of the environmental impact of vehicle fleets are based on emissions inventories calculated from the number of existing vehicles, their annual mileage, and their actual emission factors in grams per kilometer, which all need to be obtained for each model year. In the case of heavy-duty vehicles, emission factors are given in grams per kilowatt hour of energy produced, which can be converted to g/km based on fuel consumption measured in the engine and vehicle.

This is an extensive task that depends on various statistics, which are often affected by significant errors. However, with the concept developed above, a comparative inventory between different fuels for a region can be easily and quickly estimated from the total fuel consumption verified in the region, multiplied by the ratio between emission factors in grams per kilogram of fuel burned, which can be weighted by category. This approach reduces some uncertainties in the inventory and is very important for detecting specific flaws in environmental legislation and for planning future strategies, before data is available for a more precise detailed inventory. In addition, it also allows for the analysis of very different types of machinery, such as cars, trucks, trains, generators, etc.

In the case of this analysis, the aim is to compare only the future trends in particulate matter emissions from heavy-duty vehicles with those from light-duty vehicles, grouped only by model year. The analysis of the last two phases of PROCONVE predicts that the evolution of each of these categories will reverse the balance of particulate matter control in the two fleets.

Furthermore, considering that national fuel demand is divided into 50% diesel, 33% gasoline, and 16% ethanol, as shown in Table 3, these fleets will, in the medium term, have half of their fuel consumption (or energy spent on transportation) subject to lower particulate matter emission factors (P8 diesel vehicles) and the other half burning in vehicles powered by Otto cycle engines from the L8 phase, which are less controlled.

Thus, as time passes without a correction of PM limits for gasoline engines in particular, their emissions will approach the characteristics of these two phases, making light-duty vehicles the largest contributors to particulate matter emissions. This effect will completely offset the hard-won benefits of controlling heavy-duty Diesel vehicles as both fleets modernize, as indicated by the overall averages shown in Figure 5

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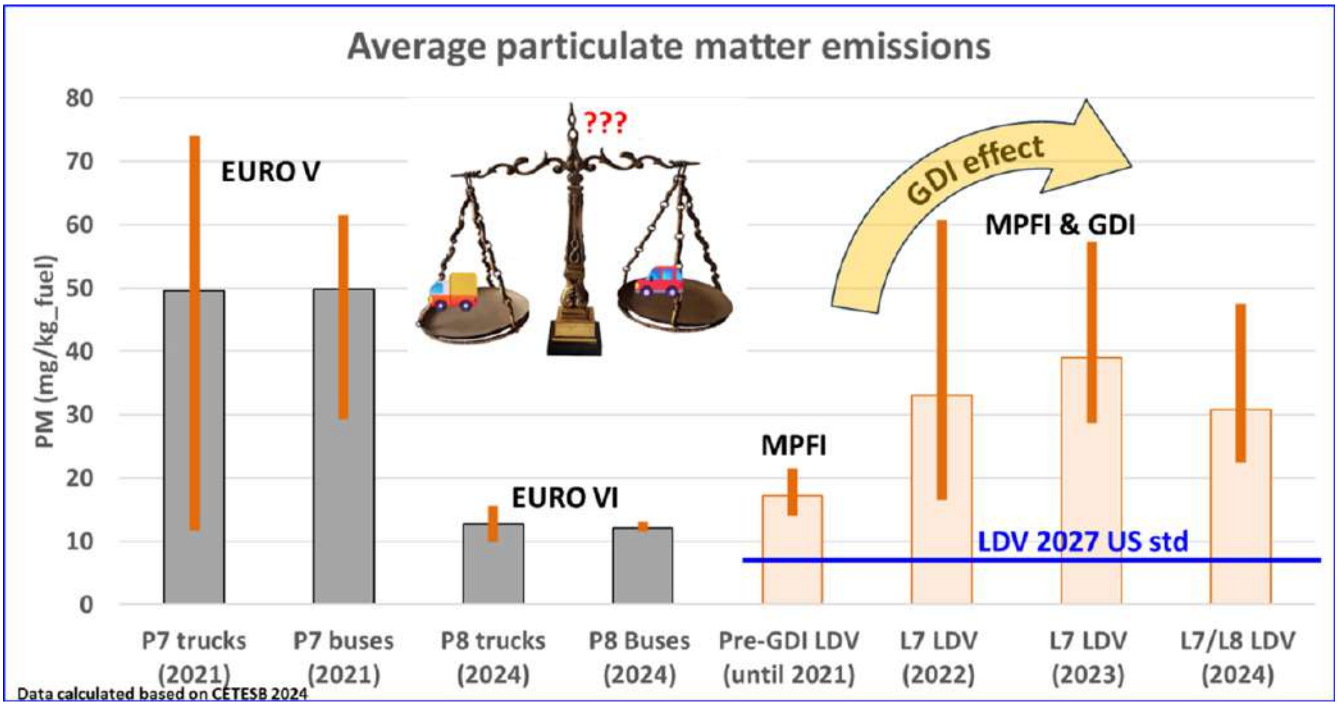
Table 3 – Fuel consumption by Brazilian region in 2024 – ANP [VII]

Base year: 2024	HYDRATED ETHANOL	E27 GASOHOL	DIESEL OIL
BRAZIL	**16%**	**33%**	**50%**
SÃO PAULO STATE	31%	28%	41%
SOUTHEAST REGION	25%	30%	46%
NORTHEAST REGION	8%	44%	49%
SOUTH REGION	7%	40%	53%
CENTRAL-WEST REGION	21%	22%	57%
NORTH REGION	4%	33%	63%

Source: based on ANP data (National Agency for Petroleum, Natural Gas and Biofuels)

Figure 5 – Average PM emissions expressed in g/kg of burned fuel



In the state of São Paulo, these percentages are even worse, with 59% of fuel demand concentrated in Otto vehicles, and it is likely that this is also the case in larger cities. In other regions, these effects are similar because Otto vehicles still have significant participation, even at the regional average level.

In summary, this situation shows the disparity between the PM emission control strategies adopted for light-duty and heavy-duty vehicles, which can be corrected by limiting PM emissions from light-duty vehicles to 0.3 mg/km (0.06 g/kg of fuel), as planned in the US to take effect in 2027.

Health impacts

Traditionally, analyses and regulations on particulate matter emissions have focused on the mass of particles emitted per kilometer traveled, in the case of light-duty vehicles, or per kilowatt hour of power generated, in the case of heavy-duty diesel engines. In the environmental analysis, the parameters for assessing air quality are based on the atmospheric concentrations of PM10 and PM2.5 measured in µg/m3, i.e., the mass of particles with a diameter of less than 10µm or 2.5µm, respectively. However, as mentioned earlier, with the significant increase in fuel injection pressure, initially in diesel engines and more recently in direct injection gasoline engines, particle size has been greatly reduced, leading to the formation of particulate matter with a diameter of around 0.1μm (PM0.1), so that even an emission with a small particle mass can contain a very large number of ultrafine particles.

In terms of public health, this fact is extremely important, since these particles penetrate the pulmonary alveoli and can only be eliminated through the bloodstream, always carrying a load of hydrocarbons that can lead to much more serious consequences than coarser particulates, such as the development of various types of cancer.

Figure 6 compares the statistical distributions of particle size for different metrics of number, particle surface area, lung deposited surface area (LDSA), and mass. The areas under the distributions of these variables (Ctotal) were normalized relative to their respective totals. The black line at the top of the figure shows the probability of respiratory deposition based on the ICRP (International Commission on Radiological Protection, 1994) model for light exercise with nasal breathing at 25 L/min. The particles were modeled as spherical, with a density of 1 g/cm^3.

It is important to note that the horizontal axis has a logarithmic scale, so that the areas under the aforementioned statistical distribution curves are actually smaller on the left side of the graphs than on the right.

This model highlights three zones of particulate matter emission control associated with particle size, with the following characteristics:

a) Particles with a diameter greater than 1000 nm (red zone) are highly likely to be deposited in the lungs (black curve), given the large amount of mass present in this class, despite the low number of particles. This emission corresponds to the visible range and is generally corrected by combustion process control.

b) Particles with diameters between 23 nm and 1000 nm (yellow zone) still account for a considerable portion of the mass, and their number starts to become significant for diameters below 200 nm. However, larger particles in this range (>200 nm) have a smaller surface area and deposition in the lungs (green and yellow curves) and a low probability of deposition in the lungs (black curve). This intermediate zone is still in the diameter range where mass, rather than particle number, is the control parameter. The use of clean fuels, such as ethanol, or the use of particle filters allows for an intermediate degree of control in this category, even with more restrictive PM mass requirements.

c) Particles with a diameter of less than 23 nm (blue zone) are formed from semi-volatile precursors that have negligible mass but a high number of particles (blue curve) with a large surface area and a high probability of deposition in the lungs (yellow and black curves). In this case, controlling the combustion process is not sufficient and must be carried out by limiting the number of particles, which has been implemented internationally with standards for counting particles larger than 10 nm in diameter (or NP10), possibly due to technological limitations in measurement and process control. This requirement generally leads to the application of ceramic filters, often impregnated with catalysts to facilitate the burning of particles.

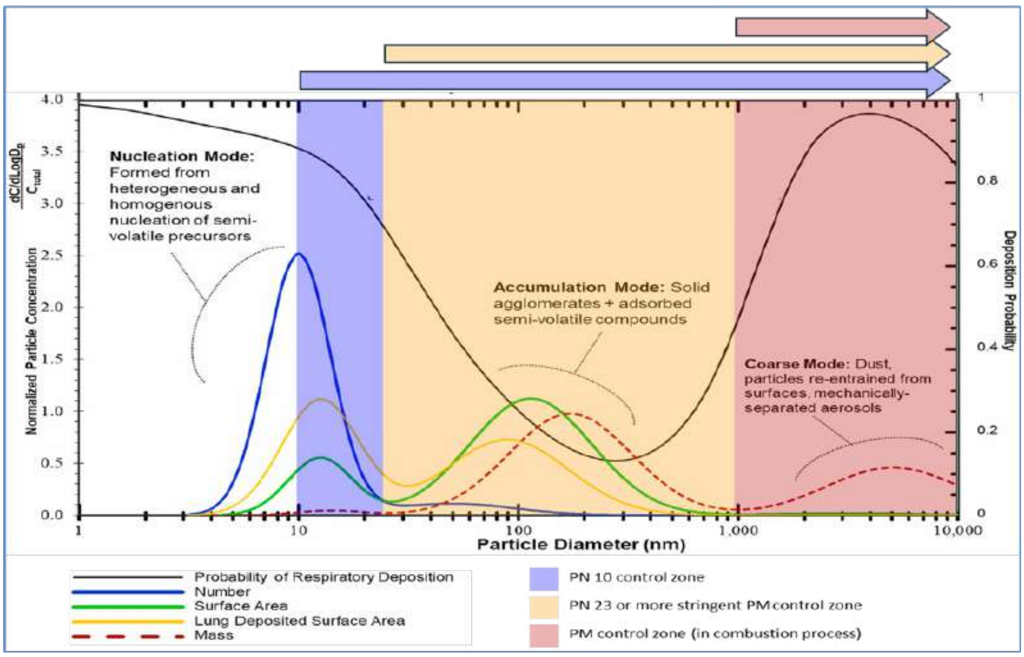


Figure 6: Particle size distribution in exhaust emissions from a typical engine
(Adapted from Kassel, 2013) VIII

A correct understanding of the mechanisms that explain particle deposition as a function of their diameter depends on a more in-depth knowledge of the respiratory system's physiology and its modeling. However, from these three characteristics, it can be concluded that controlling mass emissions is important, but controlling the number of particles becomes the focus from a public health perspective as the diameter of the particles is reduced as a result of technological advances in injection systems, although the mass of ultrafine particles tends to be negligible in this case in relation to the total mass of particulates.

It is important to note that, also for 10 nm particles, the surface area again assumes significant values, which is an indicator of the hydrocarbon adsorption capacity of these particles, greatly aggravating their toxicity.

For these reasons, the European Community began to place greater emphasis on controlling the number of ultrafine particles from GDI vehicles, leaving the control of the mass itself in the background, and established a limit of 6×10^{11} particles per kilometer traveled in the Euro 6 regulation, implemented in 2017.

In Brazil, the growing sales of light-duty vehicles with GDI engines means that the European approach must be followed in order to control ultrafine particulate emissions, reducing not only the mass of particles but also their impact on public health.

However, as the PM emissions are still very high and increasing, it is important to establish an urgent strategy to halt this effect by reducing mass emissions, returning to the levels seen before GDI engines entered the market, to be complemented by the establishment of particle number limits to effectively solve this problem.

Brazilian fuels are part of the solution

A study conducted by Ford showed that increasing the ethanol content in gasoline reduces particulate matter emissions from GDI engines, so that Brazilian gasoline already provides lower PM values than international standards. This reduction is small up to levels of 20%, but gasoline with ethanol levels above 30% reduces the mass and number of particles by between 30% and 45%, with little influence on particle size and a slight increase in the soot's organic fraction. The low sulfur content of all Brazilian fuels also contributes to the reduction of particulate emissions due to the absence of sulfates.

These factors lead to the recommendation that the reference gasoline be updated to the commercial ethanol contents, currently at 25% and 30% for premium and regular fuels, respectively, so that the results obtained are representative of the Brazilian reality and allow for the most appropriate technology to be chosen for PM and NP control.

In the case of ethanol-fuelled vehicles, the International Energy Agency report presents a comparison of particulate matter emissions, expressed in mass and number of particles, for gasoline (RON 95), ethanol (E85), and methanol (M56), which indicated much higher emissions in GDI engines, but significantly reduced when using E85 fuel, as shown in Figure 7. The tests were carried out following the European NEDC test cycle on two GDI vehicles (2.4 L, US standard, naturally aspirated, 2014, and 2.0 L, Euro 5, turbo, 2011) and one MPFI vehicle (1.6 L, EURO 5, 2012).

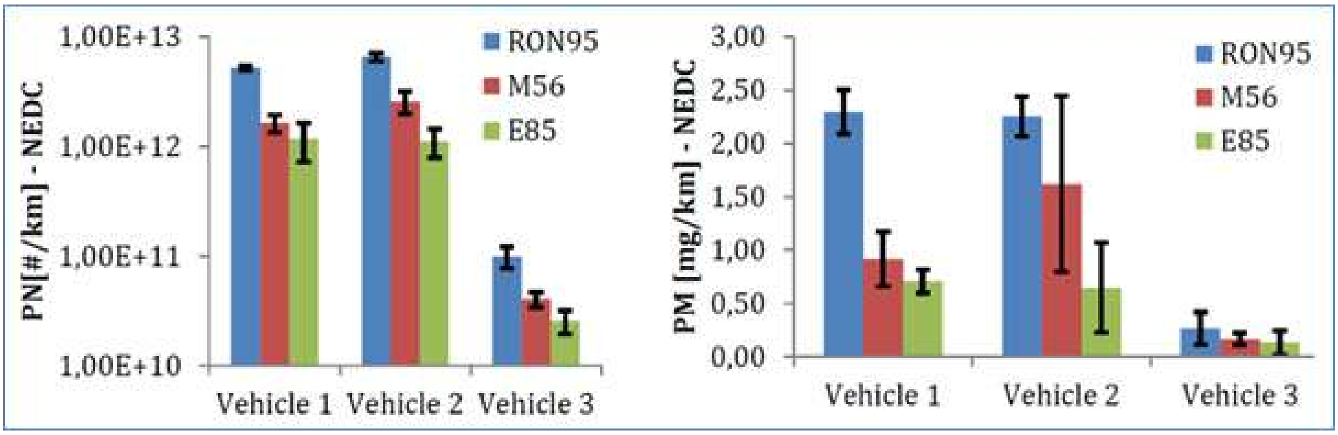


Figure 7 – PM and PN emissions in three vehicles according to the European NEDC test cycle
Source: Rosenblatt et al.(2020)8

These results indicate that using ethanol reduces particulate emissions from GDI engines by 70% for PM and 80% for PN, while in MPFI engines these reductions were 55% and 75%, respectively, despite these being originally an order of magnitude lower than in GDI engines.

Although these measurements were taken according to the European NEDC test cycle, which underestimates them, the relative proportions between the results suggest that ethanol enhances the compliance of GDI vehicles with the 1 mg/km limit, corresponding to current Brazilian MPFI vehicles, at least for flex-fuel engines running on ethanol, in a transition phase to the desired limits of 0.3 mg/km and $6x10^{11}$ part/km, to be progressively implemented in a definitive phase.

Strategy recommendations for light-duty vehicles

Technologically speaking, the best solution for definitively correcting the particulate matter emissions increase in light-duty vehicles, observed in the last few years, is to apply ceramic filters to vehicles with Otto GDI engines, as is already done for light-duty and heavy-duty diesel engines.

Since its first generation, this technology has reduced PM emissions to below 0.3 mg/km, equivalent to 6 mg/kg of fuel, which is compatible with the levels practiced in all Diesel engines currently sold in Brazil, and will be required for all light-duty vehicles in the US Tier 4 phase starting in 2027 and Euro 7 in 2028 as well.

In addition, the application of ceramic filters in GDI engines will simultaneously reduce the number of particles in exhaust gases - PN by about 90%, i.e., typically from (2 to 5) $x10^{12}$ particles/km (for engines without PN control) to $6x10^{11}$ particles/km (currently feasible limit for first-generation ceramic filter technology), with the potential for further reduction to $1x10^{9}$ with fourth-generation filters, as show the graphs in Figure 8. This limit corresponds to significantly greater protection of public health due to the reduction in toxicity. It is important to note that the European limit for the number of particles and the American limit for mass are achievable with the same first-generation filter technology.

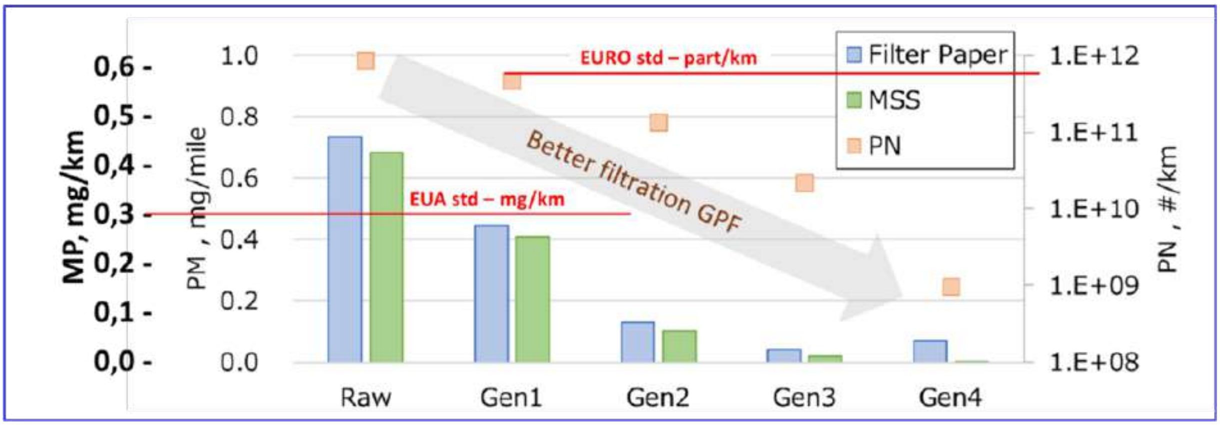


Figure 8 – PM and PN levels after the ceramic filter (1st to 4th generation – FTP driving cycle)[XII]

[a] *Measurements on filter paper correspond to the official measurement method for certification, which includes soot and organic components, while those performed by MSS (Micro Soot Sensor) measure only the carbon portion and are used for real-time assessments.*

Considering that this development involves revising the vehicle and engine design, it will be necessary to consider a minimum timeframe for implementing such modifications. However, it seems reasonable to immediately implement an intermediate stage in the regulation by requiring a standard of 1.0 mg/km to return Otto engines to the usual levels practiced in Brazil until 2021, which will naturally be met by traditional MPFI engines and Diesel utility vehicles. This standard can be considered feasible immediately, since there are existing vehicles with GDI engines that meet it, especially when running on ethanol. It is therefore reasonable for this requirement to come into effect in the very short term for at least 80% of each manufacturer's light-duty vehicle production. The remaining 20% of vehicles may keep their GDI engines unchanged for an additional period until the next phase, when all vehicles must comply with the 0.3 mg/km standard, even if they require more extensive modifications to achieve this reduction.

This strategy has the advantage of imposing immediate action to halt the already observed increase in PM emissions from light-duty vehicles, while not preventing the production of these vehicles with GDI engines, but forcing their progressive development towards stricter control of particulate matter emissions, which can be introduced as each manufacturer's commercial plans prioritize interest in these engines.

It is important to note that the limits of 0.3 mg/km and $6x10^{11}$ particles/km mentioned above can be met simultaneously with first-generation ceramic filters, which are sufficient for the current Brazilian situation, but there exist four generation technologies capable of achieving considerably greater reductions, as shown in Figure 8.

Regarding particle count, this approach was led by Europe, which established particulate matter standards for Otto cycle engines, defined by the joint requirement of limits on mass and particle count. The table below shows the current values in different parts of the world.

Regulations	mg/km	particles/km
EURO 6/7	4,5	**$6x10^{11}$**
EUA Tier 3	1,9	---
EUA Tier 4 - 2027	**0,3**	---
California - 2023	0,6	---
CHINA 6 - 2023	3	$6x10^{11}$
CHINA 7 - planned	1 a 2	1 a 3 x 10^{11}

Table 4 - Particulate matter standards for light-duty gasoline vehicles

In light of the suggestions proposed above, Table 5 presents a summary of the values currently applied in Brazil and the corrections necessary to rebalance particulate matter control requirements for all vehicle categories, to be implemented through the following steps:

a) an urgent adjustment to be applied in the L8 phase to prevent emissions from continuing to increase;

b) a new L9 phase to reduce PM emissions from light-duty vehicles in line with the best available and economically feasible technologies, bringing them into line with those of the most advanced Diesel vehicles.

PROCONVE	Category	Particulate Matter Emissions		
		Standards		mg/kg_{fuel}
Phase P8	trucks and buses	10mg/kWh	$6x10^{11}$ part/kWh WHTC	10 a 16 (2024 averages)
Phase L8	cars and pickup trucks	4mg/km	---	29 a 57 (2024 averages)
Phase L8 adjustment	cars and pickup trucks	1mg/km	---	18 (2021 averages)
New Phase L9	cars and pickup trucks	0.3mg/km	$6x10^{11}$ part/km	06 (~ 1/3 of pre-GDI)

Table 5 - Typical particulate matter emissions from vehicles and engines

In addition, it is necessary to anticipate the growing use of diesel or natural gas generators to supplement the Brazilian energy matrix. In cases where batteries are recharged with electricity generated by thermoelectric sources and small generators used during peak hours, the emissions produced in this generation are induced by electric vehicles. Under the concept of "from the well to wheel", established by the Fuel of the Future Law, these emissions must be considered as being associated to the vehicle and need to be compatible with those of traditional vehicles with internal combustion engines, especially in cities that depend on electricity supplied exclusively by thermoelectric plants.

In these cases, the increased demand for recharging electric vehicle batteries imposes new emission standards on Diesel engines for generator sets, before these emissions become environmentally significant, given that these machines remain in use for several decades. In this sense, it is necessary to establish emission limits equivalent to those of P8 engines, i.e., 10 mg/kWh and $6x10^{11}$ particles/kWh (similar to Stage V, already available in Europe).

In addition to these requirements, it is recommended to take advantage of the creation of this new regulation to establish the foundations for the inspection of vehicle and engine emissions by remote sensing, which is a fundamental tool for effectively monitoring the results of PROCONVE to avoid distortions such as those pointed out in this paper. This type of monitoring must rely on "reference values" calculated for all categories, as conceptualized in this study and expressed in grams of pollutant per kilogram of fuel, or per mole of carbon, which is the native unit of measurement for this method and also directly applicable to all fuels, whether oxygenated or not. These reference values should be proposed in accordance with the desired severity of the inspection program, but respecting the minimum limits obtained by dividing the emission values by the fuel consumption values expressed in the same units, both certified according to PROCONVE..

Extension of this analysis to engines of other machines and generators

Environmental impact analysis based on emissions per kilogram of burned fuel also allows comparison with other types of machines whose operation is completely different from that of vehicle engines, but which have an important correlation with them.

In the case of non-road machinery, inventories have shown that this fleet's total emissions are higher than those of the truck fleet, which is much larger. This led to the proposal for a new PROCONVE MAR II phase, with US Tier 4 Final requirements for off-road machinery, which lead to technologies equivalent to those of the P7 phase for trucks and buses. This shows that further development will be necessary to reach the equivalent of phase P8, so that the stringency of machinery controls is brought into line with that of the heavy-duty and light-duty road vehicles currently under discussion.

Similarly, generator set emissions control has been discussed along the same principles as non-road machinery, with a tendency to accept Tier 4 final levels as appropriate for them, as a program start, at least for generators with the greatest environmental impact.

In the case of generators, it is necessary to gradually bring this group of machines to levels equivalent to those of phase P8 for all regulated pollutants, to prevent vehicle electrification from causing greater environmental impacts than vehicles with internal combustion engines. This aspect is particularly important for large generators that supply entire cities and for those frequently used in urban areas, giving them a special class of "low-emission generators" when they are also used to recharge electric vehicle batteries.

Table 6 shows the status of the various types of PM emissions sources currently under discussion, and indicates the cases to be prioritized for the benefit of compliance with air quality standards for particulate matter, considering their consistency and equivalence with the technologies applied for the control of emissions from road vehicles. However, this assessment needs to be extended to other regulated pollutants as well, in order to establish regulatory consistency with Diesel vehicle engines, whose details are beyond the scope of this study.

PROCONVE	Category	Particulate Matter Emissions		
		Standards		mg/kg_{fuel}
Phase MAR I	non-road machinery	200 to 600 mg/kWh	---	900 to 2400 (average depending on machine type)
Phase MAR II	non-road machinery	20 to 30 mg/kWh	---	90 to 125 (standards) 50 (expected average - equivalent to P7)
Current market (unregulated)	generators	---	---	2200 to 4200 (estimated as Tier 1)
New program	generators	20mg/kWh	---	90 to 125 (standards) 50 (average - equivalent to P7/MAR II)
New program	special generators	10mg/kWh	$6x10^{11}$ part/kWh	10 to 16 (equivalent to average P8, for recharging electric vehicles)

Table 6 - Typical particulate matter emissions from machinery and generators

Given this vision, particulate matter emissions could be brought to the same control level in all regions of the country, regardless of the type of vehicle or machine present, such as mixed fleets, segregated corridors, cities in general, highways, power generation, agricultural and construction machinery, road and non-road machinery, locomotives, etc.

Final conclusions

This paper presents a method, based on energy demand, that converts the particulate emission factors of any vehicle or engine category to a common unit, expressed in g_pollutant/kg_fuel, which allows for an assessment in terms of the energy production of engines, that is, the "environmental efficiency" of the various technologies employed. This method is particularly useful for comparing engines of different categories and for monitoring emissions by remote sensing.

This study compared the importance of PM emissions from heavy-duty diesel vehicles with those from light-duty ethanol and gasoline vehicles, both expressed in g_PM/kg_fuel, and detected a distortion in the particulate matter control strategy for light-duty vehicles, caused by the introduction of direct injection Otto cycle engines on the market, already verified in the United States for over a decade and which has recently been increasingly present in Brazil. It is recommended to extend this analysis to other pollutants, aiming at a complete balance in the control of emissions from all vehicles and machines that use internal combustion engines.

This analysis showed that the technological standard of heavy-duty vehicles in phase P8 already exceeds the features currently applied to light-duty gasoline and flex-fuel vehicles, and suggests the establishment of new emission standards and strategies for controlling particulate matter emissions for light-duty vehicles in two stages to encourage the implementation of the best available and economically viable practices for GDI engines, bringing them up to the same technological level as diesel vehicles.

Thus, the strategy suggested for Brazil should follow the following steps, proving the values through dynamometer tests according to the procedures of US FTP 75 procedures, to be complemented in the future by applicable requirements based on real driving emissions (RDE) tests:

a) **Route Correction:** January 1, 2029 - change in BIN 30 and BIN 20 for light-duty passenger vehicles and acquisition of equipment and expertise for particle number control

- Correction of the corporate PM emission standard to 1 mg/km (mass);
- Determination of typical NP10 values for vehicles with MPFI and GDI engines, measured in dynamometers.

b) **PM emission standard reduction:** January 1, 2031 - change in BIN 30 and BIN 20 for light-duty passenger and commercial vehicles:

- PM (mass) standard of 0.3 mg/km;
- PN10 standard of $6x_{10}^{11}$ particles/km

Since the Brazilian data correspond to the certification averages obtained with E22 gasoline and the international data are based on RON95 gasoline, it is recommended to extend this analysis to individual results of specific measurements of PM mass and particle number – NP in current Brazilian vehicles, distinguishing between GDI and MPFI vehicles, using E100 ethanol and E30 gasohol, in order to conduct a detailed feasibility analysis of the technologies considered.

Filtration technologies associated with catalysts have led to significant reductions in particulate matter emissions and provide better protection for public health, as well as helping to meet the Air Quality Standards established by recent legislation. However, the use of ethanol and higher alcohol content blends are important contributing factors in meeting the suggested limits.

