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NAVIGATING THE FUTURE OF EMISSION CONTROL: A COMMERCIAL VEHICLE MANUFACTURER'S PERSPECTIVE

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India also committed to the EV30@30 campaign, which aims for electric vehicles (EVs) to make up at least 30% of new vehicle sales by 2030. These goals align with the global push for decarbonization, with countries like Japan, the USA, Germany, and China committing to significant greenhouse gas (GHG) reductions by 2030. For instance, Japan plans to reduce GHG emissions by 46% by 2030, while China aims to install 1,200 GW of solar power and have 40% of new vehicles be EVs by 2030.

In the climate change debate, internal combustion engines (ICEs) are often seen as a significant contributor to global emissions, while EVs are increasingly promoted as the future of mobility. However, for commercial vehicle manufacturers, where diesel engines have long been central to long-haul and heavy-duty transportation, the transition to cleaner technologies presents challenges. Electrification offers a promising path forward particularly when powered by renewable energy but the immediate challenge is optimizing and innovating within existing ICE technologies to meet increasingly stringent environmental regulations.

As Akio Toyoda, chairman of Toyota Motor Corporation, noted: "Carbon is our enemy, not the internal combustion engine. We must reduce CO2 emissions in all processes of producing, transporting, and using energy. There must be more than one route to reach

Climate management is on top of global concerns, and during COP26, India set ambitious targets for 2030 to decarbonize its energy sector, including reducing carbon emissions by 50% and achieving 500 gigawatts of renewable energy capacity. targeting 2070, the path to a sustainable future will depend on a combination of electrification, alternative powertrains, material circularity (through recycling and reuse), and shared mobility solutions such as public transport. These approaches can reduce pollution, conserve resources, and drive sustainability across the entire ecosystem.

At Ashok Leyland, we believe that, while electrification is gaining momentum, ICE particularly diesel engineswill continue to play a crucial role in heavy-duty commercial vehicles for the foreseeable future. Achieving a sustainable future will depend on improving emission control technologies, developing alternative fuels, and optimizing powertrains. This article examines the evolution of exhaust aftertreatment systems, the challenges posed by Euro VII / Bharat Stage VII (BS VII) regulations, and the potential of hydrogen internal combustion engines (H2-ICE) as a promising route to zero-emission transportation.

1. The Role of Diesel Engines and Advanced Exhaust Aftertreatment Systems

Diesel engines have long been the workhorses of the commercial vehicle sector, offering unparalleled efficiency for long-haul and heavy-load operations. However, their environmental impact carbon neutrality. Regulations should not limit our choice of technologies." This philosophy emphasizes that decarbonization will require multiple solutions, including improving ICE technologies, exploring lowand no-carbon fuels, and advancing emission control systems.

While the world aims for net zero carbon emissions by mid-century, with India To meet current and future emission standards, diesel engines rely on several key aftertreatment components:

- **Diesel Oxidation Catalyst (DOC):** Converts pollutants such as carbon monoxide (CO) and hydrocarbons (HC) into less harmful carbon dioxide (CO2) and water vapor.
- **Diesel Particulate Filter (DPF):** Captures particulate matter (PM) produced during combustion to prevent its release into the atmosphere.
- Reducing PM2.5 is particularly important for improving air quality and life expectancy, as these fine particles are known to cause severe health issues. A study by ECMA and ARAI demonstrates that appropriate exhaust aftertreatment devices, particularly paticulate filters, can reduce PM2.5 and PM10 pollutants to extremely low levels, regardless of the air quality index the vehicle is exposed to. In fact, on a lighter note, one might even breathe cleaner air from the exhaust of a BSVI diesel vehicle than the surrounding ambient air!
- **Selective Catalytic Reduction (SCR):** Reduces nitrogen oxides (NOx) by injecting a ureabased solution (AdBlue) into the exhaust, converting NOx into nitrogen and water vapor.
- **Ammonia Slip Catalyst (ASC):** Prevents unreacted ammonia from

especially in terms of carbon dioxide (CO2), nitrogen oxides (NOx),and particulate matter (PM) requires continuous improvement in exhaust aftertreatment systems.

a) Modern Diesel Aftertreatment Technologies

especially with real driving emissions (RDE) testing, even more advanced solutions will be required.

b) Enhancing Thermal Management: Electrically Heated Catalysts (EHC) and CATVAP Technology

A significant challenge in diesel aftertreatment is maintaining optimal temperatures, especially during cold starts or low-load conditions. Advanced thermal management technologies like **Electrically Heated Catalysts (EHC)** and **CATVAP technology** help address this issue:

- **EHCs:**Electrically Heated Catalysts help bring aftertreatment systems to optimal temperatures faster, reducing NOx emissions during the warm-up phase particularly in urban environments with frequent stop-and-go traffic.
- However, the 24V electric architecture commonly used in commercial vehicles limits the heating power available, reducing EHCs' effectiveness in larger vehicles. Transitioning to a 48V architecture could increase heating power but presents challenges such s a significant reengineering, increased costs, and compatibility issues with existing components.
- **CATVAP (Catalytic Vaporizer):** Developed by Albonair, CATVAP enhances aftertreatment performance by providing flexible heating and heat retention. It

escaping into the atmosphere, ensuring cleaner exhaust emissions.

These technologies are crucial for reducing emissions from commercial diesel vehicles. However, as emission standards evolve, soot accumulation and improving system efficiency.

By integrating these technologies, manufacturers can ensure that aftertreatment systems operate effectively across various engine loads, reducing emissions and improving fuel efficiency.

c) Compact, Modular Designs for Future Systems

As emission standards become stricter, manufacturers are focusing on developing more compact and integrated aftertreatment systems. By combining DOC, DPF, and SCR components into modular units, these systems save space and reduce weight important factors for maximizing payload and efficiency in commercial vehicles.

2. Meeting Euro VII / BS VII Emission Standards

The upcoming Euro VII and Bharat Stage VII (BS VII) regulations represent a significant shift in how the automotive industry approaches emissions control. These new standards will introduce stricter limits on both tailpipe and non-tailpipe emissions, suchas those generated from tire and brake wear.

a) Key Requirements of Euro VII / BS VII

- **Stricter NOx and Particulate Matter Limits:** Euro VII regulations will impose even lower limits on NOx and particulate matter (PM), especially under real-world driving conditions. In addition to reducing PM mass, vehicles must also meet stringent PN10 (Particle Number) requirements, targeting ultrafine particles. These changes will require further advancements in SCR and operates in multiple modes, including **Burner Mode** for fast heating, **Heat Retention Mode** for maintaining temperature, and **DPF Regeneration Mode** for reducing DPF technologies to ensure compliance.
- **Non-Tailpipe Emissions:** For the first time, Euro VII / BS VII will regulate non-exhaust emissions, including particles from tire and brake wear. These emissions contribute significantly to airborne particulate matter (PM) and have historically gone unregulated. To comply, manufacturers will need to explore new materials, such as low-wear, longer-lasting tires, and advanced brake systems like regenerative braking, which reduces reliance on traditional friction braking. This is applicable to all vehicles, including electric and hydrogen vehicles, which, despite producing no tailpipe emissions, still contribute to particulate pollution from tires and brakes. These new regulations aim to reduce the total environmental impact of all vehicles.
- **Enhanced Real Driving Emissions (RDE) Testing:** Vehicles will need to meet emission standards across a broader range of driving conditions and temperatures, making it crucial for aftertreatment systems to be robust and adaptable.

b) Technological Responses to Euro VII / BS VII

To meet these stringent requirements, manufacturers are adopting several key technologies:

- **Dual-Dosing SCR Systems:** SCR systems now feature dual-dosing setups, with urea injected at two points in the exhaust stream. This configuration enhances NOx reduction, particularly during cold starts and transient operations.

- The first injection in the close coupled SCR system provides immediate NOx reduction as the engine warms up, while the second injection in the main SCR system ensures continuous NOx control during steady-state operations. A combination of V-SCR and Cu-SCR is being increasingly adopted to balance low N2O formation and high NOx reduction efficiency across different temperature ranges.
- **Multi-Oxidation Catalysts (DOC + SCR/ASC):** Manufacturers are considering integrated systems that combine DOC, SCR, and ASC components to maximize space and efficiency. This configuration increases the SCR volume and improves NH3 control, ensuring compliance with stringent NOx and PM limits while reducing system complexity.
- **Advanced DPF Technologies:** Innovations in DPF technology, supported by CATVAP, improve particulate capture and reduce regeneration cycles. To meet stricter PN 10 nm limits, manufacturers are incorporating filter coatings and low-porosity filters to trap ultrafine particles. A secondary filter may also be required to trap urea particles formed during NOx reduction.
- **Hybrid Powertrains and Electrification:** Electrified components and hybrid powertrains will complement diesel engines, especially in urban environments where low-speed operations dominate. These systems reduce the reliance on diesel combustion, lowering overall emissions.

3. Hydrogen Internal Combustion Engines (H2-ICE): A Promising Alternative

While diesel engines will remain important in the foreseeable future, hydrogen internal combustion engines (H2-ICE) are emerging as a promising alternative for zero-carbon emissions in long-haul transportation. With the ability to leverage existing internal combustion engine technology, H2-ICE offers a familiar, robust solution for the future of transportation. As we embrace hydrogen, it's clear that "ICE is NICE, say YES to ICE," highlighting the continued relevance and adaptability of internal combustion engines in a zero-emissions future.

a) Characteristics of Hydrogen Combustion

H2-ICE retains the advantages of traditional ICEs, including fuel density, robustness, and availability, while eliminating CO2 emissions. However, high combustion temperatures still produce NOx due to oxidation of N2 in intake air, which must be controlled with advanced aftertreatment systems.

b) Emission Control for H2-ICE

To manage NOx emissions from H2 combustion, H2-ICE engines will use familiar aftertreatment technologies to meet BS VI emission levels; for BS IV no aftertreatment required:

- **Oxicat:** Improves SCR performance by facilitating hydrogen oxidation and generating NO2, which enhances NOx conversion. However, it may contribute to N2O production and is less relevant in H2 combustion due to the absence of HC/CO emissions.