In addition, the introduction of the PN limit brings Proconve into line with the most modern international standards (Euro 6 and 7, China 6 and 7, among others), opening doors to new potential markets. Another important aspect is the appreciation of the strategic role of ethanol and Brazil with its biofuels, which already show superior performance in terms of particulate emissions. Thus, controlling particulates by number and mass is a necessary step to reduce environmental and public health impacts and ensure that the Brazilian fleet keeps pace with global best practices.

Furthermore, it is recommended that a program be created for the gradual establishment of emission limits for generator set engines that may eventually be used to power electric vehicle charging systems, so that these do not induce emissions higher than those of traditional vehicles. Such a program should start with the Tier 4F standard and gradually evolve to levels equivalent to the P8 phase limits for heavy-duty vehicles.

The analysis developed in this study focused on the Brazilian case, but it raises some strategic aspects that are important for other countries, such as India, which has already been intensifying the use of ethanol as fuel and may include in its strategies the control of PM and NP in vehicles with GDI engines and the use of ethanol contents of up to 30% in gasoline to benefit this control, taking advantage of the Brazilian experience, which has already reached this proportion.

This study was prepared by Environ Mentality at the request of AFEEVAS in August 2025 to support discussions on rebalancing particulate matter control under PROCONVE, given the growing share of GDI engines in the light-duty vehicle market.

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Life Cycle Assessment (LCA) of Light- and Heavy-duty Vehicles - Focus on GHG Emissions and Primary Energy

2

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Abstract

EU legislation is reducing the fleet average tailpipe CO_2 emissions targets for passenger cars, vans and trucks to mitigate climate change, focusing on increasing the sales of zero tailpipe emission vehicles. Vehicles with a combustion engine on sustainable renewable fuels are not included within the targets, but EU legislators are currently considering widening the scope including a special vehicle category running exclusively on CO_2-neutral fuels (CNFs). The European Commission and UNECE is also developing a methodology for life cycle emissions of light-duty vehicles within 2025, and heavy-duty vehicles will follow.

The study presented here conducts a life cycle assessment (LCA) of different powertrain technologies for light- and heavy-duty vehicles, looking at the Global Warming Potential (GWP, expressed in g CO_2eq/km or g CO_2eq/t-km) and Primary Energy Demand (PED, expressed in kWh/km or kWh/t-km).

Basis for the analysis are the AECC LDV and HDV demonstrator vehicles for zero-impact pollutant emissions, which have been tested on different CNFs like e-gasoline, e-diesel and HVO.

Objective is to check impact of potential LCA methodology decisions on initial baseline results, including energy consumption, vehicle mileage, allocation, end-of life, among other items.

Results show the vehicles using a high share of renewable energy have similarly low GHG emissions for all powertrains, whether it is ICE on e-gasoline/e-diesel/HVO/renewable H_2, FCEV on renewable H_2 or BEV on renewable electricity. BEV on renewable electricity and ICE with HVO100_UCO (Used Cooking Oil) have the lowest PED of the renewable sources. Regarding methodologies, the main impact is coming from the base technical data of the vehicle and energy carrier.

Keywords: LCA, CO_2-neutral fuels, LDV, HDV

1. Introduction

EU legislation is reducing the fleet average tailpipe CO_2 emissions targets for passenger cars, vans and trucks to mitigate climate change. Targets led to innovation in engine efficiency and hybridisation in addition to development of zero tailpipe emission vehicles.

Recent focus of the legislator is on the introduction of zero tailpipe emission vehicles. For passenger cars and vans for example a target has been set for 100% share of new vehicle sales as zero tailpipe emissions by 2035.

Regulations in the EU have also encouraged the development and incorporation of renewable fuels for transport with a view to reduce its carbon footprint through the Renewable Energy Directive (RED). Although it opens the door to development of new type of fuels, the target levels within the recently revised Renewable Energy Directive are not in line with the overall ambition to reduce EU's GHG emissions by 55% compared to a 1990 reference. And there is no roadmap beyond 2030.

EU legislators are currently considering widening the scope of the CO_2 legislation in two aspects. First it is being considered to include a special vehicle category running exclusively on CO_2-neutral fuels (CNFs) outside of the targets. Second, the European Commission is developing a methodology for life cycle emissions determination, going beyond current tailpipe considerations. For light-duty vehicles, a method is expected within 2025 and heavy-duty vehicles will follow. Also, in an international context, life cycle methodology is being considered, at the United Nations Economic Commission for Europe (UNECE).

2. LCA Methodology

2.1 Goal and Scope

The goal of this study is to extend the existing Well-to-Wheel (WtW) analysis of CO_2 emissions of the AECC-IPA demonstrator vehicles [1, 2, 3] to Life Cycle Assessment (LCA). The 3 AECC LDV and HDV demonstrator vehicles for zero-impact pollutant emissions were tested on different CO_2-neutral fuels like e-gasoline, e-diesel and HVO.

Based on the ongoing discussions by UNECE and EU towards a harmonised methodology of LCA application to vehicles, the influence of different methodological options on the environmental impacts are analysed.

From all potential environmental impact categories, two specific impacts are investigated in this study.

- GHG emissions in CO_2-eq covering CO_2, CH_4, N_2O and H_2
- Primary Energy Demand (PED) with its shares on fossil and renewable energy.

There was no specific data available for the actual AECC-IPA demonstrator vehicles. Therefore following data sources have been used as representative vehicles

- LDVs from GreenNCAP database [5]
- HDV from IEA EV Task 46 vehicles [4]

2.2 Initial Methodology

Joanneum Research is developing and applying LCA methodology since 1993 in the automotive sector, e.g. vehicles with different fuels, (bio)fuel supply, e-fuel production, vehicle and its component manufacturing, infrastructure. This LCA methodology is applied taking the different methodology options into account. The most prominent current applications of this LCA methodology are in activities for IEA (since 2011: Task 19, 30, 33, 40, 46 and 52), FIA and GreenNCAP (since 2018). More details on the initial methodology used have been published by GreenNCAP [5].

The Figure 1 and Figure 2 show the system boundaries of the LCA for a diesel B7 and a FAME vehicle using different feedstocks. The functional unit for passenger cars is 1 km and for trucks due to the different payload 1 t-km.

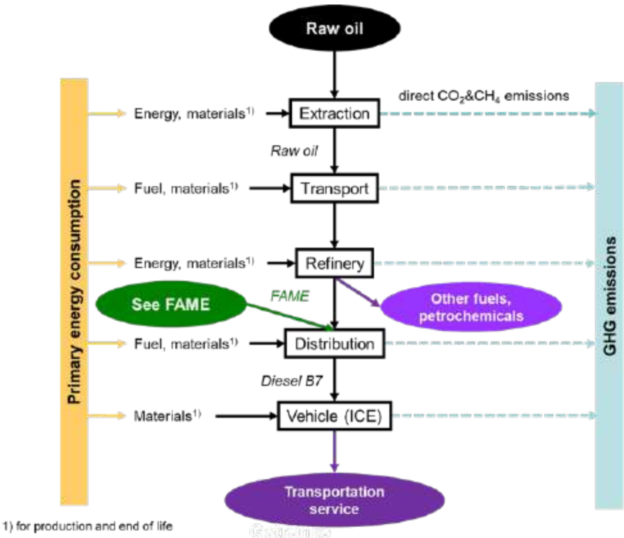

Figure1: System boundary for diesel B7 vehicle

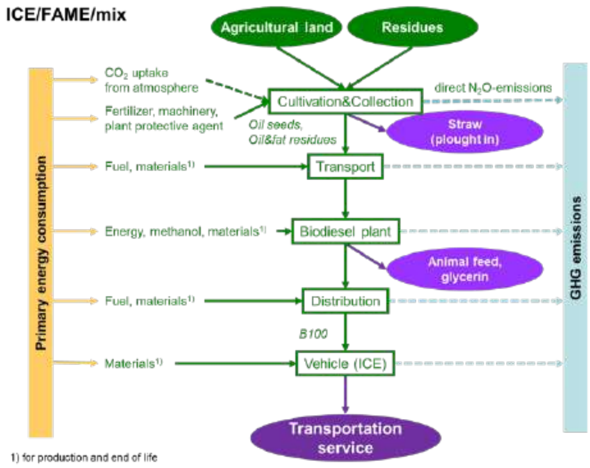

Figure2: System boundary for FAME vehicle

The shows the selected vehicle and fuel combinations modelled. A total of 11 cases are investigated for passenger cars and 8 for trucks. For each energy vector (electricity and fuel) two different cases are investigated for the use phase of the vehicles. One case is representative for the current situation (e.g. EU27 electricity or E10 market gasoline) and the other case is modelling a net-zero situation (e.g. wind electricity or e-gasoline).

	Passenger car				Truck			
	Total Vehicle			Catalyst	Total vehicle			Catalyst
Propulsion	ICE	PHEV	BEV	ICE	ICE	BEV	HFC	ICE
Fuel*)								
gasoline E10	+			+				
e-gasoline E10**)	+	+						
diesel B7	+				+			+
HVO 100***)	+				+			
e-diesel*)	+				+			
electricity****)		+	+			+		
renewable gaseous hydrogen					+		+	

*) fuel/energy only varied in use phase, production & EoL generic for all vehicles
**) made from wind electricity and CO_2 from air
***) used cooking oil and rapeseed
****) EU27 grid mix and wind electricity

Table1: Selected vehicle/fuel combinations

The Tables 2, 3 and 4 show the most relevant foreground data for the vehicles and the emissions control systems. All other data are taken from the GreenNCAP methodology [5].
The footprint of PGM (Platinum Group Metal) materials are taken from the 2nd IPA LCA study (not yet updated to the recently published 3rd study [6]).
A summary of the main key assumptions are the use of 2024 global average value for the production of energy and vehicles. Energy pathway variation has only been applied in the use phase. 240k km is used as vehicle lifetime in the case of cars. For the truck cases this was 1.2m km or 12 years. E-gasoline and e-diesel are from wind & Direct Air Capture. HVO is from Used Cooking Oil (and 1 rapeseed case for the truck). CO_2eq includes CO_2, CH_4 and N_2O

		Passenger car 2024							
Propulsion		ICE	ICE	ICE	ICE	ICE	PHEV	PHEV	BEV
Fuel/energy		gasoline E10_mix	e-gasoline E10 wind	diesel B7_mix	HVO100_UCO	e-diesel wind	gasoline E10& electricity	e-gasoline E10& electricity	ren. electricity
Weight	[kg]	1,415	1,415	1,485	1,485	1,485	1,583	1,583	1,763
Annual kilometres	[km/a]	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000
Lifetime	[a]	16	16	16	16	16	16	16	16
Lifetime mileage	[km]	240,000	240,000	240,000	240,000	240,000	240,000	240,000	240,000
Battery									
capacity	[kWh]	1.3	1.3	1.3	1.3	1.3	13	13	62
lifetime	[a]	16	16	16	16	16	16	16	16
weight	[kg]	9	9	9	9	9	153	153	413
Energy consumption									
average									
grid electricity	[kWh/km]						0.05	0.05	0.20
fuel	[kWh/km]	0.54	0.54	0.44	0.44	0.44	0.44	0.44	
best									
grid electricity	[kWh/km]						0.13	0.13	0.17
fuel	[kWh/km]	0.50	0.50	0.33	0.33	0.33	0.09	0.09	
worst									
grid electricity	[kWh/km]						0.00	0.00	0.38
fuel	[kWh/km]	0.62	0.62	0.54	0.54	0.54	0.78	0.78	
Emissions									
CO2 *)	[g/km]	134	0	109	0	0	110	0	0
CH4	[mg/km]	3	3.0	2.8	2.8	2.8	2.4	2.4	0
N2O	[mg/km]	1	1.1	6.9	6.9	6.9	0.7	0.7	0
CO2-eq	[g/km]	134	0.43	111	2.15	2.15	110	0.29	0
Vehicle operation									
tires	[kg/VH a]	19.2	19.2	19.2	19.2	19.2	19.2	19.2	19.2
engine oil	[kg/1000 km]	0.46	0.46	0.47	0.47	0.47	0.50	0.50	0
spare parts	[kg/VH a]	7.1	7.1	7.4	7.4	7.4	7.9	7.9	8.8
urea	[kg/1000 km]	0	0	1.5	1.5	1.5	0	0	0
*) without CO2 from urea combustion									

Table 2 : Foreground data for passenger car cases [5]

		N3 Truck 2024						
Propulsion		ICE	ICE	ICE	ICE	BEV	FC	ICE
Fuel/energy		diesel B7	HVO100_UCO	HVO100_rape	e-diesel wind	electricity	GH2@700	GH2@700
Weight	[kg]	13,160	13,160	13,160	13,160	18,370	14,210	14,370
Payload	[t]	26,840	26,840	26,840	26,840	21,630	25,790	25,630
Annual kilometres	[km/a]	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Lifetime	[a]	12	12	12	12	12	12	12
Lifetime mileage	[km]	1,200,000	1,200,000	1,200,000	1,200,000	1,200,000	1,200,000	1,200,000
Battery				-				
capacity	[kWh]	10	10	10	10	1,100	54	10
lifetime	[a]	12	12	12	12	12	12	12
weight	[kg]	120	120	120	120	7,216	500	120
Energy consumption *)	[kWh/km]	2.88	2.88	2.88	2.88	1.89	2.83	3.51
Emissions								
CO2 **)	[g/km]	697	0	0	0	0	0	0
CH4	[g/km]	0.0008	0.0008	0.0008	0.0008	0	0	0
N2O	[g/km]	0.05	0.05	0.05	0.05	0	0	0.008
CO2-eq	[g/km]	712	15	15	15	0	0	2.38
estimated H2 losses	[g/km]	0	0	0	0	0	0.6	0.6
Vehicle operation								
tires	[kg/VH a]	247	247	247	247	247	247	247
engine oil	[kg/100 km]	0.016	0.016	0.016	0.016	0	0	0.016
spare parts	[kg/VH a]	33	33	33	33	46	36	36
urea	[kg/100 km]	1.20	1.20	1.20	1.20	0	0	1.20
*) best/worst: -5%/+15%								
**) without CO2 from urea combustion								

Table 3 : Foreground data for truck cases [4]

Weight	**Main material**	**Gasoline passenger car**		**Diesel truck N3**	
		kg	%	kg	%
Catalyst system					
housing	steel, aluminum	5.75	82%	145.8	83%
substrate		1.25	18%	29.2	17%
total		7.00	100%	175.0	100%
Substrate					
bare	ceramic	1.20	96.4%	21	72.6%
washcoat	Aluminiumoxid, Zirkoniumdioxid, Cerdioxid	0.041	3.3%	8.0	27.4%
catalyst		0.0036	0.3%	0.011	0.04%
sub-total		1.25	100%	29	100%
Catalyst					
Platinum		0	0.0%	0.0064	56.7%
Rhodium		0.00036	10.1%	0	0.0%
Palladium		0.0032	89.9%	0.0049	43.3%
sub-total		0.0036	100%	0.011	100%

Table4: Foreground data for the emission control system (own data)

2.3 Methodological options

The impact of following methodological options was analysed on top of the initial methodology

- Energy consumption
- Lifetime mileage
- Direct H_2 emissions as greenhouse gas for H_2 trucks with FC and ICE
- Allocation for biofuels; comparing RED methodology vs. system expansion used in the GreenNCAP methodology
- End-of-Life (EoL): comparison of different methodological options at the end of life e.g. CFF (Circular Footprint Formula)
- Levelling concept 1 – 4
- Other greenhouse gases and
- Relevance of infrastructure

This paper only documents the impact of the energy consumption and the direct H_2 emissions with its possible contribution to GHG emissions.

3. Results

3.1 Passenger cars

The shows the GHG emissions of the passenger car cases investigated.
ICE and BEV have similar emissions for production of vehicle body in light blue. Battery production is additionally significant for PHEV and BEV, in red. Remaining ICE emissions are mainly from fuel supply, in yellow, and combustion, in black. The combustion part goes to net-zero in case of e-fuel or HVO (UCO being used cooking oil). Remaining BEV emissions are from electricity supply, in dark yellow.
It can be seen in Figure 3 that all LDV powertrains have similarly low GHG emissions when operated on renewable electricity/fuel. This is indicated by the transparent horizontal green area. Differences are within general LCA modelling uncertainties.

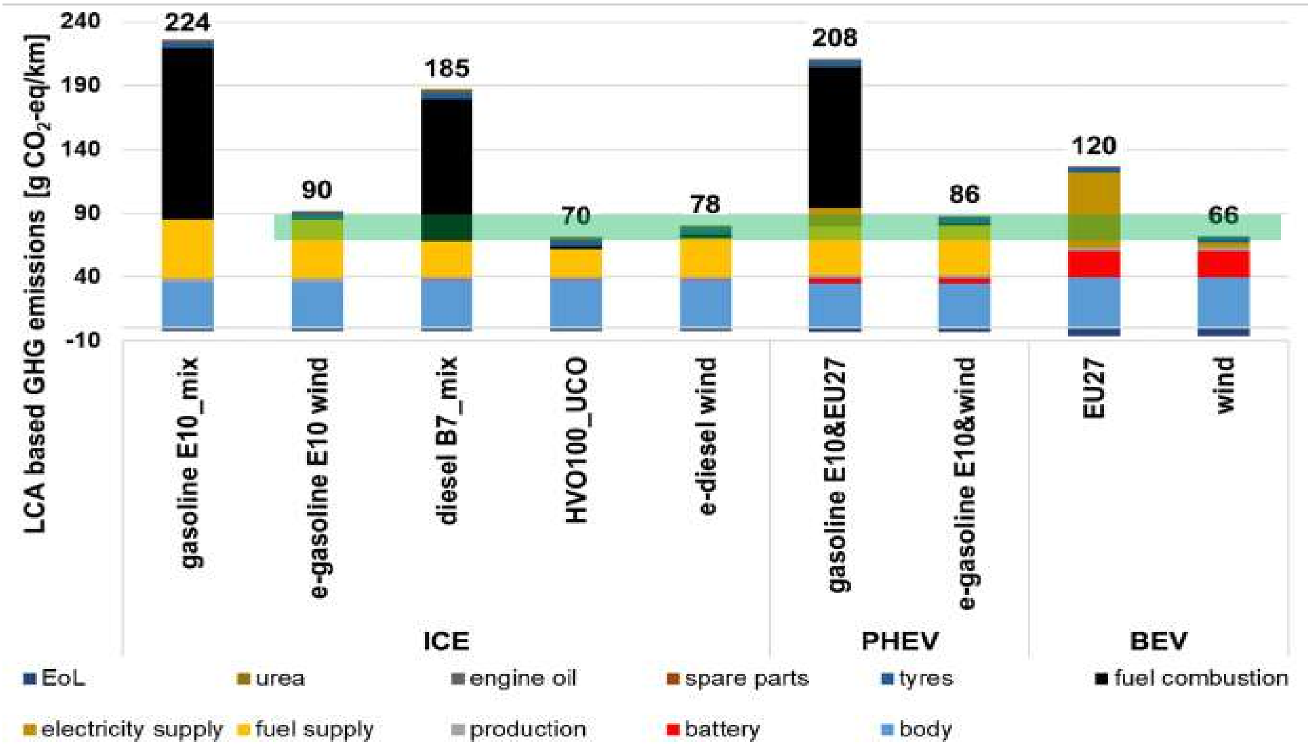

Figure3: GHG emissions passenger car cases

The Figure 4 shows the Primary Energy Demand (PED) results of the different passenger car cases from Figure 3. Energy demand from fossil resources are plotted in black, those of renewable resources in green. All cases have a black portion due to the assumption of today's global average input data for example the energy and vehicle construction.

BEV on wind and ICE on HVO (UCO) have the lowest PED from those powertrain options that are relying on renewables sources.

ICE on e-gasoline has higher PED, requiring a higher amount of renewable energy due to the conversion from electricity via H_2 to e-fuel. But the e-fuel can be an energy carrier of renewable energy sources elsewhere in the world

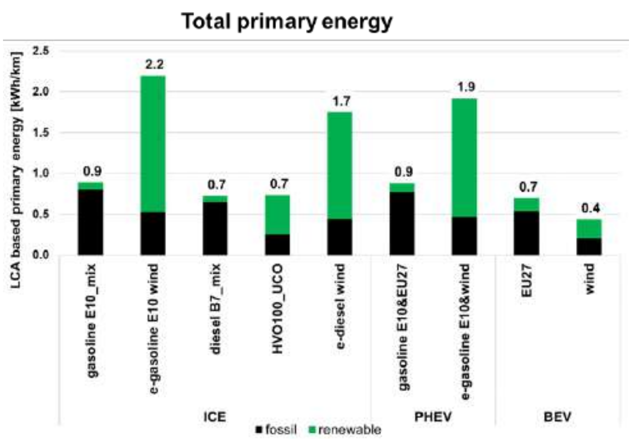

Figure4: Primary Energy Demand passenger car cases

3.2 Trucks

The Figure 5 shows the GHG emissions of the truck cases in a similar way as Figure 3 for cars. Here the unit is in t.km.

ICE, FCEV and BEV have similar emissions for production of vehicle body, in light blue. Battery production (red) or H_2 tank (light grey) are additionally significant for ICE, FCEV and BEV.

Additional ICE emissions are mainly from fuel supply (yellow) and combustion (black). This combustion part goes towards net-zero in case of e-fuel, H_2 or HVO (UCO and rape). The UCO and rapeseed HVO case differ in the fuel supply contribution.

Additional FCEV and BEV emissions are from H2 or electricity supply in dark yellow.

It can be seen that all HDV powertrains have similarly low GHG emissions when operated on renewable electricity/fuel. This is illustrated by the transparent horizontal green bar. All differences are within general LCA modelling uncertainties.

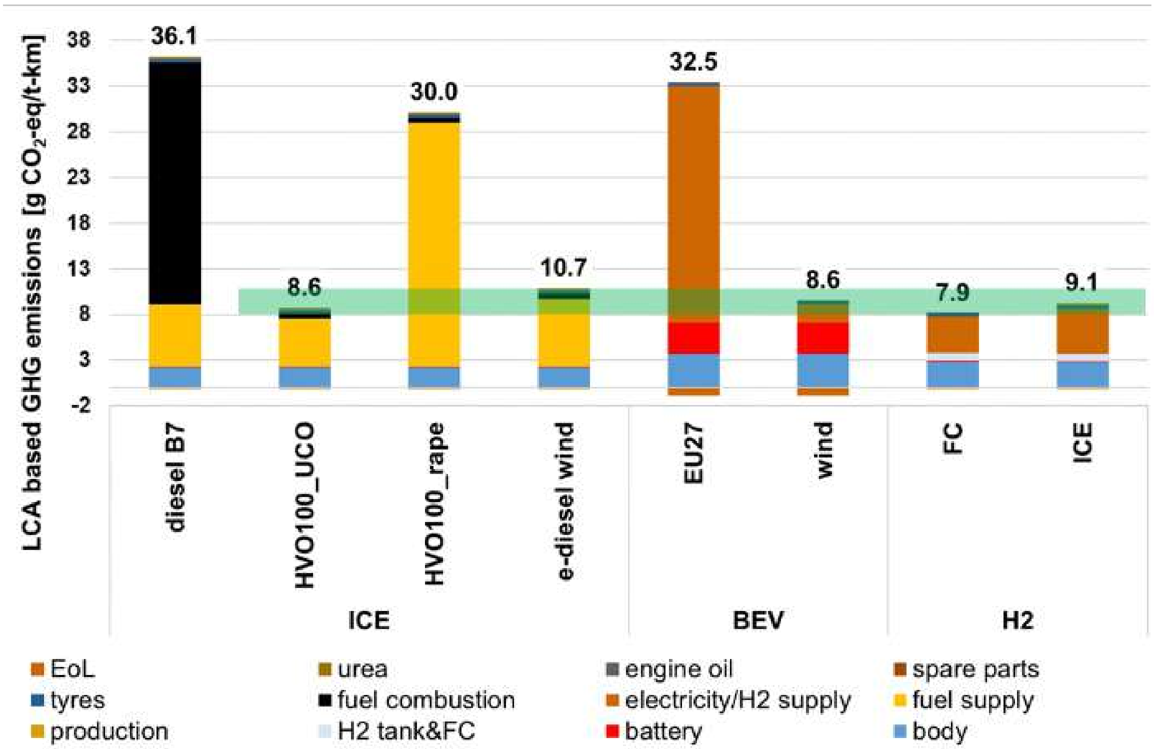

Figure5: GHG emissions truck cases

Figure 6 shows the Primary Energy Demand of the truck cases as before for cars.

BEV on wind and ICE on HVO (UCO) have the lowest PED from those powertrain options that are relying on renewables sources.

H_2 ICE and FCEV have higher PED, requiring higher amount of renewable sources. ICE on e-diesel has highest PED, requiring highest amount of renewable energy. However, H_2 and e-diesel can be an energy carrier of renewable energy sources elsewhere in the world.

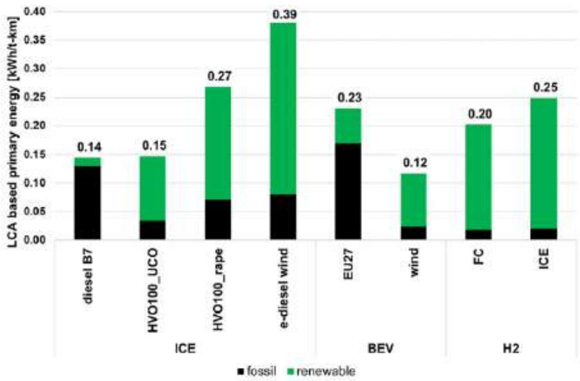

Figure 6: Primary Energy Demand truck cases

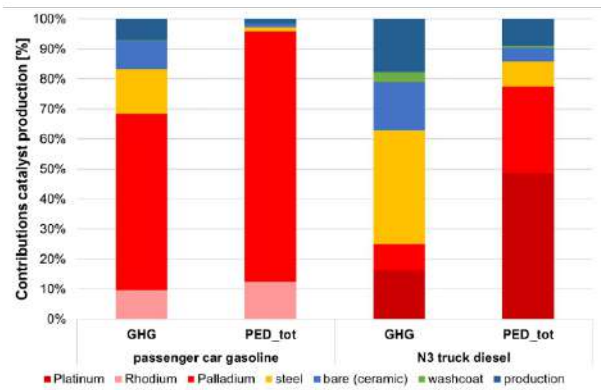

Figure 7: Primary Energy Demand truck cases

3.3 Emission control system

Figure 7 shows the shares of GHG emissions and primary energy for the emission control systems.

It is first noteworthy that the overall contribution of the emission control system within the LCA of vehicles is small. For cars it is calculated to be 0.04 g CO2-eq/km (compared to the total range between 66 and 224 g CO_2-eq/km). For the truck it is 0.08 g CO_2-eq/t-km (compared to the total range between 7.9 and 36.1 CO_2-eq/t-km).

On a relative scale, GHG emissions and Primary Energy Demand of the catalyst are strongly determined by the PGMs (Platinum Group Metals).

3.4 Other methodological options

After the application of the initial methodology described above, selected methodological options are applied to analyse its influence on the results. This paper describes the effect of two of these methodologies investigated. First, the influences of the energy consumption of the vehicles are described. Second, potential effect of including H_2 emissions as a species with Global Warming Potential is shown.

To investigate the effect of the energy consumption, the "Best – average – worst" variations of vehicle´s energy consumption are taken from the measurement of GreenNCAP in its testing procedure [7]. Previous results shown above were taking into account the average value of this range.

The figure 8 shows the impact of the energy consumption in the use phase of passenger cars on GHG emissions. It shows that the energy demand is one of the most relevant parameters for all systems. The effect becomes smaller when the share of renewable energy/fuel increases, because extra amount of energy is not resulting in extra GHG emissions in this case. The effect is the largest for PHEVs, because depending on the share of fuel and electricity consumption, the results can be that of an ICE (worst case) or that of a BEV (best case). For this powertrain technology, it is essential that the vehicle is charged frequently and operated with sufficient share of electric driving to reduce its GHG emissions footprint. Similar to other systems, the effect reduces significantly in the case of renewable fuel and electricity.

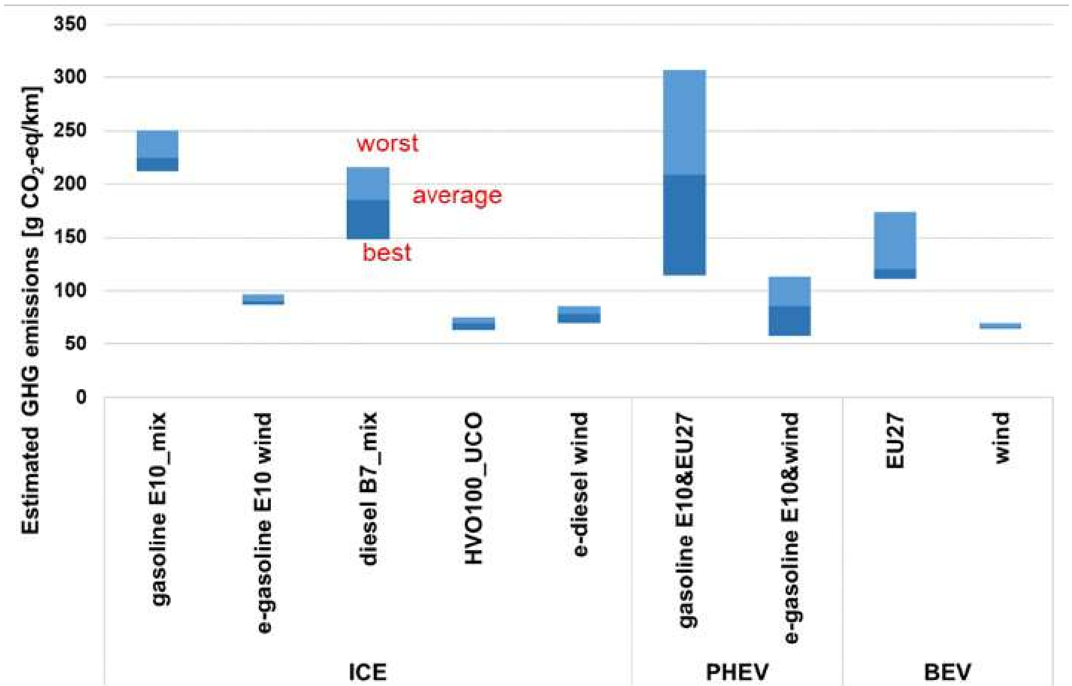

Figure8: Impact of energy consumption

To investigate the effect of including direct H_2 emissions, preliminary literature values are taken. A first value is that of direct H_2 losses in the energy supply from nature to the H_2 filling station. A range of 2.6 – 5.9% of hydrogen use is considered for this. A second value is the Global Warming Potential of H_2, for which a range of 6.5 – 15 kg_CO_2-eq/kg_H_2 is used.

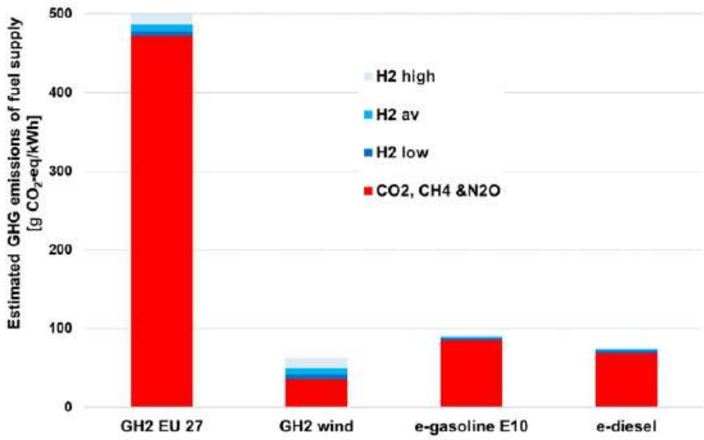

Figure9: GHG emissions of H_2 supply incl. direct H_2 emissions from possible losses

Figure 9 shows the GHG emissions including direct H_2 emissions for different fuel supply cases. Especially for renewably produced hydrogen the contribution from direct H_2 emissions can be up to 40% of the total GHG emissions. For liquid hydrogen, not analysed here, it might be even higher. Further research on this topic is required, but it seems direct H_2 emissions are relevant for the GHG emissions and should be considered in the future. The LCA methodology developed in the EU Horizon Europe project TranSensus [8] for example includes it.

4. Conclusion

This work investigated the LCA emissions of the AECC-IPA demonstrator vehicles and some additional powertrains. For the use case, it was investigated what the emissions of a today's energy/fuel mix are, as well as a future fully renewable case.

It was shown that all powertrains have similarly low GHG emissions when using renewables for electricity and fuel. ICE on 'HVO from UCO' and BEV on 'wind' have lowest Primary Energy Demand. ICE on H2/e-fuels and FCEV have higher Primary Energy Demand, but can tap into abundant renewable energy available in other regions of the world (solar, wind). Direct H2-losses might have substantial contribution to Global Warming, but further research is needed.

In general, for the harmonised LCA methodology under development at EU and UNECE, a transparent reporting is needed for base characteristics of vehicle, powertrain and energy/fuels.

5. Acknowledgement

The authors would kindly like to thank Gerfried Jungmeier of Joanneum Research for the conducted study. Members of the Association for Emissions Control and Climate (AECC aisbl) and the International Platinum Group Metals Association (IPA) are acknowledged for the financial support.

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7. Glossary

B7:	Diesel with 7 vol-% biofuel (FAME) blending
BEV:	Battery Electric Vehicle
CNFs:	CO_2-neutral fuels
E10:	Gasoline with 10 vol-% biofuel (EtOH) blending
EtOH:	Ethanol
e-diesel:	Synthetic diesel (in this paper made from renewable electricity and CO_2 from direct air capture)
e-gasoline:	Synthetic diesel (in this paper made from renewable electricity and CO_2 from direct air capture)
EoL:	End-of-Life
EU27:	Average electricity mix in 27 EU countries (year 2024)
FC:	Fuel Cell
GHG:	Greenhouse gas
H2:	Hydrogen
HVO:	Hydrotreated Vegetable Oil
ICE:	Internal Combustion Engine
LDV:	Light Duty Vehicle
HDV:	Heavy Duty Vehicle
PED:	Primary Energy Demand
PHEV:	Plug-In Hybrid Vehicle
RED:	Renewable Energy Directive
UCO:	Used Cooking Oil

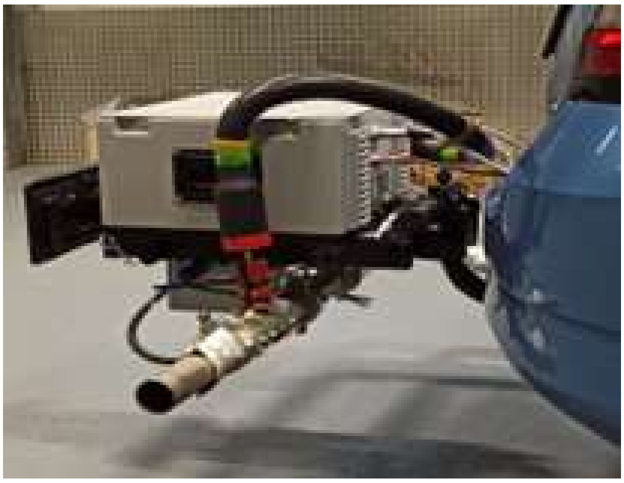
Revolutionizing Real Driving Emissions Testing: AVL M.O.V.E FT

AVL India

In the evolving landscape of global emission regulations, precision, portability, and adaptability are no longer luxuries—they are necessities. The AVL M.O.V.E FT, a compact FTIR-based emission measurement system, is a game-changer in the field of real driving emissions (RDE) testing. Designed to meet the stringent demands of Euro 7 and beyond, this innovation from AVL Analytical Technologies GmbH sets a new benchmark for mobile exhaust gas analysis.

With regulatory bodies worldwide tightening their grip on real-world emissions, traditional lab-based testing methods are no longer sufficient. The need for on-road, real-time data collection has led to the rise of Portable Emissions Measurement Systems (PEMS). However, the complexity of measuring multiple gas components—especially under varying ambient conditions—has posed significant engineering challenges.

AVL's answer is a fully integrated FTIR analyzer that combines accuracy, versatility, and mobility. Whether used as a standalone unit or as an add-on to AVL's M.O.V.E iS+ and iX systems, the M.O.V.E FT delivers high-resolution data across a wide spectrum of exhaust gases.



The AVL M.O.V.E FT is supported by intuitive software platforms—iGEM and Web UI—offering real-time diagnostics, calibration, and data visualization. From linearity checks to ANR reports, users can monitor and validate system performance with ease.

Extensive correlation studies with AVL's SESAM i60 FT SII and AMA SL systems confirm the M.O.V.E FT's reliability. Whether measuring CO_2, CO, NOx, NH_3, or HCHO, the system consistently delivers results within regulatory accuracy limits.

The AVL M.O.V.E FT is not just an instrument, it's a strategic asset for OEMs, research institutions, and regulatory bodies aiming to stay ahead in the emissions compliance race. With its robust design, comprehensive gas analysis capabilities, and seamless integration, it redefines what's possible in mobile emissions testing.

4

BS6 Particle Filter Technology an Effective Sustainable Filter to Clean the Ambient Air

Emission Controls Manufacturers Association (ECMA)

Air pollution is by far the highest cause of health risks in many countries across the globe, including India. Stricter emission regulations and other measures are being sincerely enforced in India to effectively reduce the air pollution. Implementation of BS6 emission regulation in India on the fast track has been one of the greatest achievements combining advanced technologies for engine efficiency improvement and tail-pipe emission reduction and also bringing controls on real-life on-road emissions (Real Drive Emissions - RDE) from vehicles.

Particulate Matter is released from transport vehicles, construction dust, road dust, and many other sources. These particles, when inhaled, can penetrate deeper into the respiratory system and cause respiratory ailments such as asthma, coughing, sneezing, irritation in the airways, eyes, nose, throat irritation, etc. $PM_{2.5}$ (particles that have a diameter less than 2.5 micrometers - more than 100 times thinner than a human hair) remain suspended for longer. $PM_{2.5}$ are ultrafine particles and are easily inhalable into the lungs and can induce adverse health issues. Therefore, PM and PN control from the ambient air has been the focus for research and development.

Latest available advanced exhaust after treatment technologies employed in BS6 diesel vehicles; such as DPF, SCR, ASC, etc ensuring conversion efficiencies up to 95%; have demonstrated a great potential to reduce tail pipe emissions of NOx and PM (both mass and number) to an extent of almost near-zero level and competes well with its counterpart gasoline emission levels.

PM being the major concern for poor air quality and human health, ECMA desired to explore the utility of the advanced Particulate Filters fitted on BS 6 vehicles, in filtering out PM and providing particulate-free air at the exhaust, regardless of the polluted ambient air with excessive AQI

A study project by ECMA on a BS6 Light Duty Diesel vehicle clearly and significantly endorses the above fact. That means in reality, PM Filter fitted in a BS6 diesel vehicle has experimentally shown a great contribution in cleaning the polluted ambient air both in laboratory testing and Real Driving Emission (RDE) testing on-the-road as well. Based on these results, it can be confidently stated that a PM Filter technology would be presenting similar trend when fitted in advanced diesel engines for any application – light, medium and heavy-duty vehicles, agricultural tractor, CEVs, stationary gensets, locomotives, marines, etc.

Experimental data from ECMA project reveals that if more and more advanced technology diesel vehicles ply on the road as well as off-road applications with PM Filters and NOx abatement technologies, they would very effectively clean the polluted ambient air, specially the particulate mass and number, which is of great concern to human health issues.

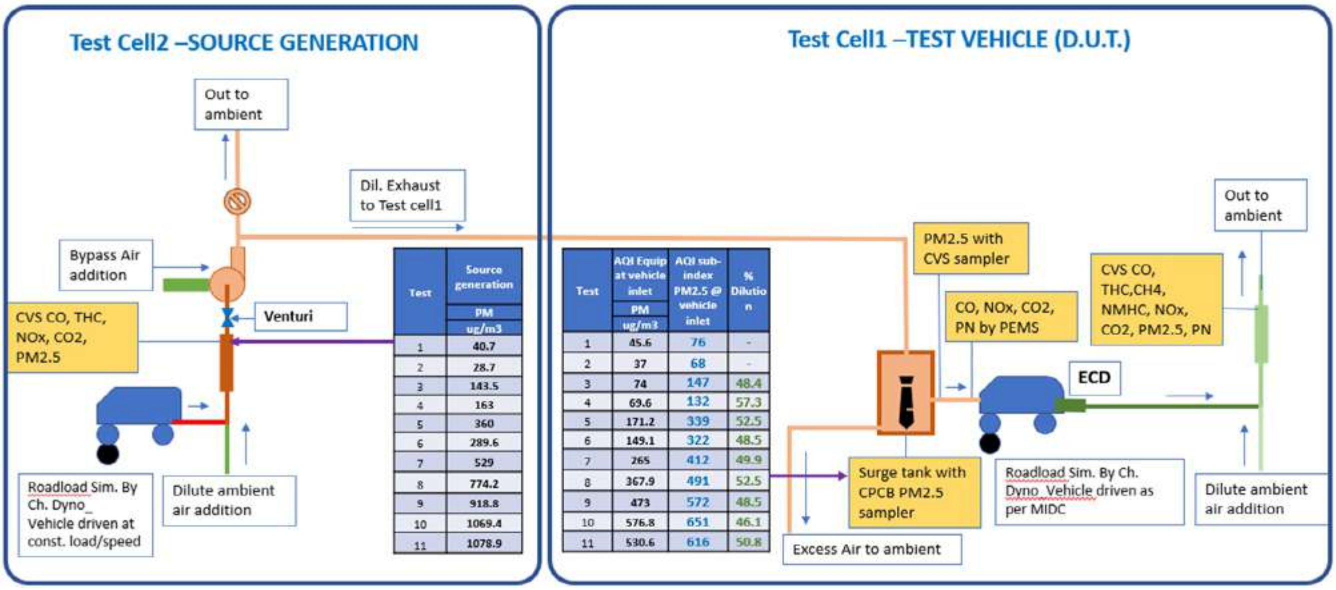
It is more interesting to note that the BS6 Diesel PM Filters will not only reduce tail-pipe emissions of PM and PN to near-zero level much below to BS6 limits, but would also grossly clean the ambient air which is polluted severely and significantly from other sources such as construction dust, road-side dust, industry pollution, crop burning, desert dust, etc; which are not otherwise handled currently by any effective technique.

ECMA conducted a project on a Vehicle of M1 category, BS-VI, OBD Stage-1 compliant, 4W, 1.5ltr, CRDI Diesel SUV employing Exhaust After Treatment Systems (EATS) comprising of EGR + LNT + DPF.

Project objective was to study the performance of Particle Filter technology by assessing the magnitude of PM and PN emissions at the vehicle tail-pipe under varying air quality numbers defined by AQIs. A specially designed methodology was adapted to conduct the experiments.

- Polluted environment was created with regard to PM and PN values in a test cell using a BS4 Source Diesel Vehicle, thus providing a polluted inlet air of varied Air Quality Index (AQI) to the project vehicle in the adjacent test cell.
- Project vehicle was tested with different AQIs (ranging 75 to 650) on a Chassis Dynamometer and emissions were measured at the tail-pipe.
- Project vehicle was also tested on the road (PEMS) - RDE test

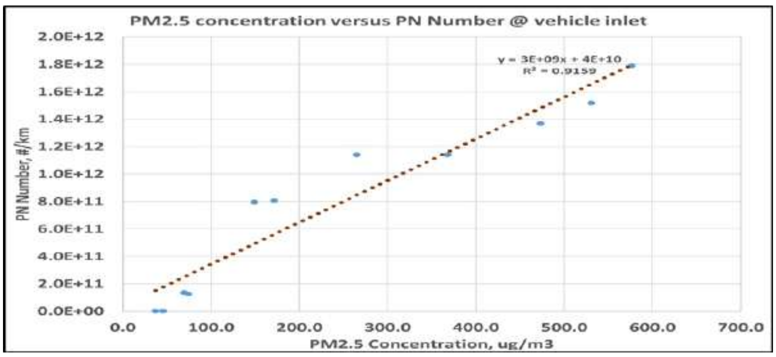
In order to achieve different levels of Air Quality Sub Index for $PM_{2.5}$, i.e. to simulate polluted urban environment for the Project vehicle, a Source-Generation vehicle was used in an adjoining test cell. Different levels of AQI $PM_{2.5}$ sub-index, were generated by running Source- Generation vehicle at different combinations of steady speeds and loads by fixing a throttle position mechanically. Different levels of AQI sub index for $PM_{2.5}$ (75, 147, 339, 412, 491, 572 and 650) were fed to the Project vehicle inlet.



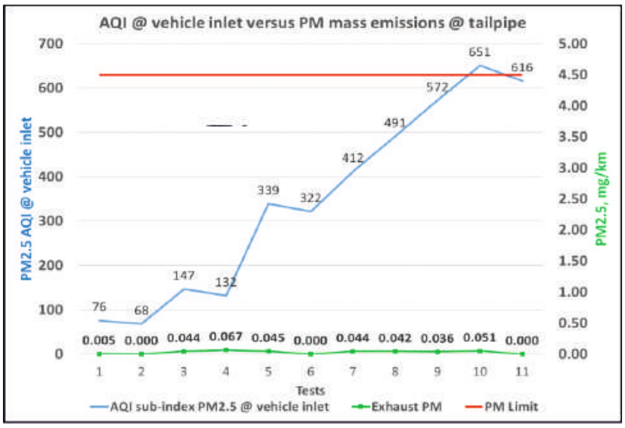
Test	Source generation PM ug/m3
1	40.7
2	28.7
3	143.5
4	163
5	360
6	289.6
7	529
8	774.2
9	918.8
10	1069.4
11	1078.9

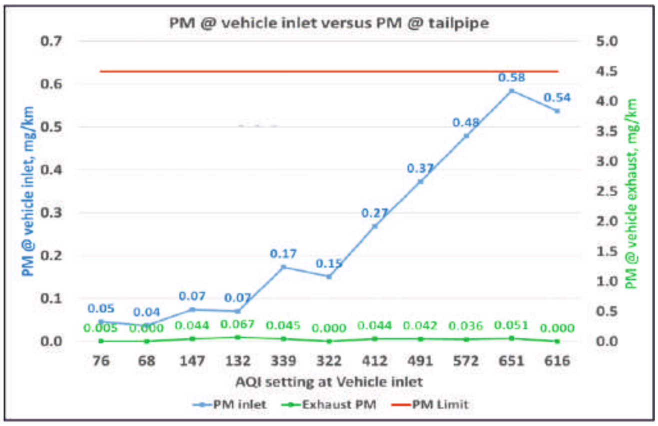
Test	AQI Equip at vehicle inlet PM ug/m3	AQI sub-index PM2.5 @ vehicle inlet	% Dilution
1	45.6	76	-
2	37	68	-
3	74	147	48.4
4	69.6	132	57.3
5	171.2	339	52.5
6	149.1	322	48.5
7	265	412	49.9
8	367.9	491	52.5
9	473	572	48.5
10	576.8	651	46.1
11	530.6	616	50.8

A good correlation is seen between $PM_{2.5}$ and PN of the inlet atmosphere created by the source generation vehicle. These PN numbers may be different then a real-field atmosphere since other sources like dust, ash, etc is missing in the source generated flow.

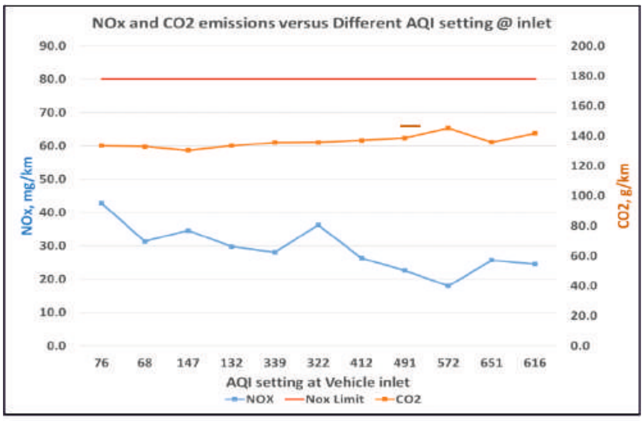


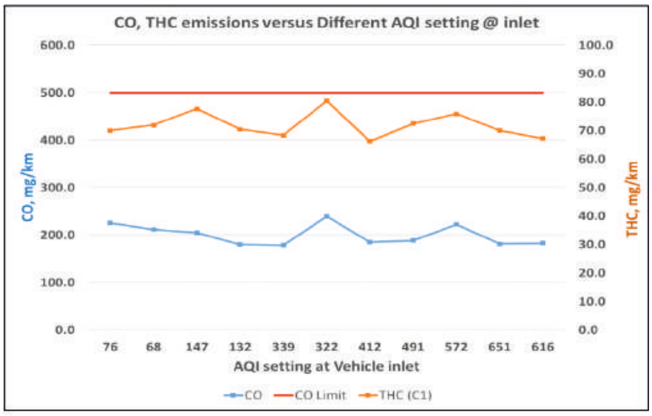
With increasing $PM_{2.5}$ AQI sub-index at vehicle inlet, the PM and PN emission at the vehicle inlet increase. However, the PM emission at the vehicle tail-pipe (mg/km) remain more or less constant and well below BS6 Certification Limit of PM, for any level of PM and PN defined by different AQI levels fed at the vehicle inlet.





With the increasing $PM_{2.5}$ AQI at vehicle inlet, it is observed that there is a marginal increase in CO_2 emission that brings in some EGR effect to decrease the NOx emission in the vehicle exhaust. NOx emissions are also well within NOx limits



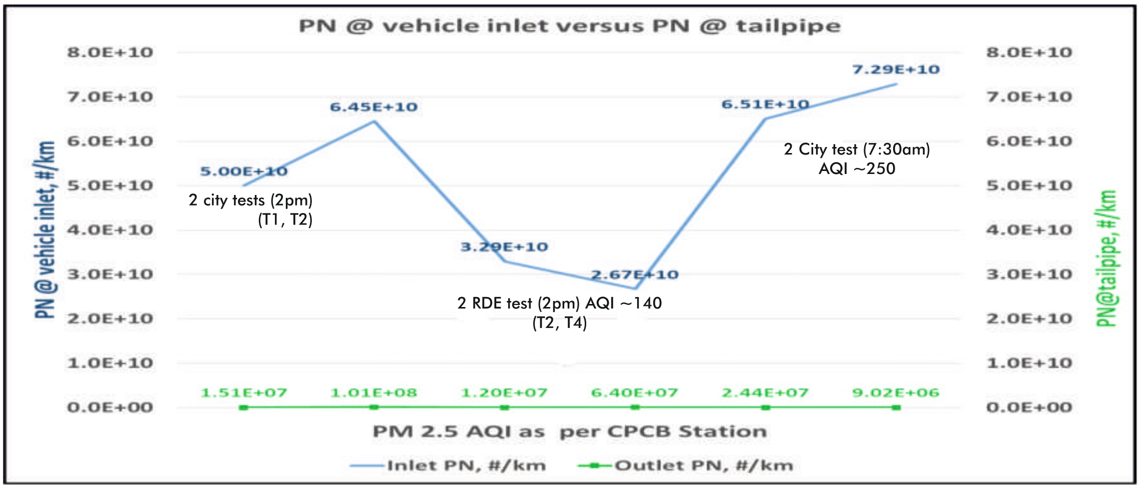


With the increasing $PM_{2.5}$ AQI at vehicle inlet, there is practically no change in CO and THC emissions at the vehicle exhaust. CO emissions are also found to be well within CO limits.

On-road tests were carried out on different time and days and of course in different driving conditions. PN concentration at vehicle ambient inlet has been varying. PN in the vehicle exhaust remained more or less constant despite different days and time of the road tests and variations in the driving conditions. It is observed that PN in vehicle exhaust is lower than PN in vehicle inlet, resulting in more than 99% reduction.

	position	CO2, g/km	PN, #/km	% eff of PN reduction	PM2.5ug/m³ CPCB Station (Shivaji Nagar)	Ambient AQI at CPCB Site
City road test –	inlet outlet	2.102 259.8	5.00E+10 1.51E+7	99.97%		
City road test – afternoon	inlet outlet	2.210 254.3	6.45E+10 1.01E+8	99.84%		
RDE test	inlet outlet	1.283 161	3.29E+10 1.20E+7	99.96%	83.35 72.60	177 142
RDE test	inlet outlet	1.242 173.9	2.67E+10 6.40E+7	99.76%	91.67	206
City road test – morning	inlet outlet	1.824 196	6.51E+10 2.44E+7	99.96%	116.52 102	287 240
City road test – morning	inlet outlet	2.08 194.4	7.29E+10 9.02E+6	99.99%	128.61 107	306 257

Avg. 24 Hr. Values (yellow)   Avg. Values during test duration (green)



Highlights of the project study

- The special test set-up provided varying AQI levels at the Project vehicle inlet. It also helped to measure and compare the exhaust emissions at the Project vehicle outlet. The AQI levels achieved during the lab tests at the vehicle inlet cover broadly the range of AQIs typically observed in the Delhi and NCR region.
- It is observed from the test results that, PM and PN emissions at the Project vehicle tail-pipe is at very low levels compared to the vehicle inlet air. This trend is demonstrated both at laboratory tests with varying AQI quality and also set of on-road tests.
- Referring to an example from a laboratory test, vehicle inlet and tailpipe $PM_{2.5}$ emissions of 0.58 and 0.051 mg/km yield effective PM reduction efficiency of about 92%
- PN emission reduction during the on-road tests is more than 99%.
- The test results reveal considerable cleaning effect of Particulate Filter on $PM_{2.5}$ emission, both at laboratory and on-road tests.
- PM and PN emissions in the tail pipe are reduced to well below legislative BS6 limits with sizeable margins.
- It is evident that a well-optimised BS6 diesel SUV vehicle fitted with the PM filter has demonstrated that the tail-pipe PM and PN emissions are much lower than at the Vehicle inlet air consistently, irrespective of the air quality sub index and varying driving conditions to which the vehicle is exposed to during on-road tests.

Remarks

- Particle filter exhibits not only the reduction of $PM_{2.5}$ and PN emissions substantially at the tail pipe to practically near-zero emission levels, but also demonstrates in the real-field situation, an opportunity of cleaning the ambient air, which could be polluted by various other sources and operating conditions
- Well optimised advanced ICE power trains, employing diesel and gasoline PM filter technology (BS6 and beyond), can be considered to be showing up a unique opportunity, to act like a promising AIR FILTER, cleaning up the Ambient Air locally, which is typically polluted by several sources based on local conditions

Further Potential

- Advanced Particle Filter are expected to show similar performance trend with other fuels and vehicle categories like on-road, off-road and for stationery applications
- Modern gasoline vehicles, employing GDI engines for improved fuel efficiency and improved emissions, would need Gasoline Particle Filter (GPF). GPF is also expected to exhibit similar performance trend at the vehicle tail pipe.
- Upcoming Euro 7 equivalent emission regulations would essentially need GPF for all gasoline/SI engines.

5

Integrated Multi-Fuel and Hybrid Powertrain Design with CO_2 Capture: The Nirvayu Engine Approach

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[1]Corresponding author – Primary Investigator, contributed to the research and writing
[2]Contributed suggestions to the naming of the project as "Nirvayu"

Abstract

The Nirvayu V8 internal combustion engine presents a novel architecture integrating dual-injection strategies, multi-fuel capability, hybrid-electric assist, and onboard amine-functionalized CO_2 sorbent cartridges for real-time carbon capture. Advanced emission control, including Selective Catalytic Reduction (SCR) and water vapor management, ensures compliance with BS7 and Euro 7 standards. A predictive ECU coordinates combustion optimization, CO_2 adsorption–desorption cycles, SCR dosing, water condensation, and hybrid load modulation to maximize thermal efficiency and minimize environmental impact. Implementation roadmap, feasibility analysis, and preliminary simulations indicate technical, operational, economic, and environmental viability, demonstrating potential for scalable, low-emission hybrid IC engines adaptable to diesel, gasoline, ethanol, hydrogen, and DME fuels. Nirvayu bridges conventional IC technology with carbon capture and hybrid strategies, offering a sustainable solution for future mobility.

1. Introduction

Despite rapid electrification, internal combustion engines (ICEs) will remain central to mobility, especially in regions with limited charging infrastructure. New regulations such as BS7 (India) and Euro 7 (Europe) demand drastic reductions in NOx, PM, CO, HC, and particularly CO_2 emissions—the main contributor to climate change.

Conventional strategies like EGR, VVT, catalytic converters, SCR, and filters have curbed regulated pollutants but leave CO_2 largely unaddressed. Improving fuel economy and shifting to alternative powertrains help, but alone may not achieve future carbon reduction targets.

Carbon capture, proven at stationary sources, faces challenges in vehicles due to space, weight, and energy constraints. Recent progress with amine-functionalized sorbents offers compact, high-capacity CO_2 capture at exhaust temperatures, with regeneration aided by water vapor. Modular cartridges within the exhaust enable real-time capture and controlled release without major energy penalties.

The proposed Nirvayu hybrid engine integrates this tailpipe CO_2 capture with advanced combustion optimization. A V8 dual-injection strategy enhances fuel-air mixing, while cooled EGR and VVT minimize NOx. Water vapor injection assists both sorbent regeneration and NOx reduction. An adaptive ECU coordinates combustion, capture cycles, and hybrid assist, maintaining efficiency and drivability. This creates a scalable path for multi-fuel, hybrid ICEs to meet BS7/Euro 7 norms while cutting greenhouse gas emissions directly at the source.

2. Combustion Chemistry and CO_2 Emissions

The chemical composition of a fuel directly influences its combustion efficiency, heat release, and carbon dioxide emissions. Fuels with a higher carbon-to-hydrogen ratio produce greater quantities of CO_2 per unit of energy, whereas hydrogen-rich and oxygenated fuels result in lower CO_2 emissions, though often at the expense of reduced energy density.