- **V-SCR + Cu-SCR Combination:** A mix of V-SCR for low N2O production and Cu-SCR for higher NOx reduction at elevated temperatures is optimal for H2-ICE, offering balanced performance across different operating conditions.
- **NSC + SCR:** Combining NOx Storage Catalyst (NSC) with SCR offers effective NOx control during cold starts, increasing NO2/NOx ratios for improved SCR efficiency.
- **Particulate Filter:** While H2 combustion produces little PM, a particulate filter is still useful for trapping secondary particulates like engine oil ash.
- **High Water Content (~35%):** The high-water content in H2-ICE exhaust can reduce ammonia storage efficiency, cause vanadium loss in V-SCR, and lead to condensation issues. Robust catalyst materials must be used to withstand moisture without degrading performance.
- **Advanced Combustion Strategies:** CO2 is negligible in H2-ICE. Techniques such as lean-burn combustion ($\lambda > 2$) and exhaust gas recirculation (EGR) will help reduce NOx formation, working alongside SCR systems to achieve near-zero emissions.

c) Path to Commercial Adoption

The widespread adoption of Hydrogen Internal Combustion Engines (H2-ICE) depends heavily on the development of hydrogen infrastructure, including the establishment of refueling networks and the reduction of hydrogen production costs. Currently, three primary types of hydrogen are available, each with varying environmental and cost implications:

- **Grey Hydrogen** This is the most commonly used form of hydrogen today and is produced through **steam methane reforming** of natural gas. However, this process releases significant amounts of CO2, making it a less sustainable option.
- **Blue Hydrogen** Similar to grey hydrogen, blue hydrogen is produced from natural gas but incorporates **Carbon Capture and Storage (CCS)** technology. This process captures and stores the CO2 produced during hydrogen generation, reducing overall carbon emissions. While it is cleaner than grey hydrogen, it still relies on fossil fuels and the efficiency of CCS technology.
- **Green Hydrogen** The most sustainable form, green hydrogen is produced through electrolysis, which uses electricity from renewable energy sources such as wind or solar to split water into hydrogen and oxygen, resulting in zero carbon emissions. However, green hydrogen is currently limited due to high production costs, largely driven by the expensive electrolyzers needed for the electrolysis process. Additionally, scaling renewable energy sources to meet the demand for green hydrogen further contributes to its high cost, making it less economically viable than grey or blue hydrogen at present.

While the industry works toward the wider availability of green hydrogen H2-ICE technology is currently being developed using grey hydrogen This allows manufacturers to build expertise, optimize engine designs, and establish the infrastructure necessary for hydrogen powered vehicles. By advancing the technology with grey hydrogen, the industry will be ready to seamlessly transition to green hydrogen once it becomes more affordable and widely available.

For H2-ICE to become a mainstream solution for long-haul and heavy-duty commercial vehicles, significant investment in hydrogen infrastructure is required, including affordable green hydrogen production and refueling networks. One of the significant challenges is hydrogen storage and transportation. For long-haul applications requiring greater range, high-pressure storage systems are needed. The industry is focusing on Type 4 tanks, which can store hydrogen at pressures of up to 700 bar, providing the necessary range for heavy-duty vehicles but presenting additional engineering challenges. In addition to storage and transportation, H2-ICE requires a low ignition energy coil to efficiently ignite hydrogen, given hydrogen's different combustion characteristics compared to traditional fuels. Specialized engine oil is also necessary to handle the unique properties of hydrogen combustion and ensure engine longevity. When these developments are realized, H2-ICE can provide a zero-carbon solution for the transportation sector, especially as green hydrogen becomes the dominant fuel in the future.

Conclusion: A Multi-Path Strategy to Emission Control

Achieving sustainability in the commercial vehicle industry requires a multi-path approach, combining advancements in ICE, alternative fuels, and emission control technologies. While electrification is a critical component, ICE technologies remain vital for heavy-duty applications, where energy density and range requirements are challenging for battery systems.

Key to success will be optimizing ICE technologies, incorporating low-carbon fuels like CNG, LNG, and biofuels, and exploring no-carbon alternatives like hydrogen. Advanced aftertreatment systems like CATVAP and EHCs will be crucial for meeting future emission standards.

Collaboration across the industry is essential. Organizations like **Emission Control Manufacturers Association (ECMA) India** play a pivotal role in facilitating the development and adoption of new technologies, setting benchmarks, and promoting alternative fuels. ECMA can foster partnerships between manufacturers, policymakers, and technology providers to ensure innovations align with regulatory and environmental goals.

By embracing a combination of improved ICE technologies, alternative fuels, and advanced emission control systems, the commercial vehicle industry can continue to provide efficient transportation while reducing its environmental impact. A sustainable future will depend on a collaborative, multi-faceted approach to emission control, ensuring the industry's continued growth and success.

As we navigate the transition over the next decade, this strategy will ensure that we are future-ready for 2030 and beyond, contributing to the vision of Vikshit Bharat 2047 and achieving a "Bagh" net-zero India by 2070.


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Identifying and Controlling the "Silent Threat" in BS7 – Evaporative and Refueling Emissions

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Executive Summary

Throughout India, petrol-fueled internal combustion engine (ICE) vehicles emit non-exhaust evaporative and refueling emissions at levels which significantly exceed tailpipe exhaust emission. The Economic Times of India has called evaporative and refueling emissions the "silent threat"[1]. This is because **during periods of heat waves, when air quality is often most unhealthy and severe, petrol-fueled ICE vehicles in India can have emissions of evaporative nonmethane hydrocarbons (NMHC) that are up to 30 grams per vehicle per day, which is 15x higher than the current BS6 evaporative emission certification standard (2.0 g/day) and 13x higher than the BS6 exhaust NMHC emission standard (68 mg/km).** Evaporative emission standards in India have remained unchanged since the implementation of Bharat 4 in 2017 and Bharat 6 in 2020, both of which are equivalent to Euro 4, resulting in India evaporative emission control systems that are outdated, undersized, and not sufficiently effective. Over the same time period, the sale of petrol-fueled ICE vehicles in India has increased by 81% to 3.26 MM annually (with petrol ICE representing more than 65% of all new car sales)[2], and India has increased the volume percentage of ethanol required to be blended into petrol up to a minimum of 20% (E20). The in-use vapor pressure of E20 sold commercially (up to 70 kPa)[3] is a higher vapor pressure than that of E0 petrol (up to 60 kPa)[4] and also higher than the fuel to which vehicles are certified for evaporative emissions under BS6 (60-65 kPa)[5]. This disparity between certification and in-use vapor pressure increases evaporative emissions in-use, whether the vehicle is parked or operated. The current situation in India is petrol-fueled ICE vehicles are more prevalent, are operating on higher vapor pressure fuels, and these vehicles are technology laggards with outdated and insufficient evaporative emission control systems. This is leading to high in-use evaporative emission rates that contribute significantly to non-methane volatile organic compounds (NMVOC), which are primary precursors for the formation of ozone (O_3) and secondary organic aerosol ($PM_{2.5}$). These air pollutants contribute to smog formation, haze and increased public health risks**. As India evaluates options for BS7, it is important to consider the unique circumstances in India that warrant a different approach than simply following Euro 7, which is the weakest evaporative emission standard when comparing against the standards implemented in the other major automotive producing countries that desire to improve air quality (US, Canada, Brazil, China).** Euro 7 applied in India would not be sufficient to mitigate the high in-use evaporative emissions that occur due to the unique circumstances in India of higher temperatures, higher in-use fuel vapor pressure, and a longer time horizon for the continued sale of ICE vehicles. **At a minimum, India should implement evaporative and refueling emission standards and limits equivalent to Brazil (0.05 g/L refueling emissions limit (ORVR) and a hot soak + 48-hr diurnal emission standard of 0.50 g/day). These standards would reduce evaporative and refueling emissions by more than 92% during all possible in-use conditions and retain**

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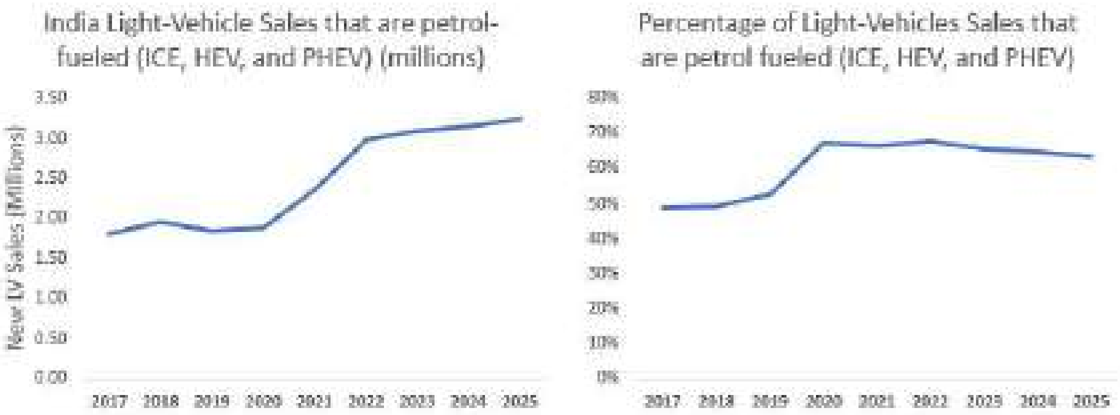
[1] Unveiling a silent threat: Need to tackle refuelling emissions for cleaner air, ET Auto (indiatimes.com)
[2] S&P Global, Mobility and Energy Future, Inflections Scenario, August 2024
[3] IS 17021:2018
[4] IS 2796:2017
[5] IS 17943:2022

the valuable fuel vapor on the vehicle to be burned in the engine as fuel, saving consumers on fuel costs and reducing their exposure to air toxics found in petrol, such as benzene.

Figure 1. Sales trends of light-vehicles that are petrol fueled (ICE, HEV, PHEV)[2]



1. Background on Evaporative Emissions Regulations and Control Technology

Tailpipe NMHC emissions consist of unburned or partially burned fuel vapors, whereas evaporative NMVOC emissions consist of volatilized fuel vapors that escape during refueling, as running losses during vehicle operation, by permeation of vapors through fuel tanks and supply lines, and as diurnal fuel tank breathing losses during parking events. While regulations have been implemented in the United States, Canada, China, and Brazil to reduce evaporative NMVOC emissions to help meet strict air quality standards, less effort has been made to regulate and reduce evaporative and refueling NMVOC emissions in Europe and India. **Euro 7 was the most recent example in a long history of Europe choosing to not prioritize control of evaporative emissions, where European co-legislators rejected the European Commission's proposal to adopt a refueling emission standard and a more stringent evaporative emission standard.** Only a slight reduction was made to the diurnal evaporative emissions limit (reduction from 2.0 g to 1.5 g), which in practical application will lead to no further changes in control technology. Euro 7 continues to place Europe as the least stringent evaporative emission standard in comparison to other countries that prioritize improving air quality. Table 1 provides a comparison of global evaporative emissions standards, which clearly shows that **Europe and India lag far behind other regions in terms of limits that have been demonstrated to be both achievable and cost-effective**.