The generalized combustion reaction for a hydrocarbon can be expressed as:

$$C_xH_y + \left(x + \frac{y}{4}\right) O_2 \rightarrow xCO_2 + \frac{y}{2} H_2O$$

From this relation, the stoichiometric air–fuel ratio (AFR) is defined as

$$AFR_{st} = \frac{4.76\,(x + \frac{y}{4}) M_{air}}{M_{fuel}}$$

Where, $M_{air} = \frac{28.97g}{mol}$ and $M_{fuel} = 12x + y.$

Table 1: Comparative properties of selected fuels

Fuel	Formula	AFR (kg air/kg fuel)	LHV (MJ/kg)	CO_2 (kg/kg fuel)	Key Insight
Gasoline	C_8H_{18}	14.7	42–44	~3.09	Widely used baseline fuel
Diesel	$C_{12}H_{23}$	14.5	42–43	~3.17	High CO_2 but energy dense
Methane	CH_4	17.2	50	~2.75	Lowest CO_2 fossil option
Methanol	CH_3OH	6.4	19.7	~1.38	Low CO_2, low energy density
Ethanol	C_2H_6O	9.0	26.8–27	~3.09	Renewable biofuel
Hydrogen	H_2	34.3	120	0	Zero-carbon combustion

This comparison indicates that while methane and hydrogen blends reduce the carbon intensity of combustion, even relatively clean hydrocarbons still emit significant CO_2. As a result, reliance on fuel switching alone cannot achieve the required emission reductions. The Nirvayu engine therefore integrates onboard capture using amine-functionalized sorbent cartridges within the exhaust manifold, enabling direct CO_2 adsorption during operation and controlled regeneration during low-load phases.

3. Chemical Kinetics Modelling

The combustion process in internal combustion engines is governed by elementary chemical reactions that determine ignition delay, flame propagation, pollutant formation, and overall efficiency. The global oxidation of hydrocarbon fuels can be represented as:

$$C_nH_m + \left(n + \frac{m}{4}\right) O_2 \rightarrow nCO_2 + \frac{m}{2} H_2O$$

For hydrogen, the reaction is expressed as:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

The rate of each elementary reaction is described by the Arrhenius expression

$$k_j(T) = A_j T^{\beta_j} \exp(\frac{E_{a,j}}{RT})$$

where A_j is the pre-exponential factor, βj is the temperature exponent, and $E_{a,j}$ is the activation energy. The temporal evolution of a chemical species is expressed as

$$\frac{d[C_i]}{dt} = \sum v_{ij} R_j$$

where v_ij are the stoichiometric coefficients and R_j are the individual reaction rates. Radical species such as OH•, HO_2•, CH_x•, and CO play an essential role in determining flame stability, ignition characteristics, and NOx formation pathways. For the onboard capture process, the adsorption–desorption dynamics on amine-functionalized sorbents are modelled as:

$$\frac{d[CCO_2]}{dt} = k_{ads}[CO_2]_{exhaust}(S_{total} - [CCO_2]) - k_{des}[CCO_2]$$

Where $[CCO_2]$ is the concentration of captured CO_2, S_{total} is the total number of active sorbent sites, and k_{ads}, k_{des} represent adsorption and desorption rate constants. These equations allow prediction of sorbent saturation and regeneration cycles. When integrated into the engine control unit (ECU), they enable adaptive management of sorbent usage, ensuring that capture efficiency is maximized without imposing significant penalties on fuel economy or drivability.

4. Onboard CO_2 Capture and Engine Integration

4.1 CO_2 Capture Cartridge Integration

The Nirvayu engine incorporates CO_2 capture cartridges directly into the exhaust manifold. Each cartridge is a modular, thermally insulated housing filled with amine-functionalized solid sorbents, designed to operate within the 200–350 °C exhaust temperature window. The location within the manifold ensures adequate thermal energy for adsorption without excessive heating requirements. Flow channels are optimized using CFD to minimize backpressure while maintaining sufficient residence time for CO_2–sorbent interaction.

The cartridges are designed as replaceable units, similar in packaging philosophy to diesel particulate filters (DPF) or three-way catalysts, allowing serviceability without major modifications to the exhaust system. Differential pressure sensors, thermocouples, and in-line CO_2 analyzers are used to monitor cartridge performance and determine saturation levels.

4.2 NOx and Water Vapor Management

Integration of CO_2 capture hardware introduces additional thermal and flow management requirements. To maintain combustion stability and protect the sorbents, the engine employs cooled exhaust gas recirculation (EGR), which reduces peak cylinder temperatures and lowers NOx formation. This not only assists conventional aftertreatment systems such as SCR but also stabilizes the exhaust environment for sorbent operation.

V8 Engine with Turbocharger Details

Water vapor present in exhaust gases is exploited to improve adsorption kinetics and plays a central role during regeneration. A controlled water vapor injection system is integrated into the manifold to support desorption, enabling the sorbents to release captured CO_2 without degradation. The ECU coordinates EGR and water vapor management to balance NOx control with effective CO_2 cycling.

4.3 Working Principle

The capture system functions in two primary modes — adsorption and regeneration. During adsorption, exhaust gases pass through the cartridges and CO_2 is retained via carbamate formation:

$$RNH_2 + CO_2 \rightarrow RNCHOO^- + H^+$$

When the sorbent approaches saturation, the ECU schedules regeneration during low-load, idle, or hybrid-assisted conditions. In this phase, exhaust heat and auxiliary electrical heaters raise cartridge temperature, while controlled water vapor injection triggers desorption:

$$RNCHOO^- + H^+ \rightarrow RNH_2 + CO_2$$

The desorbed CO_2 is routed to a sealed onboard storage tank, operating at moderate pressure (5–10 bar). This prevents re-release into the ambient environment at the tailpipe. The tank is fitted with isolation valves, sensors, and safeguards to ensure containment integrity.

The Nirvayu V8 engine architecture integrates multi-fuel combustion, dual-injection, hybrid-assist, and advanced emission control strategies. To visualize the interconnections between the eight cylinders, ECU, CO_2 capture module, SCR, water vapor management, and tailpipe, a schematic representation is provided in Figure 1. Purple dots indicate functional connections between all key components, forming a closed-loop system that ensures optimal engine performance and emissions control.

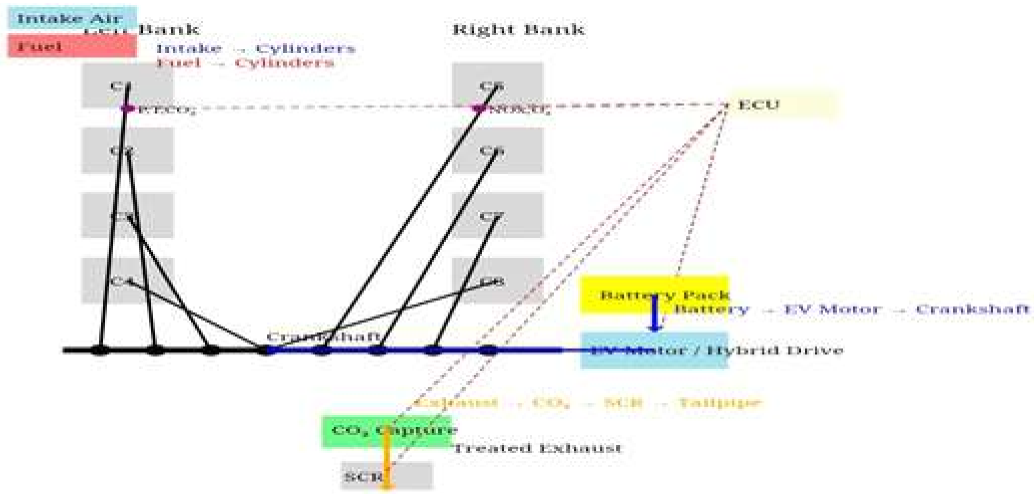
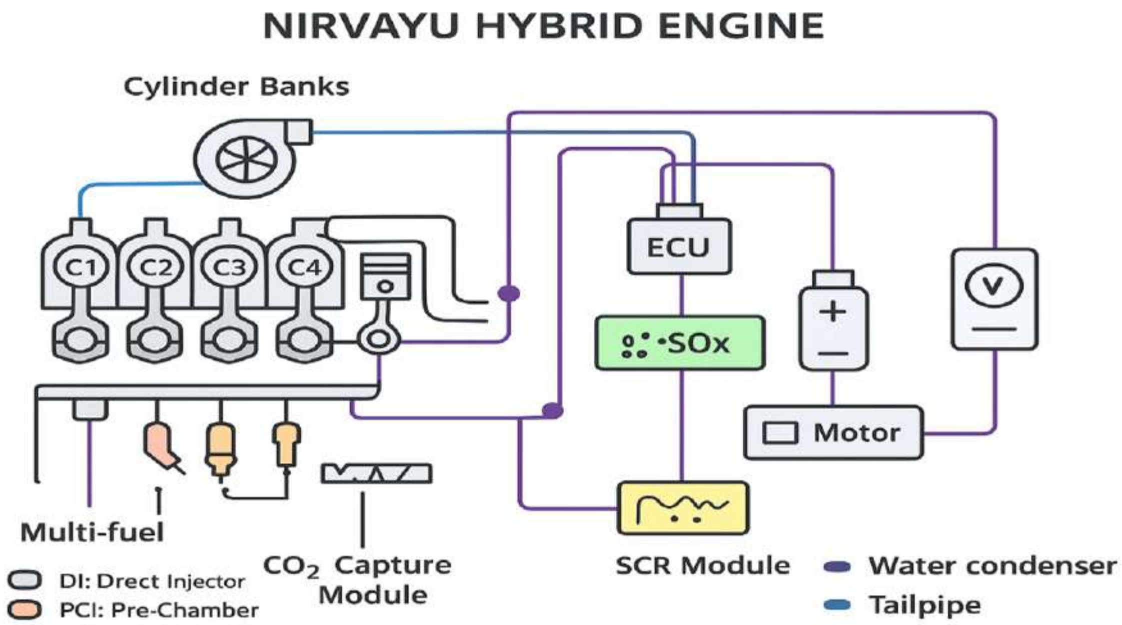


Figure 1: Schematic of the Nirvayu V8 multi-fuel IC engine with hybrid-assist, dual-injection, CO_2 capture cartridge, SCR, water vapor management, and ECU integration. Purple dots indicate functional connections between all modules.

4.4 Engine–Hybrid Coordination

The hybrid powertrain is essential for seamless operation of the capture system. Electric drive support allows regeneration to occur without loss of drivability or transient performance. The ECU synchronizes valve timing, injection phasing, and hybrid motor assistance to minimize parasitic loads. Electrical energy from the battery supports auxiliary heaters and compressors during desorption, ensuring that the IC engine is not burdened with additional load.



As depicted, exhaust gases from all cylinders are routed through the CO_2 sorbent cartridge, followed by NOx reduction via SCR and water vapor condensation, with real-time monitoring and control executed by the ECU to ensure compliance with BS7 and Euro 7 emission norms.

5. Emission Control and Carbon Capture Integration

The Nirvayu IC engine integrates advanced emission control with a compact CO_2 capture module to meet BS7 and Euro 7 norms, minimizing environmental impact. The system combines in-cylinder optimization, after-treatment devices, hybrid-load management, and real-time ECU control to reduce CO_2, NOx, and water vapor emissions.

5.1 CO_2 Capture Mechanism

A mini amine-functionalized sorbent cartridge in the exhaust manifold captures CO_2:

$$RNH_2 + CO_2 \rightarrow RNHCOO^- + H^+$$

Regeneration occurs during idle, low-load, or hybrid-assisted operation using exhaust waste heat, enabling continuous operation without performance loss and reducing fuel consumption.

5.2 NOx Reduction

A Selective Catalytic Reduction (SCR) system converts NOx to N_2 and H_2O using ammonia or urea:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

Positioned downstream of the CO_2 cartridge, SCR efficiency is optimized, working with hybrid load control to minimize NOx during transient or low-load operation.

5.3 Water Vapor Management

An inline condensation unit removes water vapor to protect SCR catalysts and CO_2 sorbents. Collected water is drained automatically, and hybrid load modulation reduces vapor production during idle or low-speed driving.

5.4 ECU Integration

The ECU coordinates all modules in real time using CO_2, NOx, temperature, pressure, and humidity sensors to:

- Optimize dual-injection timing for combustion and multi-fuel balance.
- Control CO_2 adsorption–desorption cycles.
- Regulate SCR dosing and water removal.
- Manage hybrid assistance to reduce load during high-emission conditions.

This integration ensures compliance with stringent emission standards while maintaining fuel flexibility, thermal efficiency, and near-zero emissions.

6. Engine Control and ECU Integration

The Nirvayu V8 IC engine with CO_2 capture, NOx/water vapor control, and hybrid-assist relies on a robust ECU for real-time monitoring, predictive computation, and precise actuation. The ECU integrates sensor data, applies chemical-kinetic and combustion-based control algorithms, and manages fuel injection, hybrid load assist, exhaust treatment, and sorbent regeneration.

6.1 Control Objectives

The ECU simultaneously ensures:

- **Optimized Combustion:** Maintains ideal air–fuel ratio, ignition timing, and dual-injection phasing for maximum thermal efficiency and minimal unburned hydrocarbons across all fuel types.
- **Emission Reduction:** Controls NOx and water vapor via in-cylinder optimization, SCR dosing, and condensation module actuation.
- **CO_2 Capture Management:** Monitors exhaust CO_2 and dynamically controls sorbent adsorption–desorption cycles using waste heat and hybrid load adjustment.
- **Fuel Flexibility & Hybrid Integration:** Adjusts injection parameters for diesel, gasoline, ethanol, hydrogen, DME, and coordinates electric motor assist to minimize emissions during transient or low-load conditions.

6.2 Sensor Integration

The ECU receives inputs from: cylinder pressure sensors, exhaust gas sensors (CO_2, NOx, O_2, temperature), mass air/fuel flow sensors, sorbent cartridge sensors, and hybrid system sensors (motor torque, battery state). These inputs enable real-time feedback for stable engine and hybrid performance under varying loads and conditions.

6.3 Control Algorithm Overview

The ECU employs model-based predictive control (MPC) and PID loops to:

- Maintain ideal air–fuel ratios for each fuel type.
- Predict flame speed and ignition delay to minimize NOx.
- Trigger CO_2 sorbent regeneration using exhaust heat or hybrid-managed idle.
- Synchronize SCR dosing and water condensation with exhaust composition and hybrid load.
- Coordinate electric assist to reduce engine load and emissions during high-emission periods.

```
Initialize ECU
While Engine or Hybrid Running:
    Read Sensors: CylinderPressure, Exhaust_CO2, NOx, O2, Temp, BatteryState, MotorTorque
    Calculate AFR based on fuel and load
    Adjust Direct & Pre-Chamber Injectors
    Predict Flame Speed & Ignition Delay
    If NOx > Threshold: Activate SCR Dosing
    If CO2 > Target: Initiate Sorbent Regeneration
    If WaterVapor > Threshold: Activate Condensation Unit
    If HybridAssistNeeded: Adjust Engine Load via Electric Motor
    Log Performance & Emission Data
End While
```

6.5 Software Architecture

Modular ECU software includes:

- **Sensor Layer:** Hardware interface and signal preprocessing.
- **Control Logic Layer:** Predictive combustion models, PID/MPC control, hybrid coordination, multi-objective optimization.
- **Actuator Layer:** Controls injectors, SCR, CO_2 cartridge, condensation unit, and hybrid motor.
- **Data Logging & Diagnostics Layer:** Records engine, hybrid, emission, and sorbent data for compliance and maintenance.

This integration ensures high thermal efficiency, multi-fuel flexibility, emission compliance, and onboard CO_2 mitigation, while fully supporting hybrid-electric operation to enhance sustainability.

7. Implementation Roadmap and Feasibility Analysis

The Nirvayu V8 IC engine with integrated amine-functionalized CO_2 sorbent cartridges, NOx/water vapor control, and hybrid-assist requires a structured roadmap for design, prototyping, testing, and scalability, with feasibility assessed across technical, operational, economic, and environmental dimensions.

7.1 Implementation Roadmap

- **Conceptual Design:** Define cylinder layout, bore/stroke, compression ratio, dual-injection, hybrid integration, and placement of **CO_2 sorbent cartridges,** SCR, and condensation modules.
- **Material Selection & Component Sizing:** High-strength alloys for engine/hybrid components; sorbent cartridge dimensions based on predicted CO_2 flow from kinetic simulations.
- **Prototype Development:** Manufacture engine, exhaust, and hybrid components; integrate CO_2 sorbent cartridges, SCR, condensation units, and sensors for ECU integration.
- **Control Software Implementation:** ECU modules for dual-injection, CO_2 sorbent adsorption/desorption, SCR dosing, water condensation, and hybrid coordination with predictive combustion models.

- **Testing & Validation:** Bench tests for combustion, **CO_2 capture efficiency,** NOx and water vapor reduction, and hybrid-assist; validate under transient and multi-fuel operation; refine ECU control.
- **Scale-up & Deployment:** Evaluate manufacturability, cost, and integration for 4-wheeler hybrid applications; lifecycle analysis for CO_2 mitigation, fuel efficiency, and hybrid energy benefits.

7.2 Feasibility Analysis

- **Technical:** Multi-cylinder V8 with dual-injection is compatible with current standards; **amine-functionalized CO_2 sorbent cartridges** achieve significant tailpipe CO_2 reduction without performance loss.
- **Operational:** Sorbent regeneration synchronized with idle or hybrid-assisted low-load minimizes energy penalty; NOx and water management ensures emission compliance.
- **Economic:** Compact **sorbent-based CO_2 capture** reduces cost/weight versus conventional post-combustion systems; multi-fuel and hybrid operation enable fuel savings.
- **Environmental:** Predictive chemical kinetics and hybrid load management enable 25–35% CO_2 reduction; SCR, condensation, and hybrid assist reduce NOx and water vapor for sustainable mobility.

7.3 Risk Mitigation

- Thermal/mechanical stresses: high-strength materials, optimized cooling, hybrid load reduction.
- Sorbent degradation: ECU-monitored; scheduled replacement based on real-time usage.
- Sensor failure: redundant network ensures fail-safe operation.
- Hybrid system faults: ECU monitors battery/motor; fallback to conventional IC mode if needed.

8. Conclusion and Future Work

Nirvayu integrates dual-injection, multi-fuel flexibility, hybrid-assist, and amine-functionalized CO_2 sorbent cartridges. Guided by chemical kinetics modeling, it optimizes combustion, reduces ignition delay, and controls flame propagation across conventional and alternative fuels.

Key Findings:

- **Performance:** V8 with dual-injection and hybrid-assist ensures precise AFR, reducing unburned hydrocarbons and improving thermal efficiency.
- **Emission Mitigation:** Integrated CO_2 sorbent cartridges, SCR, water management, and hybrid operation collectively reduce emissions.
- **Fuel Flexibility:** Diesel, gasoline, ethanol, hydrogen, DME.
- Control Integration: Predictive ECU algorithms manage combustion, CO_2 sorbent regeneration, emission mitigation, and hybrid-assist.
- **Feasibility:** Roadmap and analysis show technical, operational, economic, and environmental viability, scalable for 4-wheeler hybrid platforms.

Future Work:

- Prototype testing to validate CO_2 sorbent capture efficiency, NOx reduction, and hybrid-assisted combustion.
- Advanced sorbents with higher capacity and thermal stability.
- Full engine-electric integration for further emission reduction and regenerative energy recovery.
- Long-term multi-fuel impact on engine and sorbent durability.
- Lifecycle assessment for CO_2 mitigation, fuel savings, and energy efficiency.

The Nirvayu engine combines **low-emission, high-efficiency hybrid IC technology with amine-functionalized CO_2 sorbent solutions**, predictive ECU control, flexible fuels, and hybrid power management, providing a framework for sustainable mobility.

Declaration

*I hereby declare that the work presented in this study, titled **"Nirvayu: Hybrid Multi-Fuel V8 Engine with Onboard CO_2 Capture and Emission Control",** is my original work. All concepts, designs, analyses, and interpretations are developed by me, except where properly cited. I acknowledge Mr. Gouranga Das (MD, Sarvatah Projects Private Limited) for contributing to the naming of the project as "Nirvayu". I affirm that this work has not been submitted, in part or full, for any other degree, diploma, or certification, and I take full responsibility for the accuracy and authenticity of the content*

6

Innovations in Hybrid-Electric-Connected Solutions and Their Impact on Indian Mobility

Nikhil Khurana,
Folks Motor Pvt Ltd

India is at the precipice of a significant transformation in its mobility sector, with innovations in xEVs (retrofit cars), hybrid, electric, and connected solutions driving a new era of transportation. The integration of these technologies not only addresses the environmental challenges faced by the country but also paves the way for a smarter, more efficient, and sustainable future. The emergence of these solutions is a crucial response to India's growing urbanization, pollution levels, and dependence on fossil fuels.

Rise of xEVs, Hybrid and Electric Vehicles

Hybrid and electric vehicles (EVs) have become a focal point in global efforts to reduce carbon emissions and reliance on fossil fuels. The shift towards EVs in India has been further accelerated by supportive government policies, including the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, which provides subsidies and incentives to EV buyers and manufacturers. According to Fortune Business Insights The India electric vehicle (EV) market size was valued at USD 8.03 billion in 2023. The market is projected to grow from USD 23.38 billion in 2024 to USD 117.78 billion by 2032, exhibiting a CAGR of 22.4% during the forecast period.

(Source: https://www.fortunebusinessinsights.com/india-electric-vehicle-market-106623)

The government's commitment to reducing emissions and increasing EV adoption is further bolstered by the introduction of the National Electric Mobility Mission Plan (NEMMP). Additionally, automakers in India are rapidly shifting their focus to electrification, with several well-established manufacturers investing in electric mobility solutions. The market is expected to see significant growth with Electric vehicle sales in India are projected to reach 10 million units by 2030, creating 5 million jobs as per industry experts.

Connected Technology Enhancing Mobility

Connected vehicles are becoming an integral part of India's automotive landscape, offering a host of benefits from real-time tracking to improved safety features. These vehicles leverage the power of data analytics, artificial intelligence (AI), and the Internet of Things (IoT) to optimise driving experiences and contribute to smoother traffic flow in congested cities. A connected vehicle ecosystem also provides valuable insights into driver behaviour, vehicle maintenance, and overall performance, thus improving the efficiency of the mobility sector.

As connectivity becomes a core component of vehicle technology, the rollout of 5G networks in India is set to revolutionise how vehicles communicate with each other, with infrastructure, and with centralised systems. The The global connected car market is projected to grow from USD 12.4 Billion in 2024 to USD 26.4 Billion by 2030 at a CAGR of 13.3% (source: https://www.marketsandmarkets.com/Market-Reports/connected-car-market-102580117.html)

Connected technologies enable features such as over-the-air updates, remote diagnostics, predictive maintenance, and location-based services. These solutions can significantly enhance the ownership experience, lower operational costs, and improve the overall sustainability of vehicle fleets. With improved connectivity, fleet operators in India can also implement smarter logistics and supply chain solutions, optimizing fuel consumption, reducing emissions, and enhancing fleet management.

FOLKS MOTOR

India's 1st Hybrid Electric Retrofit Car Company

Hybrid Vehicles: A Transition to Clean Mobility

While EVs dominate the conversation around sustainable mobility, xEVs or hybrid vehicles play an important role in transitioning toward fully electric solutions. By combining the benefits of an internal combustion engine (ICE) and an electric motor, hybrid vehicles offer a unique solution for a market like India, where charging infrastructure is still in its early stages of development.

Hybrid vehicles are seen as a more practical choice for Indian consumers who may not have access to widespread charging stations. They provide a range of benefits, including reduced fuel consumption, lower carbon emissions, and fewer range anxiety issues. The India Hybrid Vehicles Market size is estimated at 0.42 billion USD in 2024, and is expected to reach 1.47 billion USD by 2030, growing at a CAGR of 23.30% during the forecast period (2024-2030) (Source: https://www.mordorintelligence.com/industry-reports/india-hybrid-vehicles-market)

This growth is driven by advancements in battery technology and retrofit technology that is helping achieve a more significant shift toward electrification in the auto sector.

Moreover, solutions like xEV have been designed to complement India's existing infrastructure while pushing the envelope toward clean mobility. These solutions also help manufacturers and consumers comply with increasingly stringent emission norms and fuel efficiency standards laid out by the government.

Smart Charging Infrastructure and Ecosystem

The need for efficient and widespread charging infrastructure is a critical factor in driving the adoption of hybrid and electric vehicles. The Indian government has taken steps to address this by approving a Rs 3,000 crore package for the development of EV charging stations across the country.

Innovations in smart charging are also paving the way for efficient power usage and more accessible charging solutions. Smart charging stations integrate renewable energy sources, grid optimisation, and vehicle-to-grid (V2G) technology, which allows vehicles to supply power back to the grid. This type of integrated ecosystem not only provides convenience for EV owners but also contributes to energy conservation and grid stability.

The rise of ultra-fast charging technology also means that charging times are rapidly decreasing. This technological advancement addresses one of the primary barriers to EV adoption in India—charging time—and will play a significant role in the mainstream adoption of EVs and xEVs.

The future of Indian mobility is unmistakably tied to xEVs or hybrid-electric-connected solutions. These innovations are leading to more sustainable, efficient, and safer transportation options that will transform how people and goods move across the country. As India grapples with air pollution, traffic congestion, and limited natural resources, these technologies provide a promising solution to these challenges while helping the nation reduce its carbon footprint and achieve climate goals.

With the concerted efforts of government bodies, manufacturers, and technology innovators, India is on track to redefine its mobility landscape in line with global sustainability standards. The convergence of xEVs, Evs, and connected solutions represents a powerful shift that will not only impact the future of Indian transportation but will also contribute significantly to the global push for greener, smarter, and more connected mobility solutions.

7

Do we need to look beyond the tailpipe to evaluate the true technological solutions for a sustainable transportation of future?

Neelkanth Marathe
Executive Director, Emission Controls Manufacturers Association (ECMA)

Transportation is one of the contributors to global greenhouse gas (GHG) emissions and air pollution. Addressing these emissions is crucial for achieving climate goals and improving public health. Historically, the primary focus has been on tailpipe emissions, which are the pollutants released directly from a vehicle exhaust pipe. However, a more comprehensive approach is gaining traction called Life Cycle Assessment (LCA), which considers all emissions associated with a vehicle from cradle to grave. Effort is made to compare the two approaches to determine which offers a more sustainable path for the future of transportation.

The tailpipe emission control approach focuses on reducing pollutants emitted during the operational phase of a vehicle's life. This method is the foundation of most of the regulations and standards worldwide, such as the Euro standards in Europe, CAFÉ standards in USA and BHARAT standards in India.

Tailpipe emissions are the harmful gases and particulate matter expelled from a vehicle's exhaust system. They include:

- NOx, that contributes to smog, acid rain and respiratory issues
- PM, the fine particles that can penetrate deep into the lungs and bloodstream causing serious health problems
- CO, a toxic gas that reduces the blood's ability to carry oxygen
- HC, that contributes to smog formation
- CO_2, a primary greenhouse gas contributing to climate change

Strategies for reducing tailpipe emissions involve several key technological solutions.
Modern engines are designed to burn fuel more efficiently, reducing both fuel consumption and emissions. This include technologies like Direct Injection, turbocharging, variable valve timing, etc

Advancement in exhaust after-treatment systems have greatly cleaned the gases before they are released from the tailpipe into the atmosphere. The technologies include catalytic converters converting harmful pollutants of CO, HC and NOx into less harmful substances like CO_2, H_2O and N_2 specially from gasoline exhaust, diesel particulate filters (DPF) that traps and removes particulate matter from diesel exhaust, Slective catalytic Reduction (SCR) that uses a liquid reductant like urea to convert NOx into N_2 and H_2O.

While effective in improving air quality in urban areas, the tailpipe emission control approach is now found to have significant limitations from a sustainability perspective:

- It focuses on the Use Phase only ignoring emissions from entire life cycle of a vehicle, including manufacturing, fuel production and disposal. For example, a BEV has zero tailpipe emissions, but its manufacturing process, specially for batteries, is very carbon-intensive.
- It can create a false sense of sustainability. A vehicle with low tailpipe emissions might be using a fuel that is highly polluting to produce, thereby shifting the burden.
- This approach fails to account for the carbon footprint of the materials and energy used to build the vehicle. This is particularly relevant for EVs, where battery production can negate the benefits of zero tailpipe emissions.

Life Cycle Assessment approach provides a holistic framework for evaluating the environmental impact of a product from **"cradle to grave".** For transportation this means assessing all emissions associated with a vehicle's life and so known as Well-to-Wheel life cycle emissions. LCA typically breaks down a vehicle's life cycle into four distinct phases:

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- Raw material acquisition and processing, that includes the extraction and processing of all materials used to build the vehicle such as steel, aluminium, plastics, and, for EVs lithium, cobalt and nickel for batteries.
- Manufacturing and assembly, that accounts for the energy and emissions involved in building the vehicle at the factory
- Use or Operational phase of the vehicle that includes the emissions from fuel combustion for ICEVs and electricity generation for EVs
- End of Life disposal / Recycling, that considers the emissions and environmental impact of dismantling the vehicle and disposing of or recycling its components.

It looks like that LCA has potential to offer a more accurate picture of a vehicle's true environmental impact, elaborated through following three aspects:

- Holistic view accounts for all upstream and downstream emissions providing a complete and transparent analysis. This is crucial for comparing different powertrains such as ICE, hybrids and EVs
- LCA reveals the significant emissions associated with manufacturing, specially for EVs. While a BEV has zero tailpipe emissions, its cradle to gate (manufacturing) emissions are often higher than a complete ICE vehicle.
- LCA has a potential to provide a full picture of emissions, therefore, it is likely to help better way the policy makers, manufacturers, and consumers to make more informed and balanced decisions. It encourages a shift towards cleaner manufacturing processes, more sustainable material sourcing, and efficient end-of-life recycling.

LCA might show that an EV powered by electricity from a coal-fired grid has a higher overall carbon footprint than a highly fuel-efficient gasoline car. This finding would be impossible to deduce from a tailpipe-only analysis. Below summary table would give a glimpse of tailpipe vs LCA approach:

Feature	Tailpipe emission control approach	Life Cycle Assessment (LCA) approach
Scope	Limited to vehicle's operational phase	Covers entire "cradle to grave" life cycle
Focus	Direct emissions from the exhaust pipe due to fuel combustion only	All emissions, including manufacturing, fuel production, and disposal
Metric	Pollutants like NOx, CO, HC, Particulates and new species recently included	Covers environmental impacts due to CO_2e (equivalent) comprehensively
Key advantage	Effective for improving local air quality	Provides a more comprehensive measure of sustainability
Key limitations	Does not cover upstream and downstream impacts	data-intensive and complex to calculate
Example	EV is considered zero tail-pipe emission	EV emission depends upon the source of electricity generation and approach for battery manufacturing

Currently, a single goal of "zero tailpipe emission" has been a powerful driver of the development of new powertrain technologies, most notably BEVs and H-FCEVs. This objective, however, can be misleading and is why the LCA approach is considered far more appropriate and necessary when comparing the different technologies.

Interest towards LCA is growing because of some of the following superior framework:

- A zero-tailpipe emission vehicle is not zero-emission vehicle in a broader sense. The production of BEV is very energy-intensive particularly due to the manufacturing of the battery. The mining of materials like lithium, cobalt, and nickel and the energy required to assemble the battery, create a significant carbon footprint before the vehicle even leaves the factory. Magnitude of this carbon footprint can be substantial and can take several thousand kilometres of driving to pay back this initial emission debt.

- The tailpipe metric also ignores the emissions from the source of the energy. Cleanliness of the energy used for generation of electricity is paramount for EVs. EV charged with electricity from a coal-fired power plant will have a higher overall carbon footprint than the same vehicle charges with electricity from a renewable source like solar or wind. The zero-tailpipe emission label hides this crucial variable which can lead to a false sense of sustainability.
- End-of-life process for vehicles is also ignored in the current tailpipe-only approach. The disposal or recycling of various ferrous, non-ferrous, plastic materials, glass and various types of toxic chemicals and oils used in the vehicles, irrespective of the type of powertrain used, is going to of great concern. Additionally, recycling of large complex battery from and EV has its own set of environmental challenges and emissions that are not accounted for in a tailpipe-only analysis

LCA is considered to provide an improved "Apple-to-Apples" comparison of different powertrains being proposed, incorporating a holistic view for a more reliable and scientifically based evaluation.
LCA enables a direct comparison between an ICEV, a BEV, a HEV and a FCEV by looking at the entire cradle-to-grave process.

- LCA for ICEV includes emissions from oil extraction, refining, transport, and finally, fuel combustion in the engine.
- LCA for a BEV accounts for the emissions from the manufacturing process including for the battery, the electricity generation at the power plant, and the eventual recycling or disposal of the battery.
- LCA for a HEV amounts to combination of LCA for ICEV and EV, while considering lower amount of fuel combustion and lower size of battery for manufacturing and disposal.
- LCA for FCEV considers the method of hydrogen production (from fossil-fuels which is carbon-intensive or from electrolysis using coal-based or renewable energy sources), the energy for compression and transport of hydrogen, and the emissions from the fuel cell itself

LCA reveals the environmental trade-offs between different technologies. It might show that an FCEV using hydrogen produced from fossil fuels has a higher life cycle carbon footprint than a highly efficient gasoline-powered vehicle. Conversely, it can demonstrate the significant sustainability benefits of a BEV when charged with renewable energy. These nuances cannot be observed through tailpipe-only analysis.

LCA approach, therefore, is being considered as a crucial and indispensable tool for making strategic decisions and guiding policy making. It is now anticipated that with the changing scenario, policies focused solely on tailpipe emissions could inadvertently encourage the shifting of problem, where emissions are simply moved from the transportation sector to the electricity generation or manufacturing sectors. For example, a country depending on cols-based electricity grid might be incentivizing BEV adoption, but this could actually increase its overall national carbon footprint. An LCA study may highlight and quantify this issue very well and may suggest that a faster transition to a cleaner energy grid is essential for a truly sustainable transportation system OR suggest to go slow on BEV adoption till the electricity grid id backed up substantially by cleaner renewable energy sources.

LCA is expected to help the identification of the most carbon-intensive stages of a vehicle's life cycle. Manufacturers may be able to prioritize their R&D and investment justifiably and effectively. For a BEV, it might mean focusing on developing less carbon-intensive battery manufacturing processes, improving battery recycling technology and/or sourcing materials from more sustainable suppliers. LCA approach can be very well seen as an education tool for the consumers to learn the true environmental impact of their choices. It will also help the understanding of the conversation beyond the misleading zero-emissions label and provide a more comprehensive view of a vehicle's carbon footprint from its production to its eventual end of life.

Based on all above elaborated, it can be fairly stated that while zero tailpipe emissions is an easily understandable and impactful goal presently, it is a limited and potentially deceptive metric and misleading. Considering the upcoming scenario opening up doors for new generation of and competing powertrain technologies, the Life Cycle Assessment (LCA) could emerge to be a far more appropriate framework because it offers a holistic, transparent and reliable measure of a vehicle's true environmental impact overs its life cycle. It is expected to prevent the simple shifting of the environmental burdens and provides the data needed for informed decisions and policy making that can lead to genuinely sustainable technological solutions for the transportation sector.

8

Decarbonization of the Indian Transport Sector

Dr. Yogendra Kanitkar, *VP, Research and Development,*
Mr Umesh Sawant, *COO*
Pi Green Innovations

Introduction

The Indian transport sector is both vital to economic growth and one of the largest contributors to greenhouse gas (GHG) emissions. Providing connectivity for over a billion people across a subcontinent, the system is highly fossil fuel dependent, particularly on diesel and petrol. As India has pledged to achieve net-zero emissions by 2070, the decarbonization of transport has become an urgent imperative. Policy, industry, and academia are increasingly aligned on the need for a coordinated roadmap that tackles both supply- and demand-side emissions, while ensuring system affordability and reliability.

Transport has consistently emerged as one of India's fastest-growing sources of energy consumption. In 2012, the sector used 76 million tons of oil equivalent (Mtoe), or 22% of final energy demand. By 2019, this demand had grown to 94 Mtoe (IEA, 2021). The IEA projects that India's transport energy demand will grow at 5–6% per annum to 2040, compared to only about 1.5% globally, largely on account of road transport expansion, rising urbanization, and consumption-driven economic growth. On the emissions front, the sector contributed 216 million tons of CO_2-equivalent ($MtCO_2eq$), about 8% of national GHG emissions in 2012. By 2019, this figure had increased to around 330 $MtCO_2eq$, or 13% of national emissions, according to India's Third Biennial Update Report (BUR-3) to the UNFCCC. Road transport is disproportionately dominant, accounting for about 87–90% of total transport emissions.

Energy Use and Emissions Profile

India's transport fuel use is dominated by fossil sources. Diesel forms the majority basis for freight, medium and heavy commercial vehicles, and intercity buses. Petrol is consumed primarily by passenger cars and two-wheelers, with two-wheelers forming nearly 75% of India's total registered vehicles. Compressed Natural Gas (CNG) sees uptake in urban fleets, while electricity is beginning to make inroads via electric two- and three-wheelers, buses, and small passenger cars. Aviation, shipping, and rail are secondary in comparison, but are rising with economic activity.

Fuel-specific emission factors measured in Indian contexts highlight the challenge. Petrol combustion emits 2.27 kg CO_2 per liter, diesel 2.64 kg CO_2 per liter, and CNG approximately 2.75 kg CO_2 per kg. Electricity consumption produces about 0.68–0.72 kg CO_2 per kWh, though this is falling as renewable energy grows. These figures reflect that, on a purely energy basis, EVs powered by the current coal-dependent grid do not yet guarantee significant lifecycle savings relative to efficient ICEVs.

Fleet Composition and Lifecycle Assessment

The vehicle fleet is fragmented across segments. Heavy commercial vehicles, typically diesel-dominated, suffer slow turnover, partly due to a weak scrappage incentive regime. Light commercial vehicles operate on a mix of diesel, CNG, and increasingly electricity, with urban logistics forming a dynamic subsector. Passenger vehicles are fueled by petrol and diesel, with a modest but rising EV penetration boosted by central and state incentives. Two- and three-wheelers comprise the largest share of vehicles, overwhelmingly petrol-based, but with electrification growing quickly; by 2023, 4.5% of sales were electric.

Lifecycle analysis under Indian energy conditions underscores why decarbonization must account for entire supply chains. Well-to-wheel emissions for ICEVs average around 0.24–0.27 kg CO_2eq per kilometer, with diesel performing slightly better than petrol. For EVs, lifecycle emissions lie in the range of 0.32–0.37 kg CO_2eq per kilometer, depending on the specific battery chemistry. While EVs do not yet provide an overwhelming lifecycle carbon advantage, particularly given the coal-heavy grid, they drastically reduce local pollutants (PM2.5, NOx), and as the grid greens, their lifecycle carbon profile will improve significantly. Modeling suggests that EVs could achieve 30–40% lower lifecycle emissions by 2030 relative to 2023 levels, in alignment with India's renewable energy targets.

Pathways to Decarbonization

Decarbonization of India's transport sector will require the deployment of multiple technological and policy levers in parallel rather than reliance on any single pathway.

One of the most promising interventions is Bio-CNG, generated via anaerobic digestion of agricultural residues, municipal organic waste, and animal dung. It qualifies as a carbon-neutral fuel because the captured biogenic CO_2 offsets its usage emissions. Under the Government's SATAT initiative (Sustainable Alternative Towards Affordable Transportation), India aims for the installation of 5,000 compressed biogas plants by 2025. If scaled effectively, Bio-CNG can substitute fossil CNG in urban fleets and logistics, displacing diesel and reducing lifecycle emissions by up to 80%.

Ethanol blending provides another near-term pathway. India achieved 10% ethanol blending in petrol in 2022, with the ambitious target of 20% by 2025. Ethanol blending reduces the lifecycle carbon intensity of petrol use by around 14–20%. Biodiesel, though less adopted (below 1%), could lower trucking emissions if supported by assured feedstock such as non-edible oils or waste cooking oil. Advanced biofuels like isobutanol command research interest, with trial blends showing promise due to higher energy density and better engine compatibility.

Hydrogen also features prominently in India's decarbonization agenda. Pilots in Delhi with 20% hydrogen blending in CNG bus fleets demonstrated reductions of 17–18% CO_2 emissions. The National Green Hydrogen Mission, launched in 2023 with a budget outlay of 19,744 crore, intends to build 5 million tonnes of green hydrogen capacity by 2030. Hydrogen as a standalone transport fuel remains aspirational but hydrogen-CNG blends can bridge the gap until fuel cell vehicles and refueling infrastructure become more widespread.

Electrification, however, is the central decarbonization lever for mass transport. The most immediate segment for electric mobility is India's two- and three-wheelers, where shorter ranges, lower power requirements, and urban usage make EVs competitive even without extensive charging networks. Electric buses procured under the FAME II scheme, which has an outlay of 10,000 crore, are increasingly deployed by state transport undertakings. Passenger cars and LCVs lag in electrification owing to high costs, but are expected to reach price parity with ICEVs as global lithium-ion battery costs fall below USD 100 per kWh by the late 2020s. By 2030, EVs could represent 30% of all new sales, with estimates indicating a net reduction of 846 $MtCO_2$ cumulatively by 2070 if aligned with renewable grid expansion.

Technology pathways also include refuse-derived fuels from pyrolysis of plastics, which aligns with circular economy principles by converting waste plastics into liquid fuel streams. Although currently in pilot stages, this pathway could offset a fraction of diesel demand while solving waste problems. Similarly, rail and public transport electrification presents systemic carbon benefits. The Indian Railways has committed to achieving net-zero emissions by 2030 through 100% electrification, while metro rail expansions in cities offer low-carbon passenger alternatives. Modes like rail are 60–70% more efficient in terms of energy use per tonne-km, and achieving even a modest modal shift away from road freight towards electrified rail could reduce 40–50 $MtCO_2$ annually by 2030.

Finally, none of these fuel and vehicle interventions can realize full benefit without a parallel decarbonization of electricity supply. India targets 500 GW of renewable energy capacity by 2030, most of it from solar and wind. Every additional 1% in renewable share translates to roughly 1–1.5% lower lifecycle emissions for EVs. The greening of the grid unlocks cascading benefits: not only do EVs become truly low-carbon, but green hydrogen produced from renewable electricity further accelerates decarbonization of freight and heavy-duty mobility. A CO2 capture and permanent sequestration from exiting coal fired power plants is also a prudent path that must be deployed as a policy to lower carbon footprint of such capital assets that are difficult to quickly replace looking at nation's natural resources utilization perspective. Innovations in this segment are a must such as Pi Green's "Net Zero Machine" utilizing waste ash and still providing usable end product.

Policy Enablers

Decarbonization of transport is not only about technology but also about enabling policy frameworks. India's scrappage policy, launched in 2021, attempts to retire inefficient pre-BS-IV diesel trucks. Although implementation is uneven, stronger enforcement could eliminate old vehicles whose emissions are multiple orders higher than new Bharat VI compliant fleets. Transport operators using cleaner technologies may be given access to compliance or voluntary carbon markets, allowing them to monetize emission reductions through tradable carbon credits. Alternatively, opportunity for retrofitting older vehicles to better emissions performance through type approved solutions can be thought of.

Fiscal instruments are being employed to enable adoption. EVs are taxed at 5% GST compared to 28% on ICEVs. Reduced import duties for advanced batteries, electrolyzers, and compressed biogas equipment will enhance cost viability. Programs such as FAME II and SATAT provide direct capital subsidies and assured offtake arrangements, respectively, for EVs and compressed biogas. Awareness campaigns around fuel efficiency, eco-driving, and shared mobility patterns are also critical. Though apparently small-scale, these behavioral measures can improve fuel usage efficiencies by 5–10% nationally, a non-trivial number in absolute terms.

Industry Outlook and Challenges

India's auto sector, one of the largest in the world, presents a significant opportunity to catalyze decarbonized mobility solutions at scale. Industry leaders are investing in EV manufacturing capacity, lithium refining, and biofuel distribution infrastructure. Domestic supply chains for components, coupled with localized R&D, provide the backbone for global competitiveness. Moreover, decarbonization drives a local co-benefit—air quality improvement. The transport sector ties directly with India's urban air crisis, and co-reduction of particulate pollutants and CO_2 makes industry-wide transformation socially desirable as well as politically feasible.

Challenges, however, remain formidable. Upfront costs of EVs and fuel cell technologies constrain adoption, though falling battery and hydrogen costs will mitigate this over time. Infrastructure for charging, hydrogen refueling, and biogas distribution is insufficient and requires sustained capital outlay. Feedstock challenges limit ethanol and biodiesel scaling. Finally, uncertainty over the future dominant technology pathway—whether EV, hydrogen, biofuels or hybrids—slows industry confidence in long-term investments. These challenges indicate that decarbonization will unfold in waves, with biofuels and CNG bridging the medium term, and EVs and hydrogen dominating the long-term transport landscape.

Conclusion

Transport is India's fastest-growing source of CO_2 emissions, at over 330 $MtCO_2eq$ as of 2019, increasing annually at well above global averages. Decarbonizing this sector is essential if India is to remain on course for its 2070 net-zero commitment. Achieving this transformation will demand a carefully staged but aggressive strategy: near-term diesel substitution with bio-CNG, even Hydrogen, mid-term deployment of EVs and hydrogen-CNG blending, diesel blending with isobutenol / DME and long-term electrification of fleets supported by a decarbonized grid and hydrogen economy. Complementary measures like scrappage, modal shift to electrified rail, and market instruments such as the CCTS will complete the policy ecosystem.

For industry, this represents both challenge and opportunity. Decarbonization will impose transition costs, infrastructural demands, and competitive uncertainty, but will also allow India to position itself as a leader in the global green mobility supply chain. The social co-benefits of decarbonized transport—reduced air pollution, lower oil import dependency, and healthier urban environments—underscore why this agenda deserves unwavering focus. With coordinated action, India's transport sector can pivot from being a 330 $MtCO_2$ problem today to a cornerstone solution for climate neutrality by 2070.

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Powertrain Diagnostics in Hybrid Electric Vehicles

9

AVL India

Abstract

Hybrid Electric Vehicle (HEV) development faces increasing demands for higher energy efficiency and lower emissions. This article examines the challenges of optimizing complex hybrid powertrains comprising internal combustion engines (ICE) and electric drive modules. It explores advanced measurement and diagnostic techniques that ensure module-level and system-level performance, highlighting AVL's X-ion™ platform as a key enabler for synchronized data acquisition and comprehensive powertrain evaluation on the testbed, chassis dynamometer, and road.

Introduction

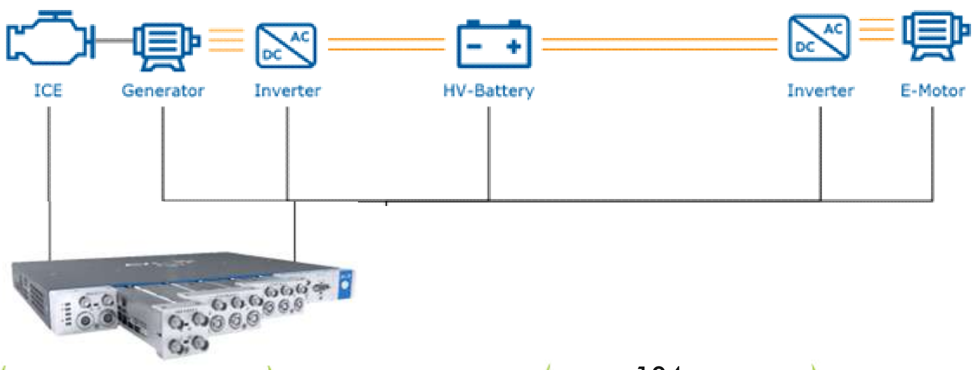
Hybrid powertrains combine the flexibility of ICE with the efficiency of electric drive systems to meet ever-rising targets for fuel efficiency and reduced emissions. Optimizing the interaction between ICE and e-power modules requires extensive measurement, analysis, and evaluation under dynamic driving conditions. Components such as the battery, inverter, generator, starter, and ICE after-treatment systems must be individually optimized and then validated in an integrated vehicle environment.

Key Challenges

- Module and System Optimization
- Accurate documentation of module performance during realistic operation, including road tests.
- Identification and root cause analysis of performance issues.
- System integration and calibration for highly dynamic operation, ensuring seamless ICE–e-motor interaction.
- Complex Sensor interface and Signal Access
- Hybrid systems demand synchronized acquisition of signals from multiple sources including CAN bus, ECU, and auxiliary sensors.
- Handling start/stop events and rapid transients requires high time-resolution and precise synchronization.

AVL's Diagnostic and Measurement Solution

AVL addresses these challenges with its X-ion™ modular data recorder platform, which provides synchronized access to sensors and onboard data. Time-based recording captures dynamic on/off operation of HEV modules, while tailored analysis packages support measurement requirements across testbeds, chassis dynos, and on-road testing. The platform allows developers to configure test setups specific to each powertrain module or the entire vehicle, ensuring accurate evaluation of energy flow, emissions, and calibration status.

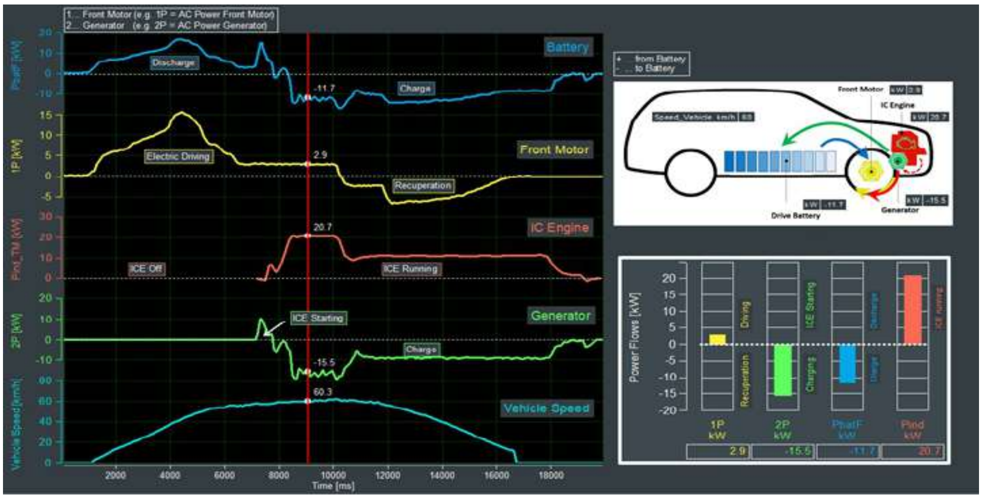


- Multiple applications in a single measurement device
- Synchronized and time stamped measurement and result data
- Unified measurement platform for complete measurement journey from configuration, measurement to result display and post processing
- Upgradability and extendibility for example NVH (Noise, vibration and harshness)
- Testbed and in-vehicle integration

Case Studies

Energy Flow Analysis

Challenge: Provide accurate real-time data on powertrain energy flow to identify behavior at various hybrid driving modes where obtained data can be used optimizing system for maximum range and fuel efficiency. Solution: Access to ICE and e-power sensors and on-board CAN interfaces with high time-resolution data recording. Benefit: Enables precise calibration and energy balance optimization.



Inverter–E-Motor Efficiency

Challenge: Achieve maximum efficiency of the inverter–e-motor combination.

Solution: Lab test procedure measuring voltage, current, and motor speed feeds data to an optimizer loop for inverter parameters.

Benefit: Delivers inverter control parameters that ensure highly efficient e-motor operation.

E-Motor NVH and Reliability

Challenge: Address vibrations and noise in e-motor driveshafts under dynamic torque requirements. Solution: Dedicated sensor–analyzer–optimizer procedures measure, evaluate, and mitigate NVH issues. Benefit: Improved NVH comfort and mechanical integrity.

Thermal Stress in Catalyst

Challenge: Frequent ICE start/restart cycles induce thermal stress in the three-way catalyst (TWC), risking damage.

Solution: Infrared surface temperature measurements detect critical thermal gradients early. Benefit: Prevents catalyst damage and ensures long-term durability.

Irregular Combustion Events

Challenge: Debugging of fuel injections, spark timing, and gas exchange requires comprehensive signal recordings.

Solution: Cycle- and crank-angle-resolved flame signal evaluations identify irregular combustion events. Benefit: Supports precise ICE actuator calibration for stable combustion cycles.

Conclusion

Hybrid powertrain development demands advanced instrumentation and diagnostic methodologies to optimize individual modules and overall vehicle performance. AVL's X-ion™ platform provides the flexible, synchronized measurement capabilities needed to address these challenges, enabling developers to meet stringent efficiency and emission targets while ensuring system durability and robust performance from the testbed to real-world driving.

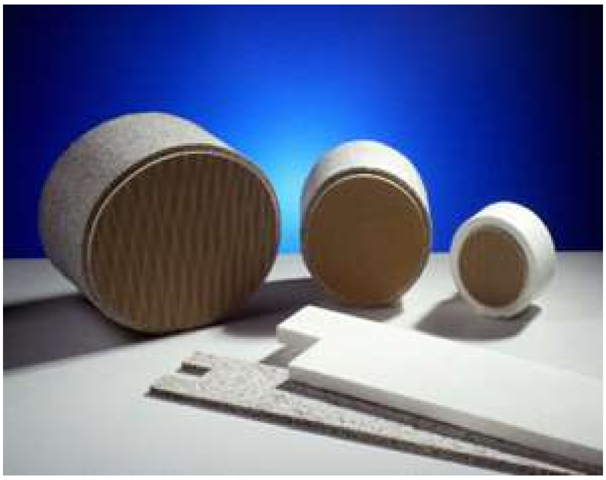
10

Critical Design Inputs for Catalytic Converter Mounting Mat Selection

Alkegen India Pvt Ltd

Abstract

With the tightening of global emission norms such as Euro 7 and BS VII, Trem V, the design of catalytic converters has become increasingly critical. This article outlines the importance of each design input required for mounting mat selection and validation, emphasizing the need for accurate data to ensure compliance with future emission standards.



Introduction

Catalytic converters play a vital role in reducing vehicular emissions. The mounting mat, which secures the substrate within the converter shell, must be designed with precision to withstand thermal and mechanical stresses. Accurate input data is essential to ensure the mat performs reliably under all operating conditions.

To streamline data delivery and ensure we capture every necessary detail, we've developed a dedicated input form. Following, we will explain to you the structure and more details.

I. General Information

- Submitter / Company / Contact Info: Ensures traceability and accountability for design inputs.
- Vehicle Brand / Program / Engine Type: Determines operating conditions and space constraints.
- Volume / SOP: Helps plan production scale and timelines, influencing material selection and cost optimization.

II. Validation Criteria

- Inlet Gas Temperature (Typical & Range): Critical for selecting mat material with appropriate thermal resistance.
- Axial g Load / Frequency: Influences mat density and resilience to vibrations and mechanical shocks.
- Pretreatment / Thermal Cycles: Helps simulate real-world aging and durability of the mat.
- Other: Allows inclusion of unique test conditions or customer-specific requirements.

III. Environment / Operational Conditions

- Fuel Type (Gasoline, Diesel, etc.): Affects exhaust composition and temperature profile.
- Isothermal or Gradient: Determines thermal distribution, impacting mat expansion and sealing.
- Heatshield (Yes/No): Influences external temperature exposure and shell protection.
- Exhaust Pressure Drop: Affects backpressure and flow dynamics, which can impact required mat pressure.
- Location on Vehicle: Determines exposure to heat, vibration, and contaminants.
- Ambient & Max Shell Temperatures: Essential for thermal management and mat material selection. Additionally, this information enables the precise modeling of the shell's thermal expansion.

IV. Substrate Information

- Cell Structure / Type / Material: Defines substrate fragility and thermal behavior.
- Minimum Design Strength: Ensures mat provides adequate cushioning without damaging the substrate.
- Maker / Thermal Expansion Coefficient: Important for compatibility and thermal matching with mat.
- Shape / Dimensions / Tolerances: Directly affects mat coverage, compression, and sealing performance.
- Coated Mass: Influences thermal inertia and mechanical load on the mat.
- Mat Width / Coverage %: Determines sealing efficiency and vibration damping.

V. Shell Information

- Metal Type / Tolerance: Affects thermal expansion and mechanical fit with the mat.
- Design Gap: Crucial for calculating mat compression and ensuring proper holding force.
- Wire Mesh Seals / Width: Enhances sealing and prevents mat erosion or blowout.

VI. Canning Information

- Process Type: Impacts mat compression method and uniformity.
- GBD Controlled / Tolerance: Ensures consistent holding force and prevents substrate damage.
- Over-Compression: Must be managed to avoid cracking the substrate or degrading mat performance.

VII. Other

- Temperature / G-Load Data: Validates mat performance under real-world conditions.
- Validation Protocols: Ensures compliance with industry standards and customer expectations.
- Other Requirements: Captures any additional constraints or performance targets.

Importance of Accurate Inputs for Future Emission Norms

With the evolution of emission regulations, catalytic converters must operate efficiently under extreme thermal and mechanical conditions. Accurate inputs ensure optimal mat selection, precise compression, reliable sealing, and compliance with future standards. This guarantees long-term durability and performance of the emission control system. The following photo illustrates a sample converter layout, highlighting all critical design inputs along with their corresponding results, e.g., material limits and safety factors.

The inputs explained in this article are essential not only to ensure consistent performance prediction, but also to provide the basis for the calculations that guide product selection—ensuring that the chosen solutions deliver durability and reliability in real-world applications.

ALKEGEN

Write over model | Write over requestor | Write over company
Write over notes

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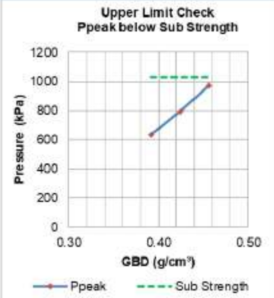
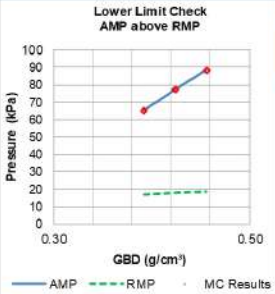
Input Data

Type	Gasoline	Shape	Round	Canning Method	GBD Controlled Can
Material	Ecoflex HBD	Sub Material	Cordierite	Shell Material	SS-439;DIN 1.4510
BBW	1696 g/m²	CPSI	400/4.5	Tolerance Method	GBD Tolerance
Gap	4 mm	Sub Diameter	118.4 mm		
Inlet Gas	950 °C				
Ambient Conditions	Underbody	Sub Length	92 mm	GBD Tolerance	0.032 g/cm³
Ambient Temp	35 °C	Mat Offset	6 mm	Assembly Damage	Standard
Shake Angle	90 °	Sub Coated Mass (D)	565 g	Tape Backing	None
g-load	20 g	Sub Strength (D)	1030 kPa	Scrim	None
Grms?	No			Display Results	Yes
Pressure Drop	10 kPa				

Design Summary Mixed Model

	Start Gap (mm)	Fiber Basis Weight (g/m²)	Bonded Basis Weight (g/m²)	Gap Fiber Density (g/cm³)	Gap Bulk Density (g/cm³)	Substrate Temp (°C)	Shell Temp (°C)	Relative Gap Expansion (%)	Peak Pressure (kPa)	Aged Mat Pressure (kPa)	Required Mat Pressure (kPa)	Factor of Safety (kPa/kPa)
Min GBD (Loose)	3.89	1440	1526	0.37	0.39	950	480	7.4	632	65	17	3.9
Nominal GBD	**4.00**	**1600**	**1696**	**0.40**	**0.42**	**950**	**480**	**7.2**	**792**	**77**	**18**	**4.3**
Max GBD (Tight)	4.09	1760	1866	0.43	0.46	950	480	7.1	971	89	18	4.8





Prediction OK

Part Size

Length (mm)	Width (mm)	Tab (mm)	Thickness (mm)	Weight (g)
404.0	86.0	35.0	10.2	59

AMP - Aged Mat Pressure
RMP - Required Mat Pressure
GBD - Gap Bulk Density
Ppeak - Peak Pressure
BBW - Bonded Basis Weight
OC - Over Compression

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11

Urgent Need for Enhanced Evaporative & Refueling Emission Standards in India

Emission Controls Manufacturers Association (ECMA)

This article highlights the significant and underestimated problem of evaporative and refueling volatile organic compound (VOC) emissions from petrol-fueled internal combustion engine (ICE) vehicles in India. Referred to as the "silent threat" by The Economic Times of India, these non-exhaust emissions far exceed tailpipe emissions and are a primary precursor to ozone and ultrafine particulate (PM2.5) formation, contributing to smog and severe public health risks.