Even though India has historically followed European emission standards through United Nations Economic Commission for Europe (UNECE) agreements, **India should evaluate their unique air quality challenges and circumstances which are different than Europe**. It should be noted that both Brazil and China made the policy decision to develop their own evaporative emission standards and shift from their history of following European standards due to their unique air quality challenges and circumstances and recognizing that the continued weakness of the European standards was insufficient to solve their challenges. Table 2 shows the progression of Euro standards with respect to evaporative and refueling emissions, demonstrating the minimal progress since Euro 4.

Table 1; International comparison of current evaporative and refueling emission standards.

Emission Standard	India BS 6	Europe Euro 7	USA Tier 3	Brazil PL 7	China 6b
Evaporative (hot soak + diurnal)	1-day 2.0 g	2-day 1.5 g	2-day & 3-day 0.30 g	2-day 0.50 g	2-day 0.70 g
On-board Refueling	None (Stage II)	None (Stage II)	0.20 g/gal (~0.05 g/L)	0.05 g/L	0.05 g/L

Table 2; History of evaporative emission limits from Euro 4 to Euro 7.

Standard	Ethanol in Certification Test Fuel (%)	Category M1 Diurnal Evaporative Emissions Limit (g/day)	Category M1 Refueling Emissions Limit (g/L)
Euro 4	0 (E0)	2.0 – 24-hr	None
Euro 5	5 (E5)	2.0 – 24-hr	None
Euro 6	5 (E5)	2.0 – 24-hr	None
Euro 6d	10 (E10)	2.0 – 48-hr	None
Euro 7	10 (E10)	1.5 – 48-hr	None

ICE vehicles incorporate an evaporative emission control system in the form of an activated carbon canister designed to adsorb petrol vapors from the fuel tank and utilize them in the engine for combustion, rather than being released to the atmosphere. In the US, Canada, China and Brazil, stringent evaporative emission regulations have driven advancements in the design of these systems to better capture emissions from refueling, vehicle operation, and at least two days of diurnal vapor generation while parked. In other regions, including Europe and India, these canister systems remain undersized—being designed to control for only one or two days of diurnal vapor generation—and therefore lack the capacity to control emissions during refueling, parking events beyond two days, or during off-cycle conditions such as heatwaves.

In addition to undersized on-vehicle activated carbon canisters, Europe and India also currently rely upon Stage II vapor recovery systems installed in petrol stations to control the refueling portion of evaporative emissions. Stage II systems utilize passive or active vacuum-assisted fuel dispensers to capture and return vapors to underground bulk storage tanks during refueling. In Europe, the certification requirement for the efficiency of a Stage II system is 85%, as established in Directive 2009/126/EC[6]. However, the certification efficiency only applies to the capture of vapors by the nozzle at the nozzle/fill pipe interface at certification and does not address efficiency losses that can occur due to malfunctioning equipment, vapor leaks in the system, or the release of vapors from the underground storage tank vent stack that occur in operation. Early US Environmental Protection Agency (US EPA) studies estimated in-use efficiency of Stage II systems to be between 62%–92%[7] depending upon the frequency and rigor of maintenance and inspection; a more recent California Air Resources Board (CARB) study estimates Stage II efficiency to be around 71%[8]. To remain effective, Stage II systems require regular inspection and maintenance, the requirements for which are not as comprehensive in Europe or India as those established in the US[9]. Stage II vapor recovery is not required by the US EPA anywhere in the US and it has been removed in all areas except California. California technology has morphed from a limited to Stage II program to a more comprehensive Enhanced Vapor Recovery (EVR) program which addresses other sources of emissions from petrol dispensing and storage of gasoline, including additional controls to prevent vapor venting from underground storage tanks by maintaining tank pressures within certain limits[10]. Considering estimated Stage II efficiencies in the US of 71% and the estimated Stage II implementation in Europe of 72% of all petrol stations[11], the actual efficiency of overall refueling emissions control in Europe is likely between 50%–60%. **The implementation rate and efficiency of Stage II in India is not well documented , so it is unknown if Stage II is effectively controlling refueling emissions in India.**

To overcome the limitations of Stage II systems, regulations in the US, Canada, China, and Brazil require petrol ICE vehicles to be equipped with Onboard Refueling Vapor Recovery (ORVR) systems. In ORVR-equipped vehicles, a seal is formed inside the vehicle's filler neck during refueling to prevent the escape of fuel vapors, which are directed to a larger carbon canister system. In the US, over 25 years of data on ORVR implementation demonstrate that it can reliably capture at least 98% of evaporative NMVOC refueling emissions throughout the useful life of the vehicle[12]. While Stage II systems must be replaced periodically and incur annual operational costs, ORVR systems require no maintenance and can be installed on new vehicles at a cost of €10–€20 (₹920 - ₹1,40) per vehicle[13]. During vehicle operation, fresh air is intermittently drawn through the ORVR canister to remove the adsorbed fuel vapor from the activated carbon. The stripped vapor is then fed to the engine for combustion, providing additional fuel savings that can offset a significant portion of the canister installation cost over the life of the vehicle.

Regulatory decisions regarding evaporative emission control technologies and strategies are dependent upon accurately modeled estimates of evaporative NMVOC inventories. As a primary driver of evaporative processes, precise temperature input is vital to the accuracy of inventory estimates since evaporative emissions exhibit a non-linear dependence on temperature. However, evaporative emission inventories, including those used for regulatory decisions in Europe and India, are often developed using average annual or seasonal temperature profiles that fail to capture extreme temperature events such as

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[6] Directive - 2009/126 - EN - EUR-Lex (europa.eu)
[7] 2000MSM2.PDF (epa.gov)
[8] GDF Emission Factor Umbrella Document (ca.gov)
[9] CP-201: Cert Procedure for GDF using UST (ca.gov)
[10] Test Procedure: 2003-10-08 TP-201.2B Flow and Pressure Measurement of Vapor Recovery Equipment (ca.gov)
[11] Evaluation of Directive 1994/63/EC on VOC emissions from petrol storage & distribution and Directive 2009/126/EC on petrol vapour recovery - Publications Office of the EU (europa.eu)
[12] Summary and Analysis of 2000-2015 Model Year IUVP Evaporative and Refueling Emission Data (sae.org)
[13] Microsoft Word - ORVR v4.docx (theicct.org)

heatwaves, which research suggests are increasing in frequency, duration, and intensity in India in response to climate changes[14]. This has historically led to the belief that evaporative emissions from vehicles are of the same magnitude as exhaust emissions; in reality, the evaporative component can be significantly larger when considering refueling emissions and increased evaporative emissions due to higher ambient temperatures. As shown in Figure 2 and 3, during periods of heat waves, when air quality is often most unhealthy, petrol-fueled ICE vehicles in India can have emissions of evaporative nonmethane hydrocarbons (NMHC) that are up to 30 grams per day, which is 15x higher than the current BS6 evaporative emission certification standard (2.0 g/day) and 13x higher than the BS6 exhaust NHMC emission standard (68 mg/km).

2. Evaporative emissions modeling methodology

The evaporative emissions model consists of MATLAB modules which calculate per-vehicle emission factors for diurnal, running loss, hot soak, permeation, and refueling sources. The frequencies and durations of driving and parking events, average trip numbers and distances, and average vehicle speeds were obtained from COPERT, which were developed for use in Europe and modified for application to India. For each scenario, inputs were adjusted to reflect India automotive evaporative emissions standards. Running loss, permeation, and hot soak rates were derived from methodologies applied in EPA MOVES3 model[15]; diurnal and refueling emissions were determined by methods described by Dong et al[16]. For all scenarios, in-use ethanol was set at 20%, 70 kPa vapor pressure. Diurnal soak requirements used for canister sizing were one day for BS6; canister sizing for the BS7 scenario was based on implementation of a 0.05 g/L refueling limit (ORVR) and a 0.50 g/day 48-hr hot soak + diurnal evaporative emission limit. The full vehicle hot soak + diurnal emissions limits were 2.0 grams for a 24-hour test for BS6 and 0.50 grams per day for a 48-hr test for BS7, with the BS7 scenario aligning with current Brazilian PROCONVE L-7 standards. Canister purge volume was determined using the shortest drive cycle time from the New European Driving Cycle (NEDC) for BS6 (60 min) and the World harmonized Light vehicle Test Procedures(WLTP) for BS7 (31.8 min) using methods described by Dong et al. Evaporative emissions exhibit a linear relationship with fuel tank volume, and an average fuel tank capacity of 60 L was used. Carbon aging was accounted for by reducing the adsorption capacity of the carbon in the canister by 16% for the BS6 scenario and 7% for the BS7 scenario, which represents the adoption of more durable carbon and the inclusion of aging procedures to ensure enhanced durability beginning with Euro6d standards. For each scenario, the model requires a base running loss and leak rate which reflect control measures, such as heat shielding designed to insulate fuel tanks and lines from radiative road surface heat during use, and on-board diagnostics designed to alert the driver of leaks in the fuel system. The base rate is then adjusted according to ambient temperature and fuel Reid Vapor Pressure (RVP) to determine actual loss rates. Since India does not currently have a running loss emission standard or leak standard, emission factors for running loss and leaks were taken from conservatively low MOVES model estimates for an enhanced or Tier 1 US vehicle for the BS6 scenario (0.72 $g\ hr^{-1}$) and Tier 2 vehicles for the BS7 scenarios (0.23 $g\ hr^{-1}$). Stage II efficiency was estimated as 60.35% based on the product of CARB's estimated in-use efficiency in the US of 71% and assuming a conservatively high 85% implementation of Stage II in petrol stations throughout India (no documentation could be found on actual implementation rate and

[14] More frequent heatwaves in India are putting lives at risk | World Economic Forum (weforum.org)
[15] Overview of EPA's MOtor Vehicle Emission Simulator (MOVES3) (EPA-420-R-21-004, March 2021)
[16] Full article: Modeling cold soak evaporative vapor emissions from gasoline-powered automobiles using a newly developed method (tandfonline.com)

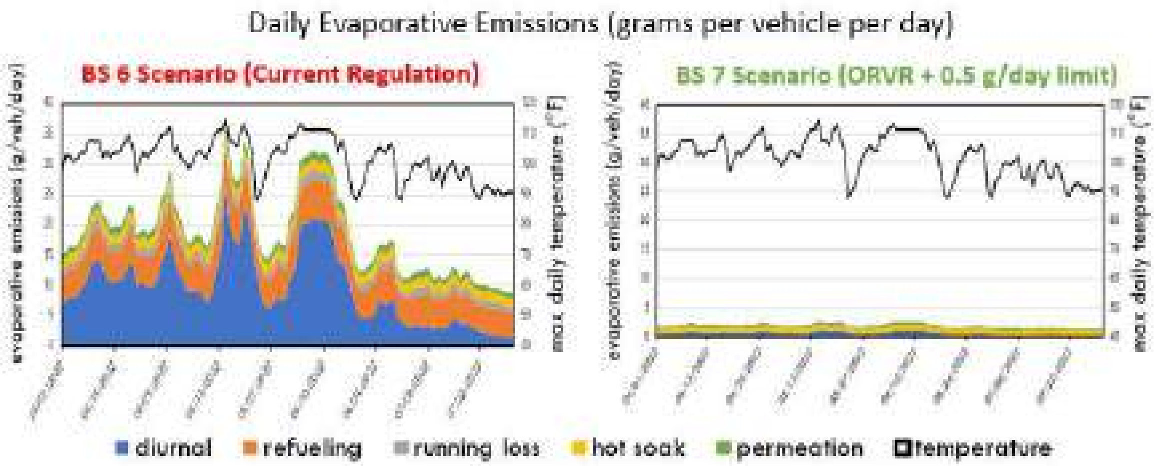
in-use efficiency). Temperatures were selected to represent a heat wave period in Delhi from April to July, 2022, which coincided with significant unhealthy smog events.

3. Evaporative emissions modeling results

The evaporative emissions modeling result for the heat wave period in New Delhi, India from April-July 2022 are shown in Figure 2 below. In both scenarios, an in-use fuel vapor pressure of 70 kPa was utilized to represent the highest vapor pressure allowed for in-use E20 fuel. For the current BS6 scenario, which is representative of current BS6 vehicles in India, the combined evaporative and refueling emissions rate exceeds 30 grams per vehicle per day during the hottest heat wave periods and, at a minimum, is 10 grams per vehicle per day. Figure 3 compares these maximum in-use emissions rates to the current BS6 evaporative emission certification limit (2.0 g/day) and the BS6 NMHC exhaust limit (68 mg/km). Using the average annual driving rate in India of 12,000 km[17], a vehicle is driven an average of 33 km/day, resulting in an average NMHC exhaust emission of 2.2 g/day. Unlike evaporative emissions which increase exponentially with temperature, exhaust emissions are not influenced by the ambient temperature. As shown in Figure 2, **during periods of heat waves, when air quality is often the most unhealthy, petrol-fueled ICE vehicles in India can have emissions of evaporative nonmethane hydrocarbons (NMHC) that are 15x higher than the current BS6 evaporative emission certification standard (2.0 g/day) and 13x higher than the BS6 exhaust NHMC emission standard (68 mg/km).** This clearly demonstrates that the current canister systems for BS6 vehicles are undersized and do not effectively control the evaporative and refueling emissions at higher temperatures and higher vapor pressures of E20 fuel.

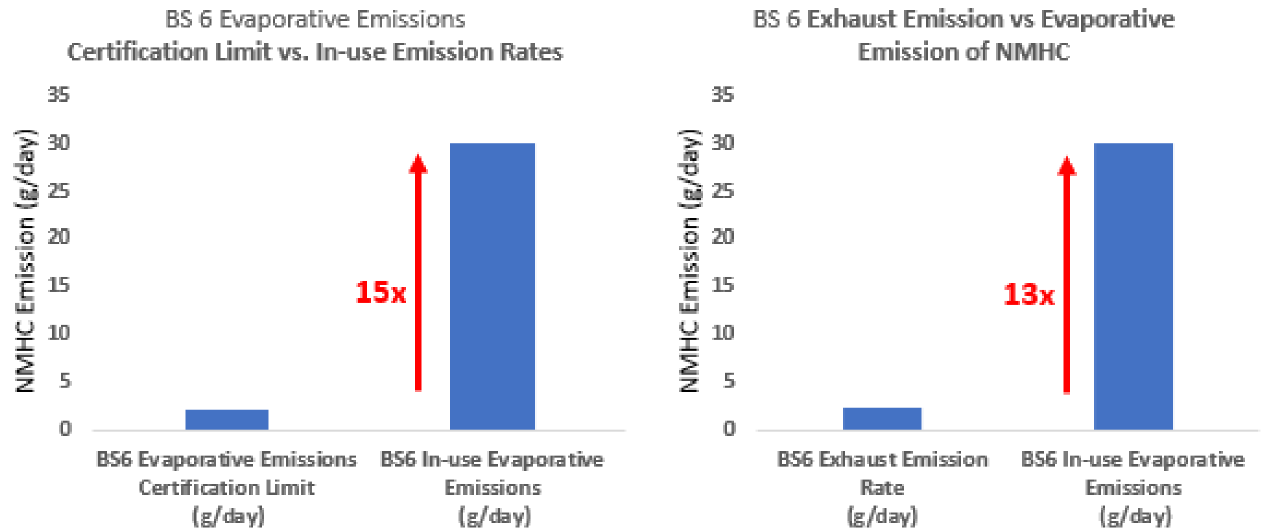
If BS7 were to adopt a refueling emission standard of 0.05 g/L (ORVR) and a 48-hr hot soak + diurnal evaporative emission limit of 0.50 g/day, the combined evaporative and refueling emissions rate can be reduced by 92% to less than 2.5 grams per vehicle per day across all temperature conditions. The canister systems to meet these standards can be produced in India and implemented by OEMs cost-effectively, as has been demonstrated for decades in the US, Canada, China, and Brazil. Most recently, Brazil has demonstrated the effectiveness of a similar standard for E22 and E22/E100 flex fuel vehicles.

Figure 2. Comparison of daily evaporative and refueling emission rates for a current BS6 standard and an optimal BS7 scenario



[17] Drive 12,000km a year? Cheaper to call cab - Times of India (indiatimes.com)

Figure 3. Comparison of daily evaporative and refueling emission rates to current BS6 certification standards for evaporative and exhaust non-methance hydrocarbons (NMHC)



4. Conclusion and Recommendations

There are unique situations in India that warrant a different approach than Euro 7 for the control of evaporative and refueling emissions. These include (1) a large and growing proportion of petrol fueled light duty vehicles, representing more than 3.2MM vehicles per year and 65% of new car sales (2) promotion of E20 fuels that have a higher in-use vapor pressure leading to higher evaporative and refueling emission rates under all in-use conditions (3) significantly higher ambient temperatures and increasing prevalence of heat waves due to climate change leading to higher in-use evaporative and refueling emissions (4) a longer time horizon for the continued sale of petrol/ethanol fueled ICE vehicles than Europe and (5) a strong need and desire to improve air quality for all Indian citizens.

Europe has a long history of not prioritizing and not advancing evaporative emissions control to improve air quality, while other regions of the world, including US, Canada, China, and Brazil, have all significantly advanced evaporative and refueling emissions control. It should be recognized that both China and Brazil made the policy decision to not follow European standards due to their desire to improve air quality and recognition that the European standards were insufficient. **At a minimum, India should implement evaporative and refueling emission standards equivalent to Brazil (0.05 g/L refueling limit (ORVR) and a 48-hr hot soak + diurnal limit of 0.50 g/day). This would reduce evaporative and refueling emissions by more than 92% during critical in-use conditions and retain the valuable fuel vapor on the vehicle to be burned in the engine as fuel, saving consumers on fuel costs and reducing their exposure to air toxics found in evaporative emissions of petrol, such as benzene.**

Other options to consider to adapt the evaporative and refueling test procedures to be more relevant to India conditions include (1) a higher diurnal temperature range (40°C or higher), such as implemented by the California Air Resources Board (CARB) to reflect conditions more representative of worst case in-use conditions for evaporative emissions when air quality needs to be controlled most (heat waves) (2) a three-day (72-hr) diurnal to reflect multi-day parking events and (3) increasing the vapor pressure of the certification fuel to 70 kPa to match the vapor pressure encountered in-use for E20 splash blends.

High Power Density Fuel Cell Systems for Commercial Vehicles

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Abstract. Fuel cells are a promising but challenging technology for achieving zero-emission heavy-duty commercial vehicles. AVL has developed a modular 156 kW fuel cell system and based on it an optimized fuel cell powertrain for a long-haul semitrailer tractor that meets the industry requirements of lifetime, driving performance, fuel consumption, driving range as well as the costs for acquisition and operation.

Keywords: Fuel Cell System, Commercial Vehicles, Fuel Cell Stack, Power Density.

1 Market Expectations on Fuel Cell Trucks

For achieving decarbonization of on-road transport of goods and corresponding emission regulation targets, it is necessary to find viable solutions as alternative to incumbent diesel truck powertrains. Battery technology has proven to be a perfect alternative to internal combustion engines in passenger cars as typical driving patterns and end-user expectations are met. However, in commercial vehicles the real-life usage especially of trans-national long-haul routes, often does not fit to battery-only solutions. Hybridized powertrains of fuel cells and battery do possess attractive properties to fulfil truck fleet operators' needs. But what does the market really want from a zero-emission powertrain? When talking to truck fleet operators, their clear wish is to maintain diesel truck properties in terms of driving range and performance to not affect daily fleet operation. Furthermore, commonality with existing diesel truck platforms and trailer architectures is a must to preserve payload capacity [1,2].

Many new players on the market aside of legacy truck OEMs are willing to tackle these challenges to provide a real zero-emission commercial vehicle solution to on-road transportation of goods. Based on announcements and observable developments, it is expected that until 2030 the global truck fuel cell market will be dominated by retrofitting or up-fitting of diesel trucks with a strong supplier-based approach. A classic OEM market with insourcing of technologies is projected for the upcoming decade when annual production volumes rise.