Evaporative emissions are especially a concern in India,, exacerbated by increasing ambient temperatures due to climate change, and the mandatory blending of ethanol into petrol, which has a higher vapor pressure than pure petrol. India has traditionally followed European emission norms, but it is now time for India to consider strengthening the evaporative test procedures and limits to better address its unique vehicular fleet and real-world ambient and fuel conditions.

Recommendations

It is strongly advocated for India to adopt the following standards as it develops the upcoming Bharat Stage (BS) 7 standards:

(1) On-board refueling emissions limit of 0.05 g/L (~ Brazil today)

(2) Revise diurnal temperature range from 20 – 35 °C in BSVI to 25 – 40 °C, to better represent ambient temperatures in India

(3) Hot soak + 2-day (48-hr) diurnal emission standard of 0.5 g (~ Brazil, US and China)

The above changes will reduce emissions by 98%, mitigate exposure to carcinogenic air toxics, & offer fuel cost savings to consumers.

The recommendations made above are aligned with India's rapid advance with clean transportation, its unique environmental challenges and will set progressive standards independent of Europe, to protect the urban air quality and health of its citizens.

Quick Facts

Evaporative emissions and their sources

Evaporative emissions consist of volatile organic compounds (VOC) associated with fuel vapors that escape during –

- Refueling
- Running losses during vehicle operation
- Permeation through fuel tanks and supply lines, and
- Diurnal fuel tank breathing losses during parking events

Magnitude of problem

For an average day of driving, a BS6 compliant modern vehicle will emit ~ 2 grams of hydrocarbon emissions at the tailpipe. In comparison, evaporative emissions can reach 25 – 30 grams (or 15X the tailpipe!) when the vehicle is parked for 2 days in typical summertime conditions – despite having been fitted with the latest sized European canister.

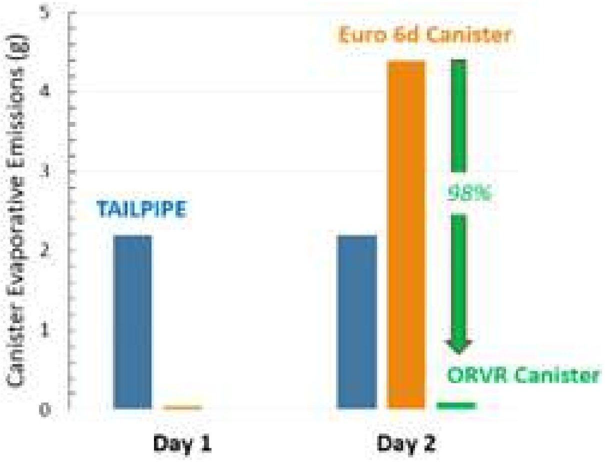


Figure shows laboratory testing with 50 Liter tank,
E20 fuel (68 kPa), 25°C – 40°C diurnal temperature profile

Emission Standards for Passenger Cars in India & Other Advanced Markets

Evaporative and Refueling Emission Standard	India BS 4 & 6*	Europe Euro 7**	Brazil PL 7	China 6b	USA Tier 3
On-board Refueling	None	None	0.05 g/L	0.05 g/L	0.05 g/L
Evaporative (hot soak + diurnal)	1-day 2.0 g	2-day 1.5 g	2-day 0.5 g	2-day 0.7 g	3-day 0.3 g

** Draft AIS-175 proposes to adopt the evaporative emission limits and test procedures of Euro6d as part of a Phase III BS6*
*** Euro 7 standards diluted by removing the proposed refueling emissions limit and only slightly lowering the evaporative limit*

Why the need for tighter standards beyond Euro 7 now?

(1) With successful implementation of BS 6, tailpipe emissions have reduced significantly, increasing the relative contribution of non-exhaust, evaporative emissions.

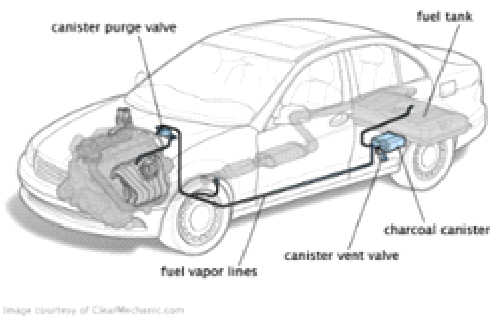
(2) India has much hotter days compared to Europe, and it is time that the test procedures are adapted to "real-world" ambient conditions in the country. Recent studies show the climate-change induced increase in temperatures, especially during heat waves.

(3) India is advancing its goal of blending higher amounts of ethanol in petrol. The vapor pressure of E20 (up to 70 kPa) is higher than that of E0 petrol (up to 60 kPa). This increases in-use evaporative emissions, whether the vehicle is parked or operated.

(4) Euro 7 final standards were significantly diluted, citing the goal of reaching 100% electric vehicle sales by 2035. Electrification in India has further to go, and it will be important to ensure that the best available technology is applied to ICE-powered vehicles.

Technology Implications & Readiness

- Evaporative emissions are controlled using an on-board activated carbon canister. Petrol vapors are routed through the canister and are stored there until the vehicle operates, at which point they are used in the engine for combustion.
- Changes recommended here for BS 7 standards will require larger canister systems to control refueling emissions and prevent excess diurnal evaporative emissions under Indian ambient and fuel conditions.



- Performance: The system can control hot soak + diurnal emissions to levels of 0.30 grams per day or less. Refueling emissions are reduced by 98% via an On-board Refueling Vapor Recovery (ORVR) canister system, which is significantly more efficient at controlling refueling VOCs than Stage II vapor recovery at petrol stations.
- BS 6-compliant vehicles in India already contain a canister to address some of the evaporative emissions. Implementation of the above recommendations will simply require the use of ORVR hardware and larger canisters.
- The evaporative control systems are commercially available, with > 25 years of successful implementation in global markets.

Cost and Durability Implications

Evaporative control systems cost less than 3000 and require no maintenance for the life of the vehicle. In fact, much of the cost is recovered and returned to the vehicle owner because of saving fuel that would have otherwise evaporated.

Conclusion

Evaporative and refueling emissions represent a significant, yet largely uncontrolled, source of air pollution in India. The current BS6 standards and reliance on Stage II vapor recovery are inadequate given India's unique climate, increasing petrol vehicle fleet, and widespread E20 fuel adoption. Implementing robust BS7 standards, specifically aligned with Brazil's PROCONVE L-7, including mandatory ORVR systems and larger carbon canisters, is not only technologically feasible and cost-effective but also crucial for safeguarding public health, improving air quality, and providing economic benefits to consumers through fuel savings. India has a critical opportunity to lead in this area, rather than continuing to follow Europe's less stringent approach.

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Design, Simulation, and Energy Management of a Hydrogen–Electric Hybrid Vehicle: A Series-Dominant Architecture for Enhanced Efficiency and Novel Powertrain Integration

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Abstract

A hybrid powertrain architecture is presented that integrates a hydrogen-fueled energy unit with a high-capacity traction battery in a series-dominant configuration. The design addresses key limitations of conventional internal combustion engines and battery-electric vehicles, including low thermal efficiency, range constraints, and reliance on fossil-derived grid electricity. In this system, a compact hydrogen power source provides both direct propulsion support and charge-sustaining capability for the traction battery during the initial operation phase. Thereafter, the vehicle transitions to battery-electric drive, ensuring sustained zero-emission operation with optimized efficiency. The architecture enables smooth energy distribution between hydrogen and electricity, supports regenerative recovery, and minimizes transient load stress on critical components. Simulation results demonstrate reductions in hydrogen consumption, enhanced system efficiency, and extended driving range compared to existing hybrid or fuel-cell-only configurations. This approach provides a scalable pathway for high-efficiency mobility with reduced emissions and improved adaptability across urban and highway conditions.

1. Introduction

Conventional internal combustion engines (ICEs) face fundamental thermodynamic limitations, with typical efficiencies below 40% and unavoidable emissions of CO_2 and NO_x. Regulatory pressure and rising environmental concerns are driving the shift toward electrification, yet battery-electric vehicles (BEVs) encounter barriers such as limited range, slow charging, and dependence on electricity generated from fossil fuels. Fuel-cell vehicles address some of these constraints, but high system costs and hydrogen infrastructure challenges limit widespread adoption.

The proposed hybrid concept introduces a series-dominant hydrogen–electric powertrain that combines the strengths of both energy carriers while minimizing their individual drawbacks. A hydrogen-based energy unit operates in controlled efficiency zones, delivering power to a generator and simultaneously charging the battery pack. The traction motor, decoupled from engine transients, provides responsive torque for all driving conditions. Once sufficient charge is achieved, the system transitions to pure electric operation, enabling zero tailpipe emissions and reducing dependence on external charging infrastructure.

This architecture ensures:

- Higher efficiency through steady-state hydrogen operation and optimized battery usage.
- Extended range with flexible energy sourcing.
- Lower emissions compared to ICE and blended-fuel solutions.
- Scalability for both urban and intercity mobility.

2. Hydrogen–Electric Hybrid Vehicle Architecture and Engine Design

The increasing demand for high-efficiency, low-emission vehicles has motivated the development of advanced hydrogen–electric hybrid architectures. The proposed system combines a hydrogen-fueled energy conversion unit, high-capacity lithium-ion battery, and a permanent magnet synchronous motor (PMSM) under a supervisory control strategy that optimizes energy allocation across multiple driving conditions. By decoupling the hydrogen engine from direct wheel torque and employing predictive energy management, the vehicle maintains high efficiency while reducing hydrogen consumption and ensuring battery longevity. This architecture supports extended urban and highway operation, smooth mode transitions, and peak power delivery during high-demand scenarios, offering a compact and cost-effective alternative to fuel-cell-only or conventional hybrid powertrains. The following sections provide a detailed description of the powertrain architecture, engine design, energy management strategy, thermal and safety systems, and simulation-based validation:

2.1 Power Source and Energy Conversion

The vehicle utilizes a series-dominant powertrain, where hydrogen is stored in a Type-IV composite tank (350–700 bar) and delivered through a two-stage regulator to the hydrogen engine or fuel-cell stack. The hydrogen energy unit operates in steady-state high-efficiency zones (36–38% brake thermal efficiency), producing electrical power that is routed to a high-voltage DC bus. This energy simultaneously drives the permanent magnet synchronous motor (PMSM) and charges the traction battery, enabling continuous propulsion and optimized energy utilization.

2.2 Energy Storage and Distribution

A lithium-ion battery pack (30–55 kWh) provides propulsion energy for vehicle launch and transient load buffering. The system incorporates bidirectional power electronics and inverters to manage energy flow between the hydrogen unit, battery, and traction motor. During urban driving, regenerative braking recovers up to 15% of kinetic energy, maintaining battery state-of-charge (SoC) within the 50–80% range. The battery SoC naturally decreases during EV-dominant operation and triggers charge-sustaining mode when it reaches the lower threshold, allowing the hydrogen engine to supply electricity and recharge the battery.

2.3 Traction Drive

The PMSM traction motor delivers peak power of 90–120 kW to the wheels through a fixed-ratio reduction gearbox. The decoupling of wheel torque from the engine-generator ensures smooth acceleration without transient disturbances. The motor handles all dynamic torque demands while the hydrogen engine operates steadily, enabling stable, zero-emission urban driving and high-demand performance.

2.4 Operating Modes and Supervisory Control

The Vehicle Control Unit (VCU) implements a predictive Equivalent Hydrogen Consumption Minimization (EHCM) algorithm, dynamically allocating power based on speed, torque demand, and SoC. The vehicle operates in multiple modes:

- EV Mode occurs when SoC is above 50% and vehicle speed is below 50 km/h, relying solely on battery power.
- Charge-Sustaining Mode is activated when SoC reaches 50%, at which point the hydrogen engine powers the generator, supplying the PMSM and recharging the battery.
- Performance-Blend Mode engages when torque demand exceeds 200 Nm or acceleration surpasses 0.5 g, allowing the battery to supplement hydrogen-generated electricity for peak power delivery up to 140–150 kW.
- Highway Cruise Mode is maintained when vehicle speed exceeds 80 km/h with torque demand below 150 Nm, with the hydrogen engine providing 70–75% of propulsion energy while the battery buffers transient loads.

These thresholds ensure seamless mode transitions and continuous propulsion, even during extended high-speed or high-demand operation.

2.5 Engine Mechanical and Combustion Features

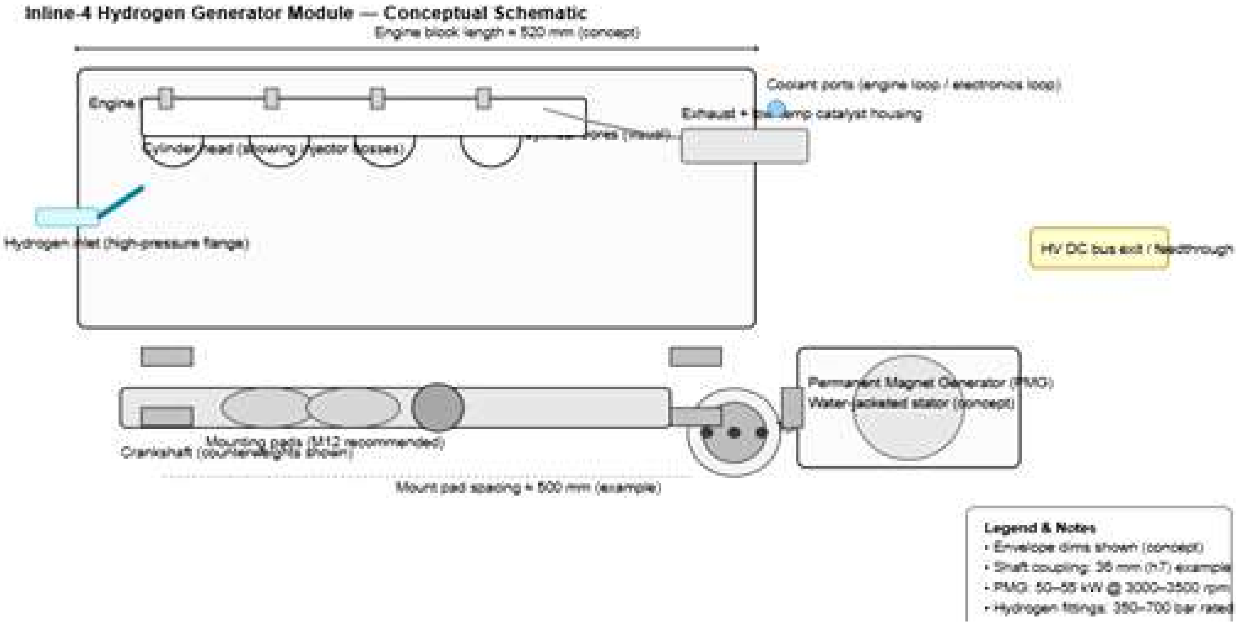
The hydrogen engine is an inline four-cylinder spark-ignition unit optimized for steady electrical generation. It features direct injection at 8–15 bar, ultra-lean combustion ($\lambda = 2.0–2.2$), cooled exhaust gas recirculation, and a high compression ratio of 12.5:1. The cranktrain is fully counterweighted and coupled to a torsionally damped permanent magnet generator, delivering 50–55 kW continuous electrical power at 3,000–3,500 rpm. Thermal management is provided by a dedicated coolant loop capable of dissipating 60–80 kW, while a low-temperature three-way catalyst ensures NOx emissions remain below 10 ppm.

2.6 Thermal Management and Safety Systems

Dual cooling loops maintain safe operating temperatures for the hydrogen engine, battery, PMSM, and power electronics. The vehicle incorporates hydrogen leak sensors, pressure relief valves, high-voltage interlocks, and an ASIL-compliant functional safety architecture, ensuring both operational reliability and regulatory compliance.

Vehicles relied on conventional internal combustion engines that were inefficient, emitted large amounts of CO_2 and NOx, and offered limited scope for hydrogen adoption. Fuel-cell vehicles, while cleaner, remained costly, complex, and prone to durability issues.

The hydrogen–electric hybrid engine operates in high-efficiency zones, drastically reducing hydrogen consumption and emissions while extending battery life. It offers a flexible and cost-effective alternative with seamless multi-mode driving for both urban and highway use.



3. Operating Modes and Energy Management with Energy Allocation

The proposed hydrogen–electric hybrid engine employs a series-dominant architecture, in which the hydrogen energy unit primarily functions as an electrical generator rather than a direct mechanical drive. This decoupling allows the engine to operate continuously within narrow high-efficiency zones, while a permanent magnet synchronous motor (PMSM) delivers variable wheel torque. Energy flow is orchestrated by a Vehicle Control Unit (VCU) implementing an Equivalent Hydrogen Consumption Minimization (EHCM) algorithm, which dynamically allocates power between the hydrogen engine, traction battery, and motor. The control strategy optimizes fuel utilization, limits battery cycling, and ensures seamless mode transitions.

3.1 EV Mode (Urban/Low-Speed Operation)

During vehicle launch and low-speed urban driving, propulsion is supplied entirely by the battery. The PMSM provides high instantaneous torque for smooth acceleration, while regenerative braking recovers up to 15% of kinetic energy. Battery SoC is maintained within a 40–80% window to prevent deep discharge and prolong cycle life. This zero-emission mode conserves hydrogen for high-demand conditions and enables efficient urban mobility. Mode transitions are triggered by vehicle speed (<50 km/h) and battery SoC (>80%).

3.2 Charge-Sustaining Mode

When the battery SoC approaches its lower threshold (<50%), the system enters charge-sustaining mode. The hydrogen engine operates at a fixed point corresponding to maximum brake thermal efficiency (36–38%), driving a generator to supply continuous electrical power. The generated energy is simultaneously directed to the PMSM and battery, maintaining propulsion while stabilizing SoC. By decoupling engine speed from transient road loads, the architecture eliminates inefficiencies typical of conventional ICE vehicles.

3.3 Performance-Blend Mode (High-Demand Operation)

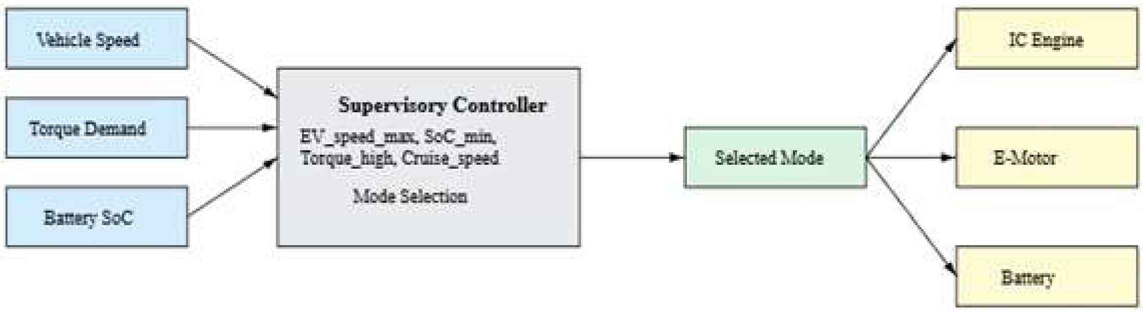
For rapid acceleration, steep gradients, or high instantaneous power requirements, the system enters performance-blend mode. The hydrogen engine continues steady-state generation while the battery supplements additional current to meet peak demand. This cooperative allocation enables peak wheel power of 140–150 kW, minimizes torque ripple (<5%), prevents voltage sag, and reduces mechanical and thermal stress on the hydrogen unit. Mode transitions are initiated based on torque demand thresholds and vehicle acceleration rates.

3.4 Highway Cruise

During steady highway driving, the hydrogen engine supplies the majority of propulsion energy at its most efficient RPM, contributing 70–75% of the load, while the battery buffers transient fluctuations such as overtaking or minor gradients. SoC variations are maintained within ±5%, and hydrogen consumption is reduced to 8–10 g/km. Overall system efficiency from hydrogen LHV to wheel output stabilizes at 31–33%, with total system efficiency exceeding 78% and peaking at 82%.

3.5 Supervisory Control and Energy Management

The VCU continuously monitors vehicle speed, torque demand, and SoC to determine optimal mode transitions. The EHCM algorithm ensures minimal hydrogen consumption by balancing short-duration hydrogen-assisted operation with extended EV drive, while protecting battery longevity. By maintaining the hydrogen engine within high-efficiency zones and assigning dynamic transient loads to the PMSM and battery, the system achieves superior energy utilization compared to conventional fuel-cell-only or hybrid architectures.



4. Simulation and Performance Validation

The hydrogen–electric hybrid system was evaluated using a comprehensive MATLAB/Simulink simulation framework, integrated with Cantera for hydrogen reaction kinetics and Simscape for battery and motor dynamics. This setup allowed real-time interaction between the hydrogen engine, generator, traction motor, and battery, simulating standardized driving cycles including urban stop–go, combined, and highway profiles. The simulation validated mode transitions, energy allocation, and system efficiency under various operational scenarios.

During pure EV operation, the lithium-ion battery supplied all propulsion energy, while regenerative braking recovered up to 15% of kinetic energy in urban conditions. The battery state-of-charge (SoC) was maintained within 40–80%, preventing deep discharge and extending battery life. Propulsion efficiency exceeded 88%, confirming zero-emission short-range capability.

When the SoC approached the lower threshold of 50%, the system transitioned into charge-sustaining mode, activating the hydrogen engine to operate in its high-efficiency range (36–38% brake thermal efficiency). The generator supplied 60–70 kW of electrical power, simultaneously driving the traction motor and recharging the battery. Hydrogen consumption in this mode averaged 9–11 g/km, significantly lower than conventional fuel-cell-only systems. Under performance-blend conditions, the hydrogen engine provided steady base power while the battery supplemented additional current to satisfy transient torque demands during acceleration or gradient climbs. Peak wheel power reached 140–150 kW, with system efficiency above 60%. This load-sharing strategy minimized instantaneous hydrogen draw while avoiding excessive battery depletion, demonstrating the effectiveness of the EHCM supervisory control algorithm.

During highway cruise, the hydrogen engine supplied 70–75% of propulsion energy at steady RPM, while the battery compensated for transient loads. Hydrogen consumption stabilized at 8–10 g/km, and system efficiency from hydrogen LHV to wheel output was 31–33%. Torque ripple during mode transitions remained below 5%, ensuring smooth drivability. Comparative analysis against a baseline fuel-cell-only system showed an 18% reduction in hydrogen consumption and improved battery longevity due to moderated depth-of-discharge cycles. To illustrate the mode transition logic and battery management, a simplified MATLAB example is provided:

```
% Parameters
BatteryCapacity = 50;    % kWh
SoC = 0.8;               % Initial State of Charge
EV_speed_max = 50; SoC_min = 0.5;
Torque_high = 200; Cruise_speed = 80;
dt = 1; T = 100;         % step (s), total time (s)

% Preallocate
time = 0:dt:T; N = length(time);
SoC_hist = zeros(1,N); mode_hist = strings(1,N); P_batt_hist = zeros(1,N);

for k = 1:N
    % Example drive profile
    vehicle_speed = 30 + 50*sin(0.05*k);
    torque_demand = 150 + 100*cos(0.03*k);

    % Supervisory mode selection
    if SoC > SoC_min && vehicle_speed <= EV_speed_max
        mode = "EV";
    elseif SoC <= SoC_min
        mode = "ChargeSustain";
    elseif torque_demand > Torque_high
        mode = "PerformanceBlend";
    elseif vehicle_speed > Cruise_speed
        mode = "HighwayCruise";
    else
        mode = "EV";
    end

    % Battery power (simplified)
    P_batt = calculateBatteryPower(mode, torque_demand); % kW
    SoC = SoC - (P_batt*dt/3600)/BatteryCapacity;

    % Store
    SoC_hist(k) = SoC; mode_hist(k) = mode; P_batt_hist(k) = P_batt;
end

% Plot
figure;
subplot(3,1,1); plot(time,SoC_hist,'LineWidth',1.5); ylabel('SoC'); grid on
subplot(3,1,2); plot(time,mode_hist,'LineWidth',1.5); ylabel('Mode'); grid on
subplot(3,1,3); plot(time,P_batt_hist,'LineWidth',1.5); ylabel('P_{batt} (kW)'); xlabel('Time (s)'

% Dummy function
function P = calculateBatteryPower(mode,torque)
    switch mode
        case "EV", P = torque*0.05;
        case "ChargeSustain", P = -5;
        case "PerformanceBlend", P = torque*0.03;
        case "HighwayCruise", P = torque*0.02;
        otherwise, P = 0;
    end
```

This snippet demonstrates how the supervisory controller implements energy allocation based on speed, torque, and battery SoC. The function represents the EHCM-based algorithm, ensuring optimal power distribution between the hydrogen engine and battery while maintaining continuous propulsion.

5. System Operation

The proposed hydrogen–electric hybrid engine is designed to operate in a series-dominant mode, where hydrogen is utilized first to generate electricity and simultaneously charge the traction battery. Once the battery reaches its target state of charge, propulsion is transferred entirely to the electric drive. This sequential operation ensures both high efficiency and reduced hydrogen consumption.

At engine start, hydrogen stored in a high-pressure composite tank is injected into a spark-ignition unit that drives an integrated generator. The generated electrical power flows directly to the high-voltage bus, supplying the traction motor for initial propulsion while charging the lithium-ion battery pack. Within approximately 30 minutes of steady operation, the hydrogen engine restores the battery to its optimal state-of-charge range (50–80%), establishing a reserve for extended electric driving.

When the required charge level is achieved, the hydrogen engine is automatically deactivated, and the vehicle transitions into pure EV mode. In this phase, the traction motor operates exclusively on stored battery energy, providing zero-emission drive with high efficiency. Regenerative braking further replenishes the battery during deceleration and stop–go cycles, extending range without additional hydrogen use.

If the battery SoC later falls below the lower threshold, the hydrogen engine restarts in charge-sustaining mode, again supplying the generator while running at its fixed high-efficiency operating point. This cycle of hydrogen-assisted charging followed by extended EV driving minimizes total hydrogen consumption while ensuring uninterrupted mobility.

By limiting hydrogen use to short-duration, high-efficiency charging intervals, the system significantly reduces operating cost compared to continuous hydrogen or conventional fuel systems. The vehicle operates predominantly as an EV, with hydrogen serving only as an onboard enabler of range extension and grid independence. This operational logic combines the low cost and efficiency of electric drive with the flexibility and rapid refueling of hydrogen, offering a practical and scalable solution for sustainable mobility.

6. Advantages and Novelty of the Invention

The proposed hydrogen–electric hybrid architecture introduces several distinctive technical innovations that differentiate it from conventional fuel-cell-only systems, internal combustion engine (ICE) hybrids, and existing series-dominant configurations. The integration of a high-efficiency hydrogen engine, high-capacity lithium-ion battery, permanent magnet synchronous motor (PMSM), and an advanced supervisory control algorithm enables significant improvements in energy efficiency, drivability, and environmental performance.

A primary novelty lies in the Equivalent Hydrogen Consumption Minimization (EHCM) algorithm, which dynamically allocates power between the hydrogen engine and the battery based on vehicle speed, torque demand, and battery state-of-charge (SoC). Unlike conventional hybrids where the engine responds directly to transient torque fluctuations, this system decouples the hydrogen engine from wheel torque, allowing it to operate in a narrow high-efficiency band at steady RPM. This approach reduces fuel consumption, mitigates wear, and maintains thermodynamic stability under all driving conditions.

The torsionally damped generator interface between the hydrogen engine and the PMSM further enhances operational smoothness. By absorbing torsional vibrations, the interface reduces torque ripple to below 5% during mode transitions, minimizing driveline shocks and improving passenger comfort. Combined with the ultra-lean combustion operation of the hydrogen engine ($\lambda = 2.0–2.2$) and cooled exhaust gas recirculation (EGR), the system achieves high brake thermal efficiency (36–38%) while limiting NOx emissions to below 10 ppm.

Another distinguishing feature is the structured multi-mode operation:

- EV mode for zero-emission urban driving,
- Charge-sustaining mode for optimized hydrogen usage and battery SoC maintenance,
- Performance-blend mode for peak power demands, and
- Highway cruise mode with steady-state hydrogen operation and battery buffering.

The system demonstrates significant performance advantages, including:

- Up to 18% reduction in hydrogen consumption compared to fuel-cell-only architectures,
- Overall system efficiency exceeding 78%, with peak efficiency of 82% on highways,
- Extended battery life due to controlled depth-of-discharge cycles, and
- Seamless mode transitions without driveline shock, even under high torque or speed conditions.

Furthermore, the architecture is inherently scalable and adaptable to a wide range of vehicles, from passenger cars to light commercial vehicles. The combination of steady hydrogen engine operation, predictive EHCM control, and high-capacity battery energy buffering establishes a novel approach to hybrid propulsion, providing a cost-effective, compact, and environmentally sustainable alternative to conventional hybrid or fuel-cell-only vehicles.

In summary, the invention presents a patentable combination of high-efficiency hydrogen operation, predictive supervisory control, advanced mechanical damping, and multi-mode energy management, offering a transformative solution for next-generation hybrid mobility.

7. Practical Implementation and Safety Considerations

The proposed hydrogen–electric hybrid system has been designed for real-world integration into modern vehicle platforms while maintaining compliance with safety and regulatory standards. The architecture balances performance, efficiency, and packaging constraints, ensuring that all powertrain components—including the hydrogen engine, high-pressure storage tank, lithium-ion battery pack, PMSM, and power electronics—can be accommodated within standard vehicle layouts without compromising passenger space or structural integrity.

The hydrogen storage system employs a Type-IV composite tank rated for 350–700 bar, coupled with a two-stage pressure regulator to deliver stable hydrogen flow to the engine. Redundant hydrogen sensors, pressure relief valves, and safety interlocks are incorporated to prevent leaks or over-pressurization. All high-voltage electrical systems—including the traction battery, DC–DC converters, and inverter—are designed with ASIL-compliant functional safety architectures, ensuring fault-tolerant operation under abnormal conditions.

Thermal management is achieved through dedicated coolant loops for the hydrogen engine, power electronics, PMSM, and battery pack. The cooling system maintains all components within optimal operating temperatures, preventing efficiency losses and extending service life. The hydrogen engine's exhaust is treated via a low-temperature three-way catalyst, optimized for lean-burn operation, keeping NOx emissions below regulatory limits.

From a control perspective, the Vehicle Control Unit (VCU) orchestrates multi-mode operation based on vehicle speed, torque demand, and battery SoC. Mode transitions are designed to be seamless, with the EHCM supervisory algorithm predicting power requirements and adjusting engine output and battery current in real time. For example, during extended high-speed cruising, the hydrogen engine operates continuously at its optimal RPM while the battery buffers transient load peaks. Conversely, in urban stop–go conditions, the vehicle can operate entirely in EV mode, preserving hydrogen and minimizing emissions.

Safety and redundancy are further enhanced by incorporating emergency power management strategies. In the unlikely event of hydrogen engine or battery failure, the system can isolate the affected subsystem while maintaining limited propulsion using the remaining energy sources. All components are packaged with crash-resistant mounts, and the hydrogen tank is positioned to minimize impact exposure in side and frontal collisions.

Finally, the architecture has been evaluated for serviceability and scalability, enabling modular replacement of the hydrogen engine, battery modules, or power electronics. This practical design approach ensures that the vehicle can be adapted for various use cases—from urban passenger cars to light commercial vehicles—while maintaining high safety, efficiency, and durability standards.

8. Comparative Analysis and Benchmarking

To demonstrate the technical superiority and novelty of the proposed hydrogen–electric hybrid architecture, a comparative evaluation was performed against conventional fuel-cell-only systems and internal combustion engine (ICE) hybrid vehicles. Key performance metrics including hydrogen consumption, system efficiency, torque ripple, battery cycling, and peak power delivery were analyzed under standardized driving cycles.

The proposed system achieved significant reductions in hydrogen consumption, averaging 8–11 g/km across urban, combined, and highway cycles. This represents approximately 18% lower consumption compared to a baseline fuel-cell-only system, primarily due to the EHCM-based supervisory control and optimized battery-assisted load sharing. In contrast, conventional ICE hybrids exhibit higher fuel consumption in transient loads due to engine torque-following behavior, which leads to thermodynamic inefficiencies.

System efficiency was consistently superior, with overall cycle efficiency exceeding 78% and peak efficiency reaching 82% during highway cruising. In comparison, fuel-cell-only systems typically achieve 60–65% efficiency under similar operating conditions, while ICE-based hybrids rarely exceed 70% due to combustion losses during variable torque operation.

Torque ripple during mode transitions in the proposed system remained below 5%, ensuring smooth drivability without perceptible shocks. By contrast, ICE hybrids often exhibit torque ripple above 10% during transient acceleration or regenerative braking engagement. Controlled depth-of-discharge cycles for the traction battery further enhance longevity, reducing the frequency of deep cycling by more than 20% compared to conventional hybrids.

Peak wheel power delivered in performance-blend mode reached 140–150 kW, with the hydrogen engine supplying steady base power and the battery supplementing instantaneous torque. Fuel-cell-only systems are limited by fuel-cell transient response and cannot reliably deliver such high peak power without significant oversizing or additional energy storage.

A summary of comparative results is provided in Table 1.

Metric	Proposed Hydrogen–Electric Hybrid	Fuel-Cell Only	ICE Hybrid
Hydrogen/Fuel Consumption	8–11 g/km	10–13 g/km	12–15 g/km
Overall Efficiency	78–82%	60–65%	65–70%
Torque Ripple	<5%	5–8%	10–12%
Battery Depth-of-Discharge	Moderate, <50%	High, >60%	High, >60%
Peak Wheel Power	140–150 kW	100–120 kW	120–130 kW
Regenerative Energy Recovery	Up to 15%	10%	8–10%

Table 1

These results clearly illustrate the performance, efficiency, and durability advantages of the proposed hybrid architecture. By combining a steady-state hydrogen engine, predictive EHCM control, high-capacity battery, and torsionally damped generator interface, the system delivers:

- Lower hydrogen consumption,
- Higher overall efficiency,
- Smoother torque delivery, and
- Extended battery life

9. Potential Applications and Scalability

The proposed hydrogen–electric hybrid architecture is inherently scalable and adaptable, enabling deployment across a wide spectrum of vehicle types while maintaining high efficiency, reduced hydrogen consumption, and superior drivability. The modular design of the hydrogen engine, battery pack, PMSM, and power electronics allows integration into passenger cars, light commercial vehicles, and potentially medium-duty transport vehicles.

For urban passenger vehicles, the EV mode enables zero-emission operation over short distances, with regenerative braking maximizing energy recovery during stop-and-go driving. The compact hydrogen engine and torsionally damped generator allow efficient use of limited packaging space, preserving cabin and cargo volume.

For longer-range applications, including highway and intercity transport, the charge-sustaining mode ensures continuous propulsion while maintaining battery SoC above 50%, reducing the frequency of refueling stops and hydrogen consumption. The performance-blend mode enables rapid acceleration and high torque delivery, making the system suitable for both private and commercial vehicles that require high dynamic performance.

The architecture's predictive EHCM supervisory control allows energy management to be dynamically adjusted for varying vehicle weights, driving cycles, and operational conditions, supporting fleet-wide optimization in commercial or shared mobility applications. High-capacity lithium-ion battery packs can be scaled to accommodate higher payloads or extended range requirements, while the hydrogen engine can be adjusted for larger power output without compromising efficiency.

Safety and regulatory compliance have been considered across all applications. High-pressure hydrogen tanks, ASIL-compliant electrical systems, and robust thermal management ensure that the system can be deployed in diverse climates and operational conditions. The modular design facilitates easy servicing, component replacement, and system upgrades, enhancing long-term reliability and adaptability to future hydrogen infrastructure.

In summary, the proposed hybrid system provides a flexible, high-efficiency, and low-emission platform suitable for a broad range of vehicles, from urban commuter cars to light commercial fleets. Its combination of steady-state hydrogen engine operation, advanced supervisory control, and scalable battery architecture ensures that it can meet diverse mobility demands while maintaining superior performance, efficiency, and environmental compliance.

10. Conclusion

The proposed hydrogen–electric hybrid vehicle architecture represents a novel and highly efficient approach to sustainable mobility, integrating a high-efficiency hydrogen engine, high-capacity lithium-ion battery, permanent magnet synchronous motor (PMSM), and an advanced supervisory control algorithm. By decoupling the hydrogen engine from direct wheel torque and employing the Equivalent Hydrogen Consumption Minimization (EHCM) algorithm, the system achieves optimized energy allocation, reduced hydrogen consumption, and enhanced drivability across diverse operating conditions.

Simulation and comparative analyses demonstrate that the architecture consistently delivers:

- Reduced hydrogen consumption, achieving up to 18% savings compared to fuel-cell-only systems;
- High overall system efficiency, exceeding 78%, with peak efficiency of 82% under highway conditions;
- Smooth torque delivery with less than 5% torque ripple during mode transitions;
- Extended battery life through controlled depth-of-discharge cycling; and
- Scalable multi-mode operation, including EV mode, charge-sustaining mode, performance-blend mode, and highway cruise.

The hydrogen engine is specifically designed for steady-state, high-efficiency operation, employing ultra-lean combustion, cooled EGR, torsionally damped generator coupling, and optimized thermal management. Together with predictive supervisory control and regenerative energy recovery, this architecture provides a practical, safe, and modular solution suitable for passenger vehicles, light commercial vehicles, and potentially medium-duty transport applications.

The invention presents a transformative hybrid propulsion system that offers a compact, cost-effective, and environmentally sustainable alternative to conventional fuel-cell-only and ICE hybrid architectures. Its combination of high-efficiency hydrogen utilization, advanced control strategies, and modular scalability establishes a strong foundation for commercialization and patent protection, providing a next-generation solution for clean, efficient, and high-performance transportation.

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EURO 7 NORMS FOR BRAKE EMISSION

M Kandhasamy, GA Karthikeyan, B Ruban Devaprasath,
Brakes India Pvt Ltd

1. Scope & Applicability

On brake friction, regulations on asbestos, copper content, heavy metals and antimony are being practiced by different OEMs. US market demands copper free pads (< 0.5 % copper) from the year 2025. Though not a part of regulation, considering health hazards, most OEMs in Europe also insist on copper free friction and ABC free friction. Certain friction manufacturers also minimize usage of potassium titanate fibres, to avoid potential health hazards. Euro 7 regulations, for the first time, covers non exhaust emission - brake emission and tyre emission. With respect to brake emission, Euro 7 covers passenger (M1–M3) and goods vehicles (N1–N3), and certain trailers (O3–O4). Euro 7 regulation expects a 27% reduction of particles from the brakes. Current detailed criteria for brake particulate emissions are defined for M1 and N1 categories (≤ 3.5 t). The regulation is technology neutral and applies to ICE, hybrids, and BEVs. Compliance is to be demonstrated on a GTR-24-compliant brake dynamometer; there is no on-vehicle brake PM test requirement.

2. Regulatory & Research Activities behind Euro 7 — Global Overview

In 2013, UNECE WP.29 agreed with the GRPE decision to task the Informal Working Group on Particle Measurement Programme (IWG on PMP) to investigate the issues concerning the emissions of non-exhaust emissions of particles from road transport. The main objective of the IWG on PMP was to investigate whether there is a need to extend particle measurement procedures to additional sources such as brake, tyre, and road wear. With regards to brake wear emissions, the primary task of the IWG on PMP has been to define a suitable duty cycle - a set of "normal" or "typical" driving conditions, investigate the suitability of existing driving cycles for studying brake particle emissions, and develop a novel test cycle reproducing the driving and braking activity of Light-Duty vehicles in real-world conditions. Other main tasks included the broadening of the IWG on PMP to include non-exhaust experts, the development of guidelines and best practices for sampling and measuring brake wear particles, and the establishment of minimum requirements to report test results

2.1 UN GTR No. 24 (WLTP-Brake)

The UN GTR WLTP-Brake cycle is a standardized laboratory test cycle defined by UN GTR No. 24 to measure particulate matter (PM) (PM10, PM2.5) and particle number (PN) (≥10 nm) emissions from brake wear in light-duty vehicles. This cycle is derived from real-world driving data and uses a brake dynamometer to simulate typical braking conditions, providing a consistent and comparable method for assessing brake emissions and their impact on air quality

2.2 UNECE Particle Measurement Program (PMP) Task Forces

TF#1 — Platform & Cycle Execution:

Objective: Demonstrate that the WLTP-Brake cycle can be executed on an inertia brake dynamometer with control accuracy, repeatability & Reproducibility.

TF#2 — Protocol Definition (LDV/ICE focus): Minimum measurement requirements (PM gravimetry, PN), sampling plane geometry, airflow control, and reporting structure.

TF#3 — Interlaboratory Validation: Designed and ran ILS campaigns across multiple labs, vehicles and layouts to characterize R&R and to underpin Euro 7 limit-setting.

Participants: 16 laboratories (OEMs, Tier 1 suppliers, dyno manufacturers, universities). Tested 5 vehicle platforms - Hatchback (Low-Metallic & NAO), Mid-size sedan, SUV, Drum brake & Cargo van (light and heavy load)

Varied dynamometer layouts, emission instruments, and DAQ systems.

Outcome: Validated repeatability and reproducibility of brake PM/PN measurements and supported Euro 7 limit setting.

TF#4 — EV/HEV Methodology: accounting for regenerative braking (friction-share)

Thanks to these task forces, guidelines could be framed on the following factors, beyond the duty cycle establishment, test setup etc.,

1. Test system requirements

- Overall layout for the test system
- Climatic conditioning unit and cooling air
- Brake dyno and automation systems
- Brake enclosure – duct design
- Design of sampling tunnel
- Sampling plane

2. Emission measurements

- Measurement of particulate matter mass
  - Particle matter (PM) Extraction (Sampling plane, sampling probes, nozzles)
  - PM sampling (Separation device, sampling line, sampling flow etc.,)
  - Sampling media
  - Weighing procedure
- Measurement of particle number concentration
  - Sample extraction
  - Sample treatment and conditioning
  - Particle measurement (PN counter and PN sampling flow)
  - PN emission calculation
  - PN system verification procedures
- Test output
  - Event based file
  - Time based file
  - Mass measurement file
  - Test report file

3. Calibration requirements and ongoing quality controls

- General Calibration requirements
- Dynamometer – Calibration requirements
- Cooling air flow measurement device – Calibration requirements
- Particle mass and mass loss scales
- Sample treatment and conditioning devices
- Particle number counter

2.3 JASO C470:2020

JASO C470:2020 is a Japanese standard developed by JSAE that specifies the test procedures for measuring brake wear particle emissions from passenger cars using a brake dynamometer. Focuses on airborne particulate matter (PM) generated during braking, including PM10 and PM2.5, under controlled laboratory conditions.

2.4 Quick Comparison

JASO C470 (Japan)	UN GTR	
Scope / Applicability	Passenger cars; brake dynamometer per JASO C470	M1/N1 LDVs; applies to ICE, HEV, BEV;
Instrument required	PM mass equipment Mass concentration unit	PM Mass equipment Solid PN + VPR Total PN + Dilluter
Primary Metrics	PM10, PM2.5; PN	PM10 limits (e.g., 3/7/11 mg/km) & Background PN PM 2.5, SPN, TPN
Test Cycle	Wear schedule: Urban Road mode & highway mode	WLTP-Brake cycle
Air condition	23±5°C 20-80% RH	20±5°C 30-60% RH
Regenerative Braking Treatment	No fixed coefficients; regen not explicitly addressed.	Fixed coefficients by powertrain (e.g., BEV 0.17, HEV 0.72).
Legal Limits / Durability	Not defined	PM10 limits and 200,000 km / 10 years durability.
Thermocouple	0.5mm depth on disc	1mm depth on disc 1mm depth on pad

Fig (1) Particulate size

3. Limits, Durability & Targets

Euro 7 sets PM10 brake emission limits for light-duty vehicles, with durability requirements of 200,000 km or 10 years Overall policy intent is at least a 50% reduction in brake particle emissions by 2030, with further tightening thereafter.

3.1 PM10 Emission Limits (per vehicle powertrain)

Vehicle Category	Powertrain	PM10 Limit (mg/km)	Other Requirements
M1, N1 (except class 3)	Pure Electric Vehicles	3	Durability: 200,000 km or 10 years
M1, N1 (except class 3)	Hybrid-Electric Vehicles	7	Durability: 200,000 km or 10 years
N1 class 3	Pure EV / Hybrid & ICE	5 / 11	Durability: 200,000 km or 10 years

EV / Hybrid Type	Coefficient c
Battery Electric Vehicle (BEV)	0.17
Plug-in Hybrid Electric Vehicle (PHEV)	0.34
Full Hybrid (REESS > 60 V)	0.52
Mild Hybrid (20 V < REESS ≤ 60 V)	0.72
Mild Hybrid (REESS > 60 V)	0.90
ICE Vehicle	1.00

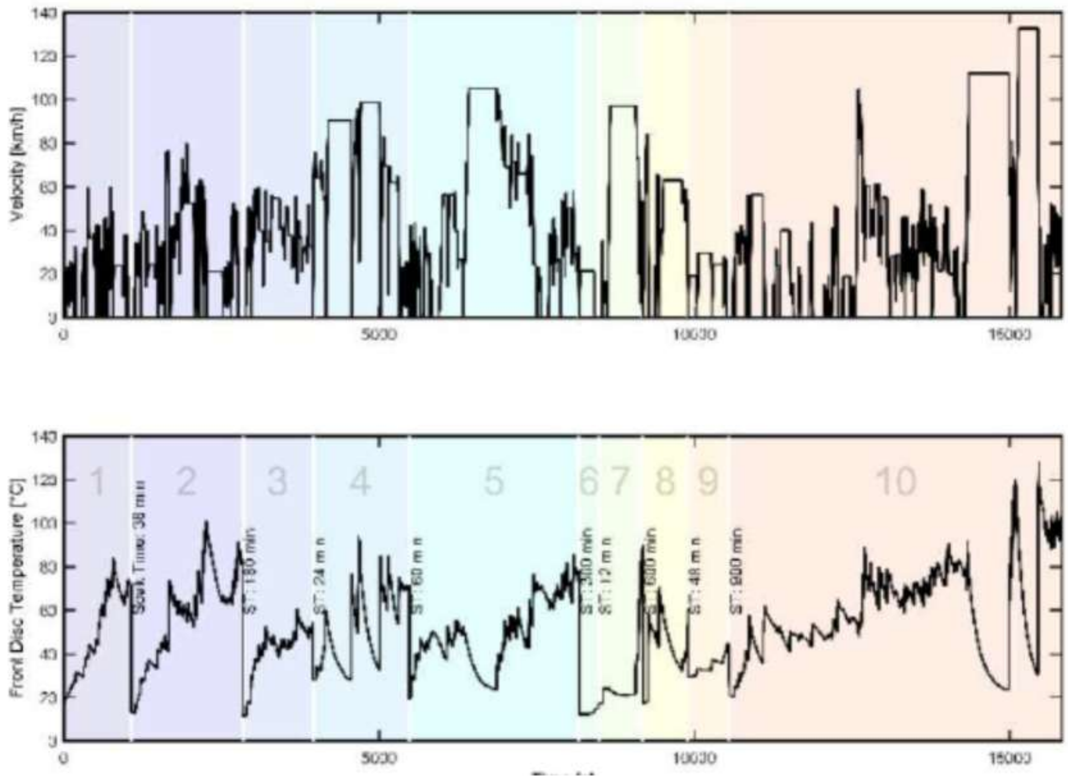
4. Regenerative Braking Coefficients (c)

Euro 7 applies fixed coefficients to account for the proportion of deceleration handled by regenerative braking. Multiply the reference PM10 emission factor from the dyno test by c to obtain the final brake emission factor.

In the latest version of GTR 24, procedure has been introduced that allows OEMs to determine a vehicle-specific friction braking share coefficient (c) using a chassis dynamometer instead of relying only on default fixed values. Disc corrosion is still a major challenge to be addressed in electric vehicles, since lesser friction working leads to lesser rust removal on discs. Which can lead to higher brake emission. FNC coatings are proven to be useful for corrosion prevention in NAO pads but uncoated discs still pose a challenge.

5.Measurement Method: WLTP-Brake (UN GTR No. 24)

Brake emissions are measured on a fully enclosed brake dynamometer using the WLTP-Brake cycle. The cycle consists of 10 trips with increasing average speed, totaling 303 brake applications, 192 km, and ~4 h 24 min. Soak periods between trips cool the disc to ~40 °C before each trip.



Parameter	Value
Trips	10
Total Brake Applications	303
Total Distance	192 km
Net Duration	4 h 24 min
Average / Max Speed	43.7 km/h / 132.5 km/h
Disc Temperature Control	Soak to ~40 °C between trips
Applied 'g' level	Min - 0.49 m/s2; Max – 2.18 m/s2**

*** Actual driving cycles may include 'g' levels more than 0.3 g also (3.0 / m/s2). Certain friction material is also designed to provide higher friction at higher 'g' through higher pad wear, but since this contributes to less than 10% of overall duty cycle for most terrains this is not considered in the above duty cycle.*

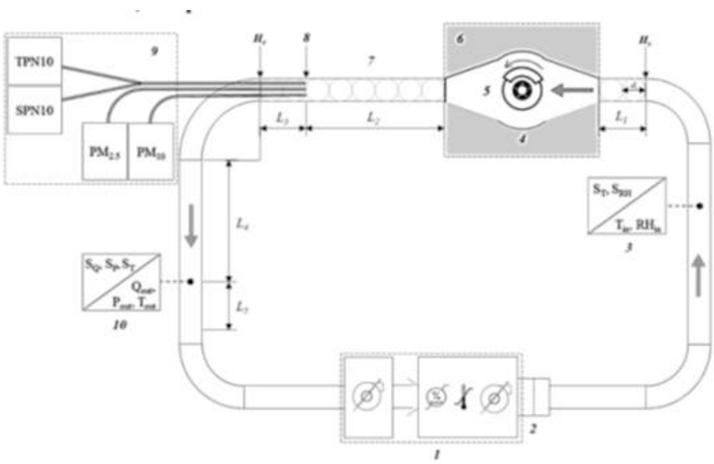


Fig (2): Typical emission dyno set up

5.1 GTR-24-Compliant Dyno Setup

1. Climatic conditioning unit with variable flow blower(s), air temperature, and air humidity control
2. Cooling air filtering medium
3. Cooling air temperature and humidity sensors;
4. Brake enclosure
5. Brake assembly
6. Brake dynamometer (not shown)
7. Sampling tunnel
8. Sampling plane
9. PM and PN instrumentation
10. Air flow rate measurement element.

5.2 Alternate method using Chassis Dynamometer

Purpose

The chassis dynamometer (chassis dyno) plays an indirect but critical role in brake emission testing. While brake particulate emissions are measured on a brake dynamometer, the chassis dyno is used to determine the regenerative braking share for electrified vehicles (BEVs, HEVs, PHEVs). This is essential for adjusting brake emission results to reflect real-world driving conditions.

How It Works

1. The vehicle is tested on a chassis dynamometer using a WLTP or similar drive cycle.
2. Data is collected on total braking energy and the portion recovered through regenerative braking.
3. The friction braking share (c) is calculated as:
   c = (Friction braking energy) / (Total braking energy)
4. This coefficient is applied to brake dyno test results to adjust PM10 emissions accordingly.

Benefits

Provides vehicle-specific coefficients for more accurate emission results.
Enables OEMs to optimize regenerative braking strategies.
Confirms real-world performance of regenerative systems.
Offers flexibility in compliance with Euro 7 standards.

6. Friction Material Strategy:

The choice of friction pair and rotor technology materially affects PM emissions, durability, and NVH.

With conventional grey cast iron discs, typical NAO (Non asbestos organic) friction might be able to meet the Euro 7 norms quite comfortably depending upon the friction pad area. Unlike European market, Passenger vehicle segment including many compact SUVs in Indian market is mostly dominated by NAO friction giving us a specific advantage with respect to emission. Typical emission results of NAO Vs low steel friction are givcen below

Low steel friction which dominates the European market due to certain requirements like AMS, lacks this advantage mainly due to high disc wear. Hence low steel friction often requires discs with special coating to minimize the disc wear. Many friction suppliers already have developed low steel friction material grades to reduce wheel black dust. Still these low steel grades may not be able to meet the Euro 7 norms when adopted with conventional grey cast iron discs. With regeneration on vehicle, this can be possible, depending upon the level of regeneration.

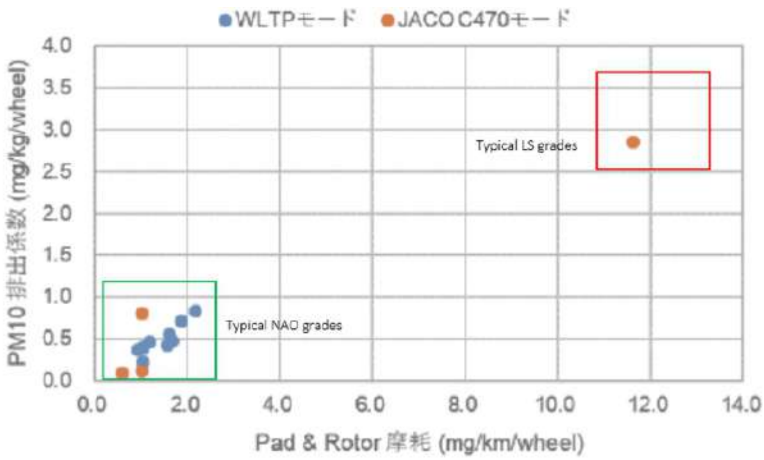


Fig (3): Typical NAO & LS grade emission test results

To strike a compromise between high temperature performance, emission between low steel friction and NAO friction, many friction suppliers have developed high performance NAOs which can meet the emission requirements similar to NAO material, but at the same time meet the AMS requirements. However High temperature wear (> 350 deg) and very high temperature performance (> 500 deg) could still be a compromise compared to low steel friction.

Aspect	NAO	Low Steel (LS)	High-Performance NAO
ICE Vehicles	Meets without disc modification	Often needs coated discs (e.g., TiN/Tungsten carbide) for emissions & stability	Can Meet without disc modification; lower dust & rotor wear
Strong Hybrids / EVs	Meets with GCI disc	Some grades can work without disc modification depending upon level of regen	Can Meet with GCI disc
Thermal Performance	Low	Superior at higher decel/temperature	Moderate
Durability & Wear	Low	Higher pad life in demanding duty	Low
NVH	Good for NVH;	Tunable with shims/coatings	Good for NVH
AMS Compliance	Can't meet the requirement	Meets with standard stopping distance	Depending upon disc mass /temperature May require compromise on stopping distance
Cost / Time	Low	Higher for ICE (disc coating). Friction finetuning could involve development time	Low

7. Rotor Surface Technology

Brake wear PM originates from third-body layer formation and disruption at the pad–disc interface. Disc Surface hardness, chemistry, and texture influence oxide-tribofilm stability, pad aggressiveness, and adhesion/brittleness of debris, all of which affect PM10 mass and PN ≥10 nm. Coatings and surface treatments on the disc can stabilize the interface, reduce adhesion wear, lower corrosion-assisted flaking, and cut PM mass without compromising friction targets when correctly matched to friction material.

Rotor selection should be tailored to the vehicle type and the extent of regenerative braking, with OEMs choosing appropriate disc coating technologies accordingly. Once the rotor surface is defined, the friction material grade might require minor finetuning to ensure compatibility and optimal performance.

The following table consolidates rotor surface technology data (surface hardness, roughness, and friction-material compatibility) to select rotor treatments aligned to Euro 7 brake PM objectives and friction pairing.

Option	Typical Process	Key Benefits	Risks / Watch-outs	Best Suitable	PM Impact (qual.)
GCI (Base)	Cast iron + machining	Low cost; proven NVH	Higher corrosion; higher PM in aggressive duty cycles	NAO / High performance NAO	Baseline
FNC (Ferritic Nitrocarburizing) on GCI disc – Single layer coating	Thermochemical diffusion	Corrosion resistance; Reduced wear ↓; stable µ	Bedding sensitivity; possible µ jump if too smooth	NAO / LS – High Regen vehicle / High perf NAO	↓ Reduced PM mass
HVOF Carbide (e.g., WC-Co) – Single layer coating	High-velocity oxy-fuel spray	Very hard; wear & dust ↓; thermal stability	Cost; brittle chips if impact; bedding critical	LS / severe ICE duty	↓↓ PM mass
Laser-clad + PVD topcoat (e.g., TiN/TiCN) – Double layer coating	Laser cladding + thin hard top layer	Thermal barrier + low wear; durability	Process complexity; run-out control; cost	LS / mixed duty	↓↓ PM mass

While the above rotor coatings can work with low steel friction meeting Euro 7 norms, cost of coating is still higher considering the volumes and emerging technology. Hence, in these cases, high performance NAOs serves as a compromised solution - which show promise in emissions reduction and also meet European performance requirements like AMS (lesser thermal stability compared to Low steel but better than conventional NAO material)

Material Type	GCI	Single / FNC coated rotor	Double coated / laser cladding with Tic Coated rotor
NAO		✓	
High Performance NAO	✓✉	✓	
Low Steel	×	×	✓

** Some HP NAO required Single coated rotors (FNC) & expecting minor performance drop*

Conclusion and Way forward:
With the above scenario, friction suppliers in India are in the process of evaluating their friction grades for compatibility against Euro 7 norms. To start with, friction suppliers are equipping themselves with dyno capability to evaluate emission in line with GTR 24 standard.