2 AVL's Fuel Cell Demo Truck Development

To demonstrate a viable solution for fuel cell trucks that considers all aspects of fleet operator demands, AVL initiated the development of a truck demonstrator. To mitigate doubts regarding real-life applicability and integrability of hybridized fuel cell powertrains into existing truck platforms, a European 4x2 semitrailer tractor with sleeping cabin and a wheelbase of 3.8 m was chosen as development basis. Certainly, this approach came with the most challenging boundaries in terms of packaging to host the fuel cell system(s), the HV battery, e-drive, and hydrogen storage systems. The corresponding high-level targets are summarized in Table 1 [2].

Table 1. Summary of High-Level Targets of AVL's Demo Truck.

Truck targets

Vehicle platform	European 4x2 semitrailer tractor with sleeping cabin and a wheelbase of 3.8 m
Vehicle gross weight	42-ton gross combination weight
Driving range	> 400 km
Re-filling time	< 15 min
Other	- Highway uphill driving without vehicle performance reduction - No performance derating up to ambient temperatures of 35 °C
AVL developed powertrain elements	- Fuel cell system - E-axle - HV Battery - Thermal management system - Vehicle energy management system

Following a holistic model- and function-based development approach, vehicle requirements were derived from analysis of real-life usage data obtained from a logistics partner within the FFG-funded project "HyTruck" [3]. For this, a vehicle model was used to determine power requirements as basis for the e-axle development. Furthermore, the optimized power split between fuel cell system(s) and HV battery was investigated to define the fuel cell system power as well as the HV battery power and capacity, also considering recuperation aspects.

The comprehensive analysis revealed that the conversion of conventional 40-ton diesel-powered trucks toward fuel cell powered zero-emission powertrains requires 540 kW peak power at the axle and about 300 kW of fuel cell power to achieve a competitive performance and cost. In order to be able to support different truck powertrains from medium-duty to heavy-duty application it was decided to follow a modular system approach and to develop a fuel cell system with about 150 kW power output. As a side-benefit, the modularized approach allows (due to redundancy) to increase uptime of the truck since failure of one module could be mitigated by a corresponding de-rated operation on a single system.

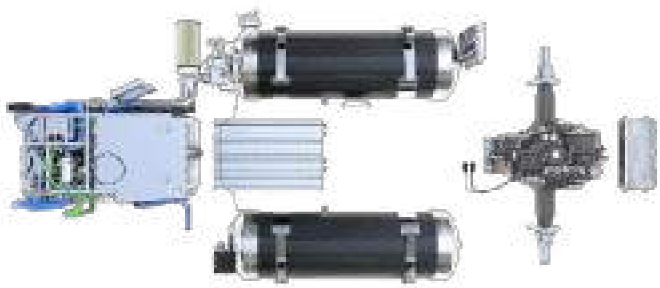

Fig. 1. New developed powertrain elements (fuel cell system, HV battery, hydrogen storage system, e-axle and power electronics) and their corresponding integration positions in the truck frame (© AVL).

From a packaging and integration point of view, most beneficial integration spaces for the powertrain elements were elaborated, considering commonality with existing vehicle platforms, safety, and weight

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distribution aspects, ultimately leading to the conclusion that the common denominator among trucks would be to retain conventional existing assembly spaces. Thus, the fuel cell system should fit into the space of the internal combustion engine, the battery should be placed into transmission space, the hydrogen storage should be arranged into the diesel tank spaces left and right of the frame and the e-axle should replace the rear-axle of a conventional truck (Fig.1).

2.1 AVL's 156 kW Heavy-Duty Fuel Cell System

The new developed dedicated heavy-duty fuel cell system is based on AVL's Gen0 fuel cell stack platform (see Fig.2 and Table 2). The stack with its power density of 4.1 kW/l was specifically designed and developed to meet commercial vehicle requirements in terms of dimensions and lifetime expectations. The basis of the stack is a single-cell row design based on carbon bipolar plates.

Fig. 2. AVL Gen0 stack platform (© AVL).

Table 2. Key Specifications of AVL's Gen0 Fuel Cell Stack.

Gen0 Fuel Cell Stack	
Power (modular)	30 - 150 kW per cell row
Efficiency at 0.6 V	48%
Power density	4.1 kW/l
Plate material	Carbon
Freeze start-up temperature	> -30 °C
Lifetime	> 15,000 h

For the development of the heavy-duty fuel cell system, a two-cell-row configuration was chosen to meet power, packaging as well as HV architecture requirements (see Fig.3). The fuel cell system was designed to ensure that two modules can be integrated on top of each other into the common assembly space of diesel engines in existing truck frames. To achieve this target, significant improvements with respect to fuel cell system power density were needed to comparable state-of-the-art concepts available in the competitor's landscape today.

Fig. 3. AVL's 156 kW heavy-duty fuel cell system based on a two-cell-row configuration of AVL's Gen0 stack (© AVL).

In Fig. 3 it is clearly visible that the cell rows of the stack incl. stack housing make up approx. 50% of the entire fuel cell system volume. Comprehensive packaging analysis considering form factors of commercial off-the-shelf fuel cell system components as well as intensive sub-system development and creativity identified the optimal arrangement of balance of plant components and the corresponding necessary routing of fuel, air and cooling pipes and hoses, leading to a favorable solution (see Table 3).

To push power density and efficiency of the fuel cell system, the collected real-life operation data were scrutinized for time shares spent at different power levels.

Obviously, compared to passenger cars, fuel cell systems operate more often at high-power levels in fuel cell trucks. An oversizing of fuel cell system power to average operation power as done in fuel cell passenger cars is not applicable in trucks due to packaging restrictions and cost efficiency attributes. Thus, the recovery of electrical power via an exhaust turbine is a feasible option to increase total efficiency and power output of the truck fuel cell system, even though this increases system complexity and number of components [4].

So, how to integrate an increased number of components in an already very restricted assembly space of a 4x2 semi-trailer tractor for European freight transport with sleeping cabin and a wheelbase of 3.8 m?

The key was to ensure multiple functions were combined into a single component: the so-called media supply unit. As a result, the hydrogen recirculation, water separator, purge, drain as well as media distribution and collection functions were integrated into a single component, drastically reducing package space demand and component weight, resulting in a high power-density fuel cell system [4].

Table 3. Key Specifications of AVL's Heavy-Duty Fuel Cell System.

Fuel Cell System

Rated power	156 kW
Efficiency at rated power	45%
Power density	0.33 kW/l
Freeze start-up temperature	> -30 °C
Lifetime	> 15,000 h

Benchmarking against other available fuel cell systems on the market revealed a significant power-density improvement by AVL's design over state-of-the-art fuel cell systems for commercial vehicles (see Fig. 4).

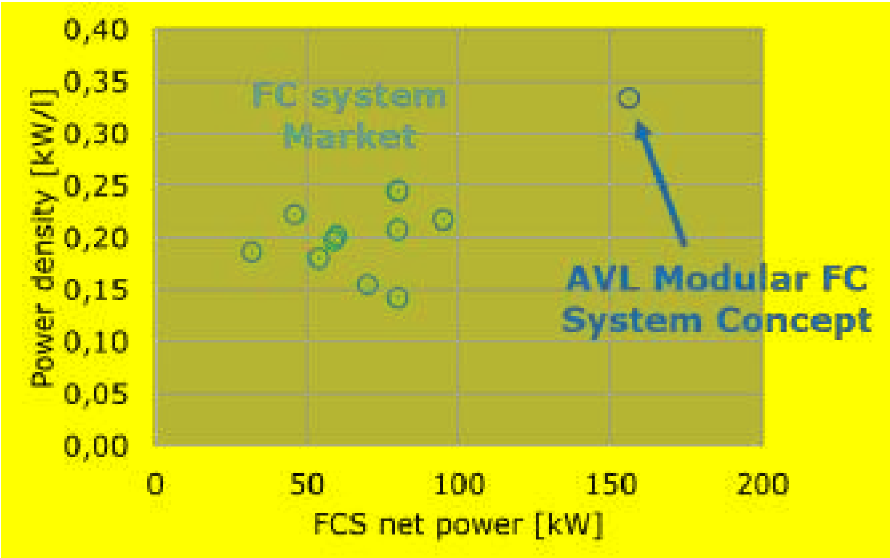

Fig. 4. AVL's heavy-duty fuel cell system possesses a significantly higher power density than other systems on the market. (© AVL)

2.2 Powertrain Integration

As described earlier, the integration areas of the new powertrain elements that make up a hybridized fuel cell truck powertrain were chosen based on truck fleet operator demands and highest commonality with incumbent diesel truck and trailer platforms to not impair payload volume and capacity. In Fig. 1 the summary and arrangement of these elements is depicted. The core powertrain elements are: i) a 312 kW fuel cell system, ii) a 72 kWh HV battery, iii) a 700 bar hydrogen storage system with a capacity of 32 kg and iv) a 540 kW peak e-axle based on two electric motors with optimized torque curve.

In a hybridized powertrain all above-mentioned elements are interconnected to ensure real-life operation targets are met. The achievable continuous power output of the powertrain is certainly determined by the cooling capacity that could be installed in the truck platform as the thermal loads of the fuel cell system(s), the e-axle, the HV battery and the brake resistors need to be dissipated [2].

A holistic and efficient thermal management was designed based on an intelligent predictive energy management and power split as well as hybridization strategy. The three cooling circuits (high-temperature (fuel cell system), medium-temperature (power electronics) and low-temperature (HV battery)) were interconnected to allow for an efficient and effective heat transfer between the elements and ambient (see Fig.5).

Additionally, the total radiator frontal surface area was increased to 1.8 m^2 that equals 180% of the initial (diesel) truck radiator size, while maintaining the entire cooling package frontal area unchanged. The required air throughput of the radiators was calculated, and aerodynamic simulations were employed to identify an efficient lead-off of air masses to avoid negative impacts on driving performance and drag.

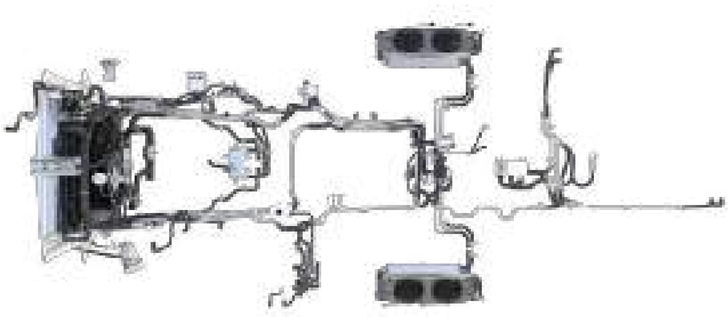

Fig. 5. Thermal management system of AVL's fuel cell demo truck. (© AVL)

To host the new powertrain elements, the structural and mechanical properties of the frame and chassis were analyzed, and the required adaptions were derived with the aim to minimize the number of changes to the original frame.

Obviously, the weight distribution of the hybrid powertrain is different to the diesel powertrain. Especially, the e-axle weighs more than the standard axle and thus, the frame structure and the chassis suspension required reinforcement. The corresponding adaptions were calculated considering excitation frequencies to ensure structural integrity, safety but also targeting driving attributes such as performance and ride comfort. The resulting optimized fuel cell truck frame is depicted in Fig. 6.

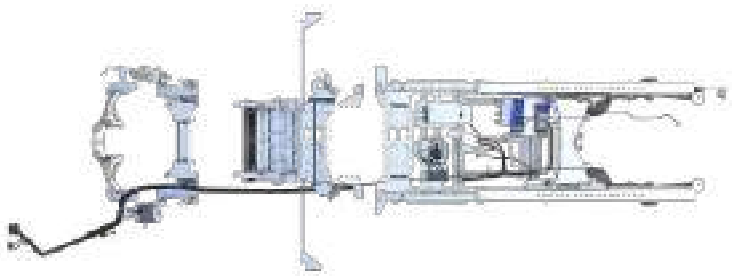

Fig. 6. The truck frame was optimized to the hybrid fuel cell powertrain. (© AVL)

Finally, the power flow and control features between the different electric powertrain elements (fuel cell system(s), HV battery, e-axle, etc.) were developed based on targeted vehicle driving functions. The coordination of complex operational targets (e.g., durability, uptime, and efficiency) and the subsequent interactions of powertrain elements, while ensuring to continuously cover the requested power demand was achieved with a model-based hybrid powertrain control software development [5].

The powertrain control is based on non-predictive and predictive software components. The non-predictive control ensures that the operating strategy can react in accordance to reached element or component limits (e.g., SOC limits of the HV battery) and deviate from efficient operating modes to charging or discharging modes. The predictive controls use information of the route ahead and calculate in a multi-object optimization the targeted element and component setpoints to avoid reaching system limits. For this short-range (e.g., < 10 km) as well as long-range (e.g., entire route) horizons were established to accomplish the specific optimization goals [5].

To demonstrate the benefits of the predictive control over conventional controls an exemplary, yet challenging, classic transport route on an Austrian highway was taken from the real-life operation data set that was available to the development team. In Fig. 7 the results are plotted, demonstrating the overall powertrain efficiency increase due to considering the properties of the route ahead.

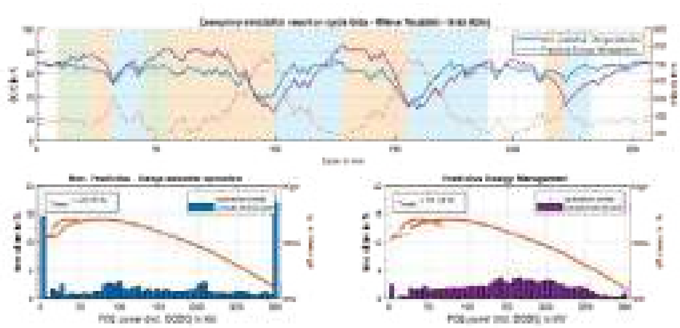

Fig. 7. Comparison of non-predictive and predictive controls for a fuel cell truck [5]. (© AVL)

The main differences between a non-predictive strategy and an advanced predictive energy management are highlighted in green and orange and are visible on the different trajectory of the HV battery SOC [5]. Sections in green color indicate that the predictive controls act in advance to charge the battery to enable support by the battery for the upcoming uphill section, shown in orange. The overall efficiency was increased by 2%, resulting in a consequent reduction of hydrogen fuel consumption.

To further optimize efficiency over lifetime and to achieve lower cost, ageing models for the fuel cell system and the HV battery can be employed to allow the predictive controls to consider the influence of degradative stressors for fuel cell stacks and battery cells during operation.

3 Summary and Conclusion

AVL demonstrated a market-oriented fuel cell powertrain and integration solution for a 4x2 semi-trailer tractor for European freight transport with sleeping cabin and a wheelbase of 3.8 m that allows to use all common trailers, despite the biggest constraints in terms of available installation space. As such, AVL's fuel cell demo truck showcases the potential of fuel cell powertrains for any other truck application (Fig.8).

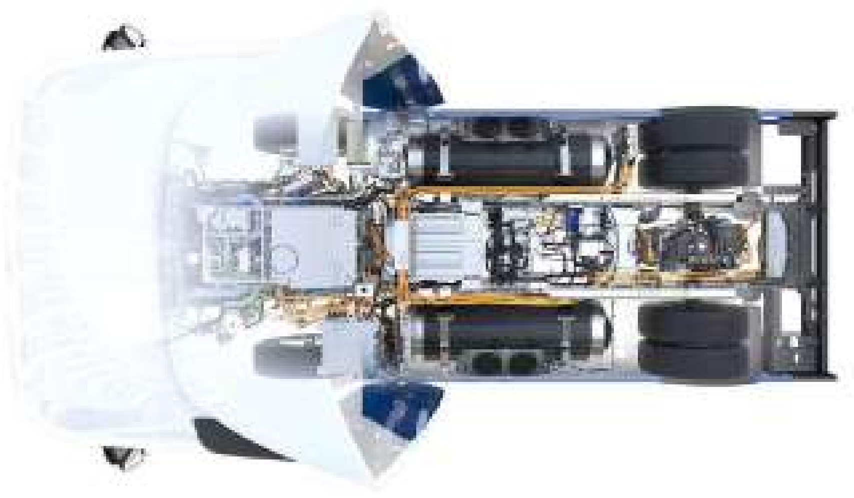

Fig. 8. The final powertrain integration of AVL's fuel cell demo truck. (© AVL)

The model- and function-based development approach allowed to tackle the integration challenges and to derive comprehensive technical solutions for an industry-ready fuel cell truck already at a virtual development stage, avoiding cost-intensive hardware loops. Holistic concepts on an energy and thermal management level that consider predictive conditioning of the powertrain elements is a key property for real-life operation of the truck on a daily basis. The understanding of aging properties and corresponding degradative stressor for fuel cell stacks and battery cells further allows to optimize the entire vehicle performance, efficiency, and cost over lifetime.

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Alternative Fuels in India: Technology and Regulatory Landscape

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Introduction

India's energy landscape is undergoing a significant transformation as the nation seeks to reduce its reliance on conventional fossil fuels and address pressing environmental concerns. The push for alternative fuels is driven by the need to enhance energy security, combat air pollution, and meet global climate commitments. This write-up delves into the various alternative fuel technologies being adopted in India, along with the regulatory framework supporting their implementation.

1. Compressed Natural Gas (CNG)

A. Overview:

Compressed Natural Gas (CNG) is primarily used as a cleaner alternative to petrol and diesel in vehicles. CNG is a fossil fuel that produces fewer emissions of harmful pollutants, making it an attractive option for urban transport.

B. Key Features

i. Environmental Benefits: CNG vehicles emit significantly lower levels of carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter compared to diesel and petrol vehicles.

ii. Cost-Effectiveness: The cost of CNG is generally lower than that of petrol and diesel, leading to reduced operating costs for vehicle owners.

iii. Infrastructure Development: India has established a robust network of CNG stations, particularly in metropolitan areas like Delhi, Mumbai, and Kolkata, with over 3,000 stations operational.

C. Challenges

i. Limited Range: CNG vehicles typically have a shorter driving range compared to their petrol or diesel counterparts, which can be a concern for long-distance travel.

ii. Infrastructure Gaps: While urban areas have a good network of CNG stations, rural regions still lack adequate refuelling infrastructure.

2. Liquefied Natural Gas (LNG)

A. Overview

Liquefied Natural Gas (LNG) is increasingly being recognized as a viable alternative fuel for heavy-duty vehicles, including trucks and buses. LNG is natural gas that has been cooled to a liquid state, allowing for more efficient storage and transportation.

B. Key Features

i. Longer Range: LNG vehicles can travel longer distances without refuelling, making them suitable for freight transport.
ii. Lower Emissions: LNG combustion results in lower greenhouse gas emissions compared to diesel, contributing to cleaner air quality.
iii. Infrastructure Initiatives: The Indian government is planning to establish around 1,000 LNG refuelling stations along major highways to facilitate the adoption of LNG vehicles.

C. Challenges

i. High Initial Investment The cost of LNG vehicles and the required infrastructure can be high, posing a barrier to widespread adoption.
ii. Public Awareness There is limited awareness among fleet operators and consumers about the benefits and availability of LNG as a fuel option.

3. Biofuels

A. Overview

Biofuels, including ethanol and biodiesel, are derived from renewable biological materials. India is focusing on biofuels to enhance energy security and reduce greenhouse gas emissions.

B. Key Features

i. Ethanol Production: India has mandated a 10% ethanol blending in petrol, with a target of 20%blending by 2025. Ethanol is primarily produced from sugarcane and other agricultural residues.
ii. Biodiesel Initiatives: Biodiesel can be produced from various feedstocks, including used cooking oil, non-edible oils, and animal fats. The government has set a voluntary target of 5% biodiesel blending in diesel.
iii. Rural Development The biofuel sector can provide additional income to farmers and create rural employment opportunities.

C. Challenges

i. Feedstock Availability The availability of feedstocks for biofuel production can be inconsistent, impacting supply chains.
ii. Competition with Food Production The use of food crops for biofuel production raises concerns about food security and pricing.

4. Hydrogen Fuel Cell Vehicles

A. Overview

Hydrogen is emerging as a promising alternative fuel, particularly in the form of Fuel Cell Electric Vehicles (FCEVs). The Indian government has launched the National Hydrogen Mission to promote hydrogen production and utilization.