High performance NAOs is also being developed to cater to the new requirements of AMS combined with low emission. With EV penetration increasing and more regeneration options available, Indian OEMs are moving forward towards reduction of emission. Some OEMs have already migrated from Low steel friction to NAO even in some of the SUVs with ICE version and even in some bigger electric SUVs also, which aids both from a noise perspective as well as emission perspective. Pick up segment vehicle is one segment where low steel grades are still preferred to cater to the higher mue level at higher overload conditions also. Friction suppliers are also working for low steel friction grades which can give lesser black dust / lesser emission and which can work with certain amount of regeneration on vehicle. Overall, we are better positioned as Indian market is already dominated by vehicles with NAO friction. Though calipers have started penetrating in rear brakes of SUVs, still most Indian vehicles have traditional drum brakes giving lesser emission – which is another advantage for us. Where emission requirements are not met, the regen strategy needs to be reviewed along with rotor / friction selection.

8. References

- UNECE PMP & UN GTR No. 24 – UNECE: Global methodology to measure particle emissions from vehicles braking
- Euro 7 Regulation: Regulation (EU) 2024/1257: Euro 7 emission limits for exhaust and non-exhaust (brake PM10)
- JASO C470: Japanese standard for brake emissions measurement
- Interlaboratory Studies

About Brakes India:

Brakes India is a leading supplier of braking systems in the Indian market and a global supplier of ferrous castings, for passenger vehicles, light commercial vehicles, heavy commercial vehicles & tractors. Promoted by the TSF Group, whose heritage dates to 1936, the company has a strong in-house R&D capability, that includes state of the art test facilities and a high-speed test track built to international standards, with revenues in excess of INR 7000 crores.

Acknowledgment

We extend our sincere thanks to our friction material partners - **Allied Resonac Brake India Pvt. Ltd. (ARBI), Apache, Rane Brake Lining (RML – BCD), ITT Motion Technologies, and Sangsin Brakes -** for their valuable contributions and technical insights on brake emission control.

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High Performance DPF Substrate Development for upcoming BSVII Norm

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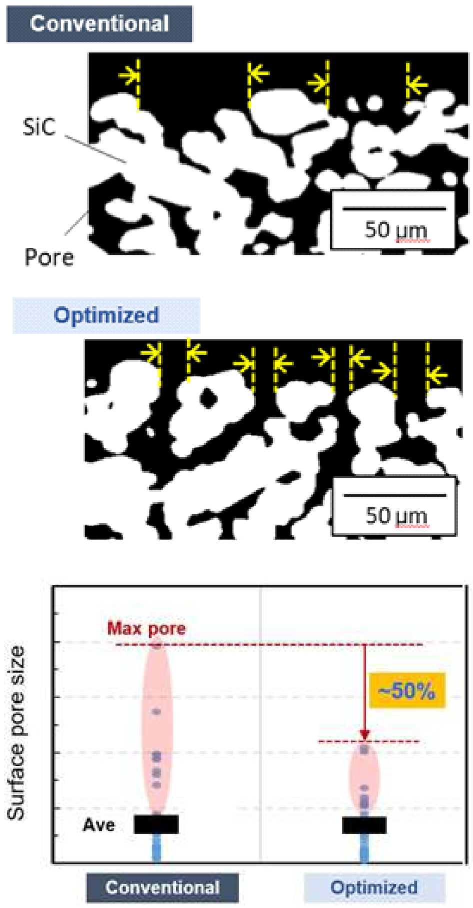
Abstract
Diesel Particulate Filter (DPF) being crucial component of the ATS system & key requirements for DPF are high filtration performance for soot particles and low-pressure loss. DPF can exhibit a wide range of performance characteristics through optimized cell and pore structures and combination of catalyst coating, enabling various design approaches. Based on our extensive ceramic technology expertise, IBIDEN offers robust DPF solutions customized to meet regulation demands and specific requirements of OEMs, thereby contributing to improved exhaust gas purification. In this study, DPF designs optimized to meet individual needs through evaluations done internally and proprietary simulation technologies are explained.

Keywords
Diesel Particulate Filter; Robustness; Filtration; Emission

1. Introduction
The upcoming Bharat Stage 7 (BS7) emission norms will likely introduce more stringent regulations aimed at reducing vehicular pollution, with a focus on cutting down particulate matter (PM), nitrogen oxides (NOx), and other harmful emissions which will be much similar to Euro 7. This will demand the development of advanced Diesel Particulate Filter (DPF) substrates that can meet these tougher emission standards.

2. Methodology
High temperature sintering is used to re-crystallized silicon carbide, which is what IBIDEN DPF, or silicon carbide DPF, is. Thus, we refer to this as R-SiC, which stands for pure SIC material. Three characteristics of R-SiC are its sharp pore distribution, excellent thermal conductivity, and strong chemical resistance. Each attribute contributes to DPF performance through filtration, heat resistance, and exhaust gas/ash resistance. The DPF substrate's pore distribution is depicted in this graph; the bulk line represents R-SiC, while the other lines represent different materials. Shape pore distribution, which denotes homogeneous pore and lack of large pore, is what our R-SiC is. As PN is easily classified and gas passes homogeneously, this contributes to good filtration efficiency.



3. Results and Discussion
Improving filter pore size distribution and designing more dense substrate structures can enhance the ability to capture ultrafine particles. Filters might need additional coatings or a secondary filtration mechanism, like wall-flow SiC substrates with optimized porosity, to ensure trapping of particles below 10 nm

Ibiden has developed graded pore structure as can be seen in reduction of around 50% of maximum surface pore size which will be main character for the filtration efficiency.

4. Conclusion
According to more strict emission norm, engine calibration and ATS need to be robust. IBIDEN continues to investigate product improving and continue that.

In point of PN filtration, Filtration performance related to input condition, Additionally, IBIDEN R-SiC DPF contributes to ATS design flexibility due to VPL technology and safety 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.

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Enhanced Role and Life for ICEVs in the New Scenario of considering Tailpipe Emission vs LCA Approach

Neelkanth Marathe
Executive Director, Emission Controls Manufacturers Association (ECMA)

The global transportation sector is undergoing one of the most disruptive transitions in its history. Driven by climate change concerns, air quality deterioration, and energy security challenges, governments and industries are accelerating the shift toward electrification. Battery Electric Vehicles (BEVs) are positioned as the "zero-emission" solution, and Internal Combustion Engine Vehicles (ICEVs) are increasingly portrayed as outdated, unsustainable, and environmentally harmful.

This narrative has emerged from a tailpipe emission-centric approach, where vehicles are judged primarily on the basis of what comes out of the exhaust pipe. In such a framework, ICEVs are the villains and BEVs the saviours. However, the ground reality is far more complex.

The transition from a regulatory focus on tailpipe emissions to a more holistic Life Cycle Assessment (LCA) of vehicles is becoming notable that is poised to fundamentally redefine the role of the internal combustion engine vehicle (ICEV). While tailpipe regulations have pushed for cleaner exhaust, an LCA approach considers emissions from "cradle to grave"—from raw material extraction and manufacturing to the vehicle's use and end-of-life disposal. This broader perspective reveals that ICEVs, especially those using advanced fuels and technologies, have a more nuanced and potentially enhanced role in a sustainable future than previously assumed.
A paradigm shift is now underway. Policymakers, researchers, and industries have begun to recognize that focusing solely on tailpipe emissions would be inadequate for addressing sustainability challenges. Instead, Life Cycle Assessment (LCA), which evaluates the total environmental footprint of a product from cradle to grave, offers a more holistic lens. This includes raw material extraction, energy use in manufacturing, logistics, vehicle operation, and end-of-life recycling.

The Shift from Tailpipe to Life Cycle:

For decades, the automotive industry has been governed by regulations centered on a vehicle's tailpipe emissions. The Euro standards in Europe, BHARAT norms in India and similar norms worldwide have successfully reduced harmful pollutants like NOx, carbon monoxide (CO), and particulate matter (PM) from vehicle exhausts. These regulations, however, create a misleading "zero-emissions" narrative for electric vehicles (EVs) by ignoring the significant carbon footprint associated with their production, particularly the battery.
An LCA methodology, on the other hand, offers a more accurate picture by accounting for all stages of a vehicle's life. This includes:

- Raw Material Extraction and Processing: The mining of resources like lithium, cobalt, and nickel for EV batteries is energy-intensive and has considerable environmental and social impacts. For ICEVs, this stage involves the extraction and refining of petroleum.
- Manufacturing: The production of a battery-electric vehicle (BEV) is currently more carbon-intensive than that of an equivalent ICEV, largely due to the energy required to manufacture the high-voltage battery.
- Vehicle Usage: This is the phase traditionally targeted by tailpipe regulations. For ICEVs, it's where the majority of emissions occur. For EVs, it depends on the carbon intensity of the electricity grid used for charging.
- End-of-Life: The disposal and recycling of vehicle components, especially the complex and heavy batteries in EVs, present a new set of environmental challenges.

By adopting an LCA framework, policymakers will be able to make more informed decisions based on a complete understanding of a vehicle's environmental impact. This new regulatory landscape will move the conversation beyond a simple statement "EVs are good, ICEVs are bad".

Disclaimer:
The views and perspectives expressed in this technical article are solely of the author and shall not be considered as the official views and perspectives of the ECMA organisation the author belongs to.

Key Insights from Global LCAs:

- BEVs have 30–60% higher embodied emissions at manufacturing stage (largely from battery production). It is dependent on grid cleanliness — in coal-heavy grids, BEVs may emit more CO_2 per km than efficient ICEs. Recycling challenges remain unresolved, especially for lithium-ion batteries.
- ICEVs have Lower manufacturing footprint. Its use-phase emissions depend on fuel quality. With low-carbon or renewable fuels (biofuels, hydrogen, e-fuels), LCA performance improves drastically.
- Thus, LCA does not declare BEVs as universally superior. Instead, it highlights that sustainability depends on context — fuel pathways, grid mix, infrastructure, and recycling systems.

With an LCA perspective, the ICEV's position changes from a legacy technology to a key player in a diversified, low-carbon mobility ecosystem. The focus shifts from elimination to optimization.

The Decarbonization of Fuels

One of the most significant advantages of the ICEV under an LCA framework is its potential to operate on low-carbon or carbon-neutral fuels. Future of ICEVs lies in their ability to use advanced alternatives.

- Biofuels: Biofuels derived from biomass like algae, agricultural waste, or sustainable crops can significantly reduce the well-to-wheel emissions of an ICEV. When produced sustainably, their carbon footprint can be much lower, as the CO2 released during combustion is offset by the CO2 absorbed by the plants during their growth.
- Synthetic Fuels (e-fuels): These are liquid hydrocarbons produced by combining captured CO2 from the atmosphere or industrial processes with hydrogen from renewable electricity (green hydrogen). When e-fuels are used in an ICEV, the CO2 released during combustion is the same CO2 that was captured to create the fuel, effectively making it carbon neutral on a life-cycle basis. This "closed-loop" carbon cycle is a game-changer.
- Hydrogen: While fuel cell vehicles (FCEVs) are a separate category, a modified ICE can also be designed to run on hydrogen. This offers a different approach to hydrogen mobility, leveraging existing engine and refueling infrastructure with a near-zero tailpipe emission profile.

By focusing on fuel decarbonization, the LCA of an ICEV can be dramatically improved without the need for the resource-intensive battery manufacturing required for EVs.

Hybrid and Plug-in Hybrid Vehicles

Hybrid Electric Vehicles (HEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) offer a compelling middle ground in an LCA-driven future. They combine the efficiency of an electric motor with the range and power of an ICE, reducing overall fuel consumption and emissions.

- HEVs: These vehicles improve fuel efficiency by using an electric motor to assist the ICE, especially in stop-and-go traffic. Their LCA is significantly better than a conventional ICEV.
- PHEVs: With the ability to drive on electric power for a certain range and recharge from the grid, PHEVs offer the best of both worlds. They have a lower carbon footprint than HEVs, particularly when charged with clean electricity, and their smaller batteries make their manufacturing footprint much less than a pure BEV. This makes them an attractive solution for consumers who need the flexibility of an ICE for long-distance travel but can handle daily commutes on electric power.

The Continued Viability of ICEV for Heavy-Duty and Long-Haul Transport

While BEVs are a great solution for urban passenger cars, their limitations in range, payload, and charging time make them less suitable for certain applications. This is where ICEVs, particularly those using advanced fuels, will maintain a crucial role.

- Trucking and Logistics: The sheer weight of batteries required for a long-haul electric truck would significantly reduce its payload capacity and increase its charging time. A diesel or hydrogen ICE truck, on the other hand, can be refueled in minutes and has a much longer range, making it the more efficient and economically viable option for long-distance freight. The use of advanced biofuels or synthetic diesel in these trucks could make them a low-carbon solution.

- Commercial Vehicles: For applications like emergency services, construction, and agriculture, the reliability and quick refueling of an ICE are critical. A zero-tailpipe emission mandate would be impractical for these sectors. An LCA-based approach allows for the use of advanced ICEVs with cleaner fuels to reduce their overall environmental impact.

The New Role for ICEVs

Under an LCA framework, the ICEV's environmental impact is no longer solely judged by its exhaust fumes. This holistic view enhances the role of ICEVs in several ways:

- Manufacturing Advantage: The production of ICEVs, while still impactful, is generally less carbon-intensive than that of battery electric vehicles (BEVs). The manufacturing of large battery packs for BEVs, including the mining and processing of materials like lithium and cobalt, contributes a significant portion of their total life-cycle emissions. In contrast, ICEVs have a lower "upfront" carbon footprint.
- Fuel and Power Grid Considerations: An LCA highlights the critical link between the vehicle's fuel source and its overall emissions. ICEVs can be optimized for cleaner fuels, such as biofuels or synthetic fuels, which can significantly reduce their well-to-wheel (or cradle-to-grave) emissions. Additionally, in regions where electricity grids are still heavily reliant on fossil fuels, a BEV's charging emissions can be high. In such scenarios, a modern, fuel-efficient ICEV can have a comparable or even lower life-cycle carbon footprint than a BEV.
- Hybridization and Efficiency: The LCA approach also underscores the value of hybrid and plug-in hybrid electric vehicles (PHEVs) that use an ICE. These vehicles can offer a practical, immediate solution to reduce emissions, especially in markets where full BEV adoption is challenging. They leverage the efficiency gains of electric motors while still using a proven and reliable power source for longer journeys, effectively bridging the gap between current technology and a fully decarbonized future.

Life for ICEVs in the New Scenario

The shift to an LCA approach doesn't eliminate ICEVs but rather forces a re-evaluation of their place in the industry. Instead of being completely phased out, ICEVs will likely see an enhanced and more specialized life:

- Continued Presence in Specific Markets: ICEVs are expected to remain the dominant vehicle type in regions with less developed charging infrastructure or with electricity grids that are not yet "green." Their simplicity and established refueling network make them a more viable option for many consumers and businesses.
- Focus on Fuel and Engine Technology: Future ICEV development will focus on maximizing efficiency and compatibility with low-carbon fuels. This means a greater emphasis on advanced engine designs, weight reduction, and the integration of mild-hybrid systems. The goal is to make the ICEV's operational phase as clean as possible to reduce its overall life-cycle impact.
- Complementary Role to EVs: Instead of being direct competitors, ICEVs may play a complementary role to EVs. They could be used for specific applications, like heavy-duty trucks, long-haul transportation, or in rural areas where the limitations of EV range and charging infrastructure are most pronounced. This allows for a more pragmatic and gradual transition to a low-carbon transport sector.

The Indian Context

India is a unique case where ICEVs may enjoy an enhanced role under LCA:

- E20 Program: Nationwide ethanol blending by 2025.
- Bio-CNG & LNG: Growing adoption in commercial transport.
- Hydrogen Pilots: For buses, trucks, and even 2/3-wheelers.
- Affordability: ICEVs remain cost-effective for consumers.
- Grid Mix: With 70% coal-based electricity, EVs may not yield net GHG reduction in the short term.

Thus, India's path to sustainable transport will be multi-technology, not EV-only. ICEVs running on renewable fuels will remain crucial.

Looking ahead, ICEVs will not disappear but will evolve:

- ICE + E-fuels: Carbon-neutral liquid fuels make existing infrastructure relevant.
- ICE + Hydrogen: Especially for heavy-duty transport.
- ICE + Hybridization: Small batteries, big efficiency gains.

The new mobility ecosystem will be diversified: BEVs, FCEVs, hybrids, and clean ICEVs coexisting.

Conclusion

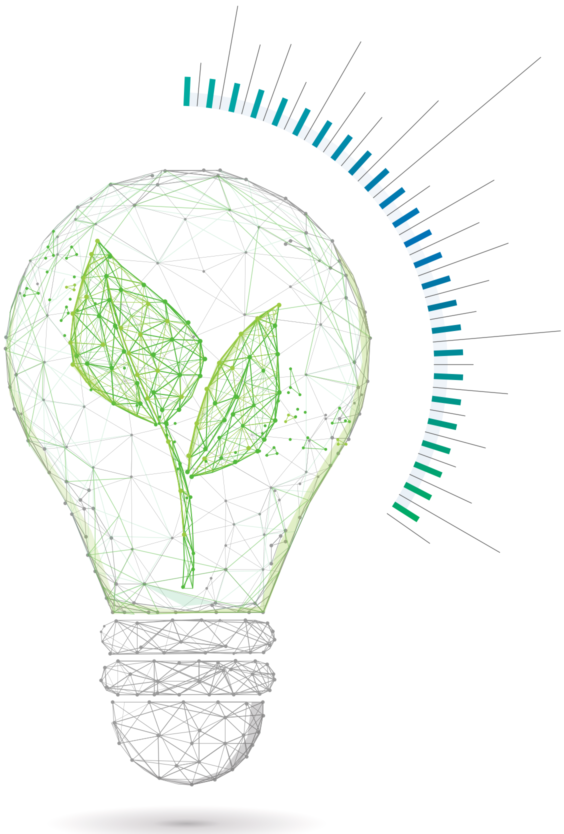
The transition from a tailpipe-only approach to a Life Cycle Assessment (LCA) framework fundamentally changes how we view ICEVs. No longer condemned as relics of the past, ICEVs emerge as adaptable, flexible, and sustainable contributors to the future of mobility provided they integrate with renewable fuels, hybridization, and circular economy principles.

For policymakers, industries, and consumers, the message is clear:

- ICEVs should not be discarded prematurely.
- With smart fuel choices and technological upgrades, they can achieve parity or superiority with BEVs on an LCA basis.
- In regions like India, ICEVs will remain indispensable for decades, driving inclusive, affordable, and sustainable mobility.

Thus, the enhanced role and life of ICEVs is not a fall back option, it is a strategic pillar of sustainable transport in the new era of holistic, lifecycle-based thinking.

In conclusion, the future of the automotive industry is not a one-size-fits-all solution. While BEVs will play a dominant role in certain sectors, an LCA-based regulatory framework reveals a crucial and enhanced role for the ICEV. By decoupling the engine from its traditional fossil fuels, and by optimizing it for specific applications, the ICEV can be a powerful tool for decarbonization. Instead of being a relic of the past, the ICEV, powered by advanced, sustainable fuels, will likely be an indispensable part of a pragmatic and successful transition to a greener future.



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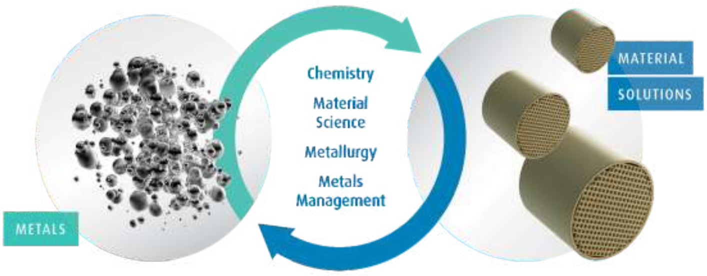

Our unique circular business model ensures that these critical elements are continuously refined and recycled, to be reintegrated in new applications.

SHARDA MOTOR
INDUSTRIES LIMITED

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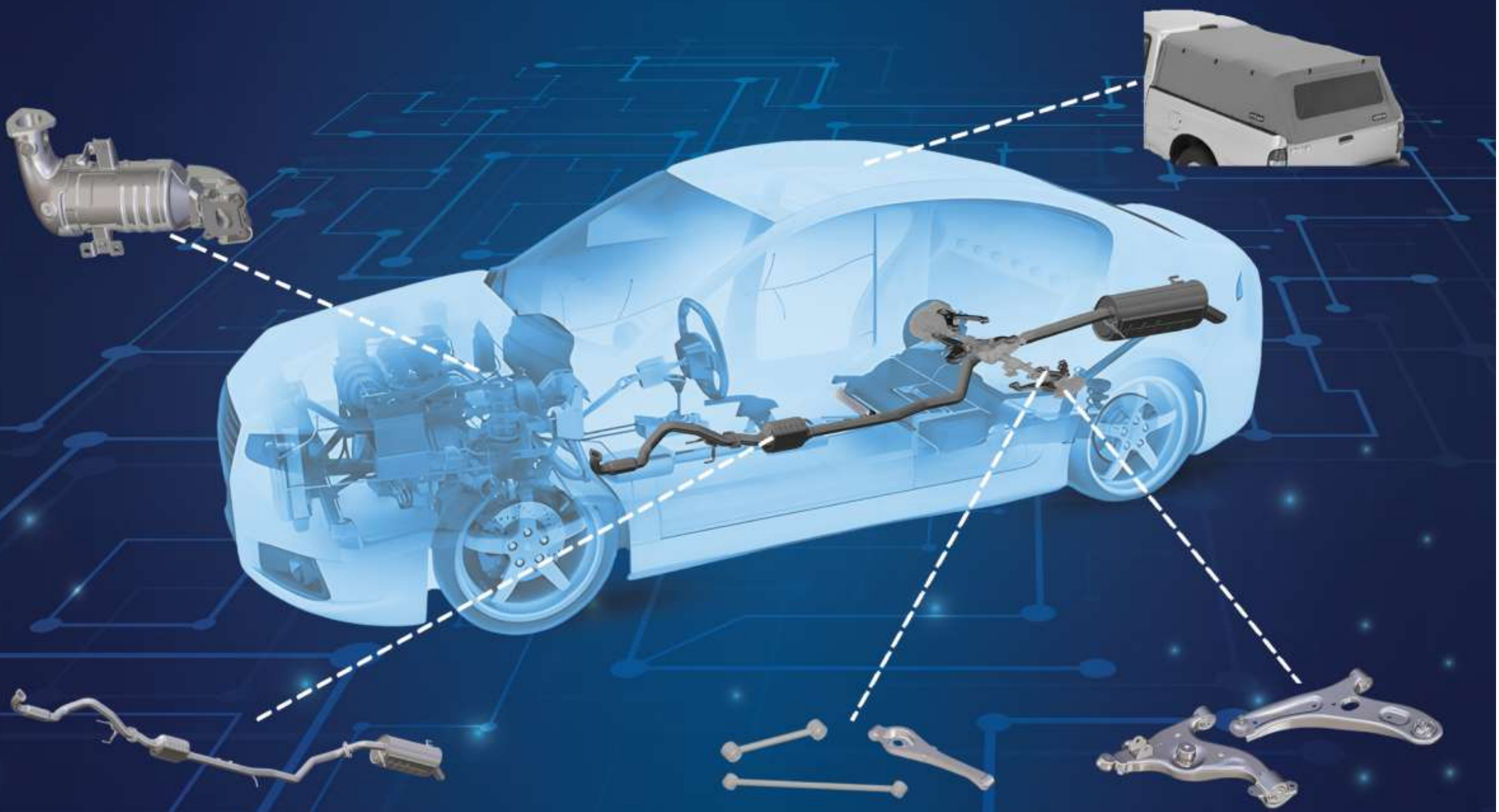

Business Verticals

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40 Years of Engineering Excellence with Global Trust

Sharda Motor Industries Ltd. (Head Office) : D-188, Okhla Industrial Area, Phase- I, New Delhi- 110020, India

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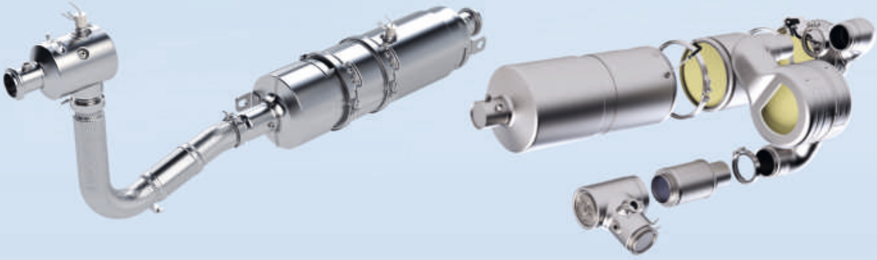
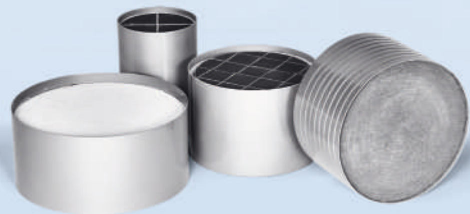
There are many pathways to a **Cleaner and Greener** transport industry.

Whatever technology or fuel that will be driving the future: **Dinex** is geared for the future and supports the **OEM!**

Diesel & Gas Engines

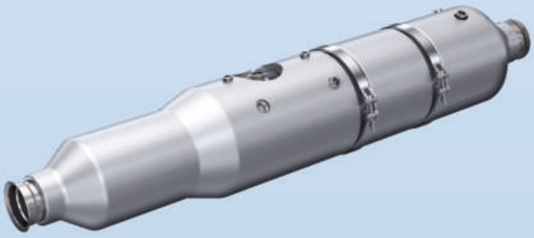


BS 7, Trem V and CEV V-compliant solutions.



Catalysts optimized for biofuels and e-fuels.

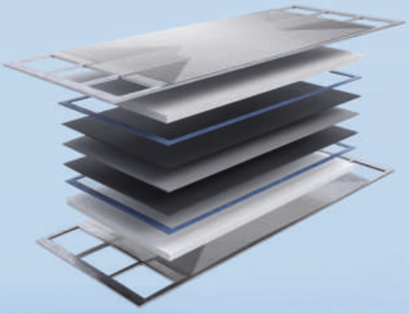
Hydrogen ICE



Complete aftertreatment solutions for H_2 Combustion engines.

Fuel Cell Electric Powertrains

Vapor discharge systemsreducing slippage and noise.



Catalyst Coated Membranes– the heart of a Fuel Cell.

India
Dinex Emission Solutions India Private Limited
Plot No 1. Phase 5, 8th Avenue,
Mahindra World City,
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Dinex.org

EMITEC TECHNOLOGIES

It's what's inside that matters

We shape solutions for our tomorrow!

- More than 35 years of experience in developing highly innovative component for exhaust gas cleaning
- More than 425 million produced Metalit ® and Emicat ®, 0 failure in the field
- More than 1100 patents
- Continuous transfer of technology to future-oriented, sustainable business fields.

It's what you can Count on

We support your solution requirements!

- System engineering: CAD concept development, rapid-prototyping, functional samples, complete exhaust system tests.
- Test center: air-conditioned engine test benches and all-wheel chassis dynamometer, commercial vehicle chassis dynamometer, test benches for examination of components with regard to flow distribution, fatigue strength and durability.

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Your SCR runs on purity.
Demand genuine AdBlue.
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VELVEX
AdBlue
20L
VELVEX
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ECMA
Clean Air Today, Cleaner Air Tomorrow

ECT-2025
16th International Conference

GLIMPSES OF ECT 2024 CONFERENCE, NEW DELHI

ECT-2025

16th International Conference

7th - 8th October 2025

DRIVING INNOVATIONS IN EMISSION CONTROL FOR SUSTAINABLE TOMORROW

In an era marked by environmental challenges and climate concerns, the push towards sustainability has become more than a choice—it's a necessity. One of the most pressing areas of innovation lies in emission control technologies, which play a critical role in reducing air pollution and advancing the transition to cleaner mobility.

With rapid urbanization and the rise in vehicular population, harmful emissions from internal combustion engines have become a major environmental issue. However, ongoing innovations are transforming this landscape. Advanced after-treatment systems, such as Selective Catalytic Reduction (SCR), Diesel Particulate Filters (DPF), and Gasoline Particulate Filters (GPF), are significantly reducing NOx and particulate emissions. Moreover, integration of smart sensors and real-time monitoring systems is enabling more efficient control over emissions throughout a vehicle's life cycle. These technologies not only enhance performance but also ensure compliance with increasingly stringent global emission norms like BS-VI, Euro 6, Euro 7 and forthcoming TREM-V & BS-VII.

The future also points toward hybrid powertrains, electrification, and hydrogen-based fuel systems, complementing traditional emission control measures. Combined with robust regulatory frameworks and industry collaboration, these advancements pave the way for a cleaner, greener, and more sustainable tomorrow.

Innovation in emission control is not just about meeting standards—it's about creating a healthier future. The journey has begun, and the drive toward a sustainable tomorrow is accelerating

Mr S K Singh
President

Mr Prakash Sardesai
Vice President

Mr Neelkanth Marathe
Executive Director

Conference Organiser

Emission Controls Manufacturers Association (ECMA)
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