B. Key Features

i. Diverse Production Methods: Hydrogen can be produced through various methods, including electrolysis, steam methane reforming, and biomass gasification.
ii. Zero Emissions: FCEVs emit only water vapor, making them an environmentally friendly option.
iii. Infrastructure Development: Plans are underway to establish hydrogen refuelling stations in urban areas and along major highways.

C. Challenges

i. Production Costs: The cost of hydrogen production remains high, particularly for green hydrogen produced from renewable energy sources.
ii. Limited Awareness: There is a lack of consumer awareness and understanding of hydrogen technologies and their benefits.

5. Hydrogen for IC Engines

The construction of an internal combustion engine powered by hydrogen necessitates a thorough comprehension of the engine's relative performance and emission characteristics in comparison to traditional fuel-powered engines (such as gasoline or diesel). Hydrogen is a sustainable and clean fuel of the future among the numerous alternative fuels. More significantly, almost no CO_2 emissions are produced when hydrogen is produced using renewable resources. The benefits of combustion stem from the ignitability and diffusivity of H_2 molecules.

A. Engine Architecture Development Aspect:

The two main categories of hydrogen engines are port injection and direct injection. The former offers the benefit of increased engine performance without aberrant combustion; however, the backpressure needed for the hydrogen injector must be increased. Conversely, the latter has the benefit of longer injector life and lower backpressure. The hydrogen ICE requires a lower compression ratio than diesel engines to avoid abnormal combustion and less protuberances that could cause hot spots.[1][2] In contrast to gasoline or diesel engines, hydrogen internal combustion engines often use three piece oil control rings rather to the two-piece rings found in base engines. This modification was done because the throttle valve predicts a negative pressure during the hydrogen ICE's intake stroke, and three-piece oil control rings work well to minimise engine oil consumption in negative pressure scenarios. By doing this, the carbon emissions from burning lubricant inside the combustion chamber will be significantly reduced. To lessen blow-by gas and hydrogen concentration in the crank case, the top ring gap is also lowered.[3][4]. Due to lower density, hydrogen has to be stored at higher storage pressure when compared to Gasoline and Diesel. Hydrogen also fall in Class A type of fuel when compared to diesel.

B. Performance Characteristics:

Due to the hydrogen fuelled ICE's significantly lower irreversibility and specific fuel consumption, it was discovered that the hydrogen fuelled engine had a greater proportion of its chemical exergy converted into work exergy, indicating a second law efficiency of 41.37% as opposed to 35.74% and 37.02% for a gasoline and diesel fuelled engine, respectively. Because there is more convective heat transfer during hydrogen combustion, the hydrogen fuelled engine produces more energy through heat transfer or thermal availability. However, the larger cooling load that lowers the power of an ICE powered by hydrogen makes this seemingly high accessible thermal energy, or thermal "exergy," misleading. [5][3][6]

C. Emission Characteristics:

Life cycle analyses suggest hydrogen ICE vehicle are more efficient than gasoline and Diesel internal combustion engine vehicles. Greenhouse gas (GHG) emissions of hydrogen ICE vehicle is 14% lower than the conventional engines, but criteria emissions of NOx are approaching or exceeding two times those of gasoline engine. The greenhouse gas emissions from fuel cell or ICE powertrains powered by green hydrogen are almost twice as high as those of an electric powertrain powered by renewable electricity.[7] The only inevitable emission is NOx in a H2ICE as compared to the Gasoline or diesel engine. There are many possible combinations of injection timing, ignition timing, lambda and EGR rate that can be used in a direct injection system to optimize the NOx. As H2ICE operate on higher lambda greater than 2, a proper reduction system is required to treat the engine out NOx.[8] According to literature studies, the H2ICE's CO_2 emissions are not zero, but they are incredibly low when measured against a EURO VI diesel and petrol engine. The primary cause of the CO_2 detected in the exhaust, even in cases where hydrogen combustion is 100%, is the ambient CO_2 content, which in this instance ranges from 0.040 to 0.041 mass %. This level of CO_2 is also detected in the engine exhaust since CO_2 enters the engine with ambient air and exits the engine unchanged.[9] For conventional internal combustion engines, NOx emissions and incomplete combustion emissions—that is, particulates, unburned hydrocarbons (HC), and carbon monoxide (CO)—are the pertinent pollutant emissions. Partially oxidised lubricating oil may be the source of unburned hydrocarbons and CO emissions from hydrogen engines.[10]

6. Bio-CNG

A. Overview

Bio-CNG, also known as Compressed Biogas, is a renewable and clean-burning transportation fuel produced by upgrading biogas to natural gas quality. It is made from organic waste materials like agricultural waste, food waste, sewage sludge, and industrial effluents.

B. Key Features

i. Renewable and Sustainable: Bio-CNG is a renewable fuel derived from organic waste, making it a sustainable alternative to traditional natural gas produced from fossil fuels.

ii. Environmental Benefits: The production and use of Bio-CNG can reduce greenhouse gas emissions, improve air quality, and contribute to a circular economy.

iii. Economic Advantages: Bio-CNG production aligns with market demand, making it economically viable. It also has the potential to generate renewable fuel credits to offset production costs.

C. Challenges

i. Insufficient Feedstock Availability: One of the primary challenges in Bio-CNG production is the inconsistent supply of suitable organic waste. Many municipalities do not effectively segregate waste, leading to contamination with non-biodegradable materials. This not only affects the quality of the feedstock but can also damage anaerobic digesters, reducing their efficiency and output.

ii. High Capital Investment: Setting up a Bio-CNG plant requires a substantial capital investment of ₹20 to ₹40 crores (approximately $2.5 to $5 million) for a facility capable of processing 100 tonnes of waste per day, which may deter small-scale investors and farmers from participating in Bio-CNG production.

iii. Use of Conventional Technology: Existing Bio-CNG plants often use outdated technology, limiting efficiency and scalability. The lack of advanced purification and upgrading technologies can impede the production of high-quality Bio-CNG meeting market standards.

iv. Lack of Infrastructure: The distribution network for Bio-CNG is still underdeveloped. There is a need for robust infrastructure for storage, transportation, and refuelling stations to make Bio-CNG widely accessible to consumers and industries.

7. Ammonia

A. Overview

Ammonia is well known as a refrigerant and its supply eco-system is well developed in India. Ammonia can be used as a carrier of hydrogen and can be stored and shipped for use in emission-free fuel cells and turbines. Efforts are also underway to combust ammonia directly in power plants and ship engines.

B. Key Features

i. Developed Infrastructure: storage facilities, ammonia pipelines and tankers are available in India to transport ammonia.

ii. Environmental Benefits: The use of ammonia can reduce greenhouse gas emissions, improve air quality due to absence of carbon

iii. Economic Advantages: Ammonia is cheaper in cost as compared to pure hydrogen and other synthetic fuels

C. Challenges

i. Lack of Recognition as a fuel Currently ammonia is not recognized as an automotive fuel. The regulations and standards permitting its use need to be developed.

ii. High Corrosivity: Ammonia is highly corrosive

8. Synthetic Fuels

A. Overview

Synthetic fuels are artificial fuels which are manufactured with designer properties using proprietary processes. Examples of synthetic fuels are DME, GTL etc..

B. Key Features

i. Superior performance: Synthetic fuels use additives for boosted performance including octane/cetane boosters, anti-corrosion & high lubricity additives.

ii. Environmental Benefits The production and use of synthetic fuels can reduce greenhouse gas emissions and improve air quality

C. Challenges

i. Insufficient Availability: The generation, storage and dispensing of synthetic fuels is inadequate in India.

ii. High Cost: Synthetic fuels are expensive as compared to the fossil fuels due to additives and small bath proprietary process production.

iii. IP Barriers Little data is available in public domain due to process confidentiality and patents.

9. Carbon Capture and Storage (CCS)

A. Overview

Carbon capture and storage (CCS) is a way of reducing carbon dioxide (CO_2) emissions, which could be key to helping to tackle global warming. It's a three-step process, involving: capturing the CO_2 produced by power generation or industrial activity, such as hydrogen production, steel or cement making; transporting it; and then permanently storing it deep underground.

B. Key Steps

There are three steps to the CCS process:

1. Capturing the CO_2 for storage

The CO_2 is separated from other gases produced in industrial processes, such as those at coal and natural-gas-fired power generation plants or steel or cement factories.

2. Transport

The CO_2 is then compressed and transported via pipelines, road transport or ships to a site for storage.

3. Storage

Finally, the CO_2 is injected into rock formations deep underground for permanent storage.

C. Challenges

i. High Costs

One of the major drawbacks of CCS is that is still has a relatively high cost. The technology requires significant investments in research, development, and infrastructure, which can be prohibitively expensive.

ii. Energy Intensive

Some CCS technologies can also be an energy-intensive process. It requires a significant amount of energy to capture carbon dioxide and transport it to storage facilities.

iii. **Environmental Risks**

Carbon capture and storage involves the injection of carbon dioxide into geological formations. While this can be an effective method for storing carbon dioxide, it also poses environmental risks, such as leakage or seepage into groundwater or the atmosphere.

10. Regulatory Framework for Alternative Fuels in India

India's regulatory environment plays a crucial role in promoting alternative fuels. The government has implemented several policies and initiatives to support the transition to cleaner fuels:

A. CMVR Regulations

The government has notified several alternative fuels through various GSRs which are added in the rule 115b of CMVR.

B. Automotive Industry Standards (AIS)

The AIS outlines technical specifications and safety requirements for alternative fuel vehicles, ensuring that they meet safety and performance standards.

C. Bureau of Indian Standards (BIS)

The BIS sets quality standards for alternative fuels, including specifications for biofuels, CNG, and LNG, ensuring that they meet safety and environmental requirements.

Summary:

Hydrogen and other alternative fuels are a desirable energy source for transportation due to its high-power output, clean emissions, and abundant availability, which can be produced from water and surplus solar and thermal energy. Additionally, by reducing the cost of ownership, the ICE strategy outperforms the FCV approach in terms of cost and performance. ICE technology has been around for more than a century, making it well- suited for mass production at reasonable prices. The heavy- duty internal combustion engine (ICE) industry has shown increased interest in hydrogen, biofuel and natural gas combustion engines as a means of expediting the decarbonisation of well to- wheel emissions. Driven by the govt initiatives, contribution of all key stakeholders is essential for the establishment of a carbon neutral economy.

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Commercial Hydrogen Engine with 50 % BTE

- Expert Article

September 03, 2024

- **Anton Arnberger**
  Senior Product Manager Commercial Engines

View Profile on

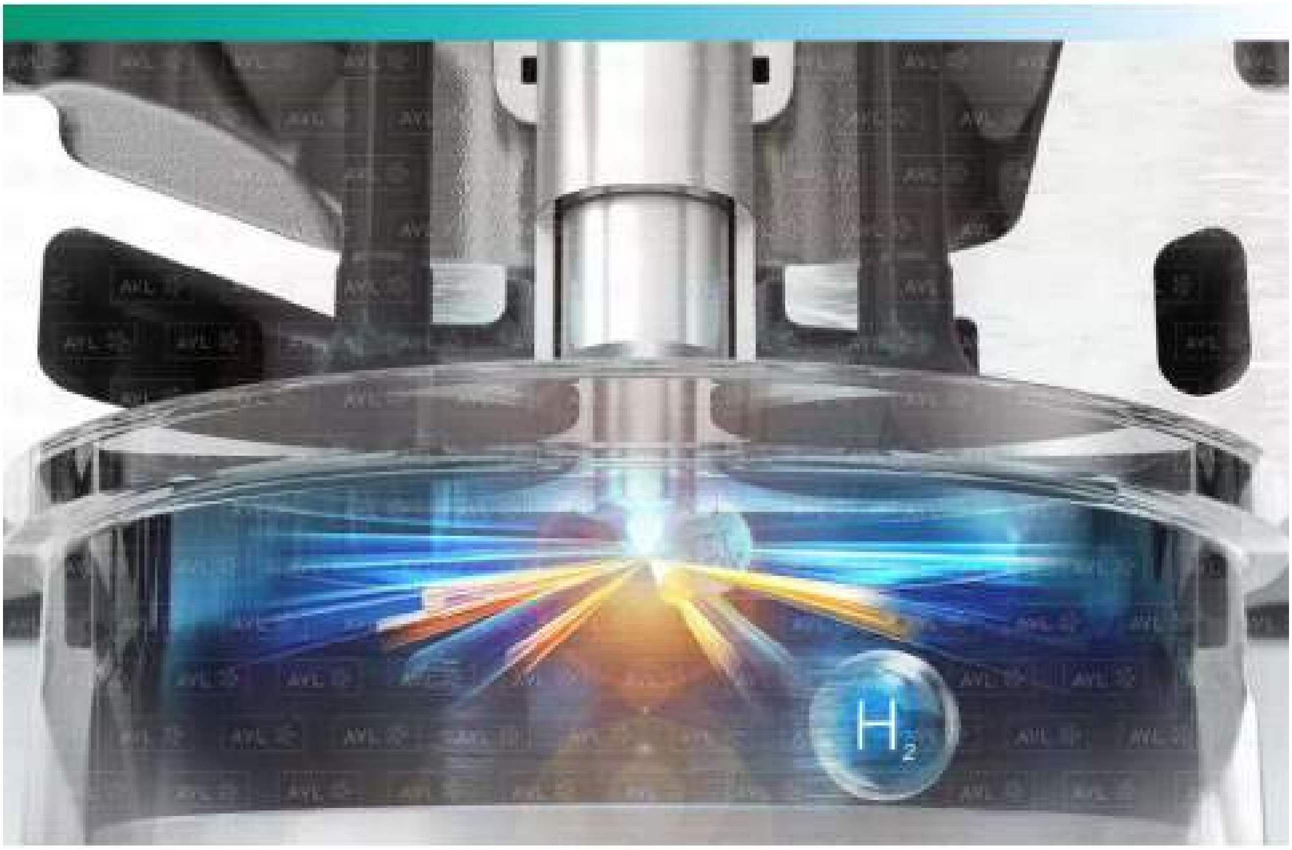
- CO_2 reduction goals for commercial vehicle fleets are pushing the developments of hydrogen engines. Hydrogen as a fuel in internal combustion engines for commercial applications allows either spark ignited lean burn or high-pressure direct injection concepts. Such late cycle direct injection offers benefits in terms of power density and transient response. Also, the fuel efficiency potential is outstanding, a major contributor to optimize total cost of ownership (TCO) for HD (heavy-duty) vehicles.
  AVL, Tupy and other partners demonstrated a 50 % BTE on a heavy-duty hydrogen engine using Westport's HPDI (High Pressure Direct Injection) system.

Drivers and Motivation

- The European Union has set stringent CO_2 reduction targets for heavy commercial vehicles, with new regulations introduced in February 2023. These regulations propose stricter fleet targets starting in 2030 and reconsider the potential of hydrogen internal combustion engines as a key powertrain for Zero-CO_2-Emission Vehicles (ZEV). The role of synthetic fuels, such as e-fuels, is still under discussion, with growing political support for their inclusion in the CO_2 reduction strategy.
  The EU primarily follows a Tank-to-Wheel (TTW) approach, emphasizing non-carbon fuels like hydrogen, though the Well-to-Wheel (WTW) approach may also gain traction in certain markets. In the US, the EPA's March 2023 update aligns with these goals, exempting vehicles using hydrogen from CO_2 testing, while California's CARB regulation aims for a zero-emission fleet by 2045, excluding hydrogen engines from the ZEV category.

Hydrogen and its Properties as Fuel for HPDI

- We compared fuel properties of hydrogen with diesel and methane, highlighting key considerations for hydrogen's use in engines. Hydrogen's internal mixture formation with direct injection results in a higher mixture calorific value, increasing the excess air ratio for the same air mass flow. It has a much lower minimum ignition energy than other fuels, making it prone to pre-ignition but suitable for late cycle direct injection. The auto-ignition temperature of hydrogen is high, like methane, requiring specific measures to achieve auto-ignition akin to diesel processes. Additionally, hydrogen exhibits wide flammability limits, accommodating both lean and rich mixtures.



The Demonstrator Program

- In a common project of AVL, TUPY, Westport and ITnA (TU-Graz) an H_2-HPDI demonstrator was designed, built up and tested. Base engine was a 13L HD multi cylinder diesel engine. The 265 -bar peak cylinder pressure capability (for demonstration purposes) was adequate for high pressure direct injection investigations with focus on maximum achievable BTE. It was equipped with high pressure EGR and a VGT (variable geometry turbine).
  The design modification was conducted by AVL. The dual-fuel injectors and the gas (H_2) conditioning module from the Westport HPDI 2.0 fuel injection system were considered. Diesel fuel and H_2 rail, the fuel pipes and the valve cover were tailored to the demands of base engine and the fuel injection system.
  AVL modified its AVL RPEMS (Rapid Prototype Engine Management Systems) for high pressure direct injection operation, which enables transient engine operation.

Efficiency Potential

- The baseline diesel engine showed highest brake thermal efficiency (BTE) of 47.6 %. After equipping the base line engine with Westport's HPDI 2.0 fuel injection system, measurements with hydrogen showed a brake thermal efficiency of 49.1 %, which is an increase in brake thermal efficiency of +1.5 %-points. Contributors were the additional expansion work due to the late cycle hydrogen direct injection and a reduced friction due to lower injected diesel quantity and lower injection pressure (between 200 and 350 bar). An additional optimization of the engine's gas exchange enabled the demonstration of a brake thermal efficiency of 50.1 %.
  For further brake thermal efficiency increase an estimation has been conducted based on 1-D simulations and comparable engine measurements. According to the estimation a brake thermal efficiency of 51.7 % could be identified by increasing the compression ratio to 23.1 and installing a high efficiency turbocharger with fixed geometry twin scroll turbine.

CO2 Reduction Potential

- The H2-HPDI engine did run on a hydrogen energy ratio of 97.5 % in full load conditions. A liquid pilot has turned out to be the only robust measure to ensure stable and robust conditions for an auto ignition of the hydrogen. Pilot quantities as currently used are low enough to fulfill a potential CO_2 limit of 3 g CO_2/t.km for HD long haul truck transport.

Summary, Outlook and Risks

- A collaborative project by AVL, TUPY, Westport, and ITnA (TU-Graz) developed and tested a hydrogen high-pressure direct injection (H_2-HPDI) engine, achieving a brake thermal efficiency (BTE) of over 50 %, with potential improvements up to nearly 52 %. The engine demonstrated performance comparable to diesel engines, with similar full load power and transient torque characteristics.
  Fuel efficiency is a major contributor to optimize total cost of ownership for heavy-duty vehicles. Therefore, high-pressure direct injection is an enabler to achieve carbon neutrality with highest efficiency for high load operation profiles combined with the robustness needed for commercial vehicle applications.
  The H_2-HPDI engine operated with a hydrogen energy ratio of 97.5 % at full load, using a small liquid pilot injection to ensure stable auto-ignition. This setup meets potential CO_2 emission targets of 3 g CO_2/t.km for heavy-duty transport.

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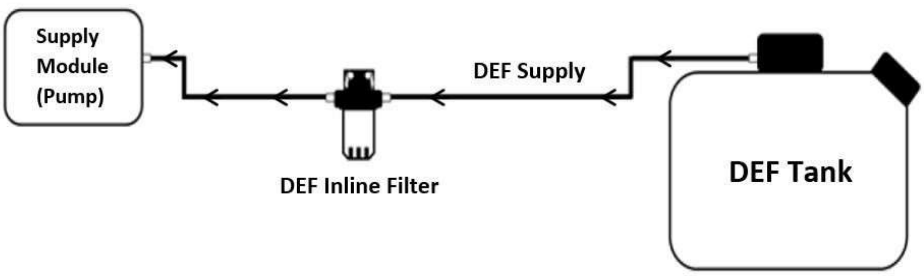

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Gasoline Particulate Filter (GPF) for Indian Market

Mr Noriyuki Hibi, NGK TECHNOLOGIES INDIA PVT. LTD., India

Background of evaluation

Upcoming Euro 7 equivalent emission regulations would essentially require GPF for all gasoline engines and the same could apply to BS7 in India. Changes from the current situation to BS6 w/ WLTC and later BS7 will require a determination of PN impact for the following, Test cycle for MIDC vs WLTC" and "PN size for PN23 vs PN10". NGK has evaluated different type of GPFs, both Coated and Uncoated type, to demonstrate the performance of meeting the upcoming BS7 or EU7 equivalent regulation. Since 2012, NGK has considerable experience in providing World-Class GPF globally, fulfilling market requirements for both Coated and Uncoated GPF.

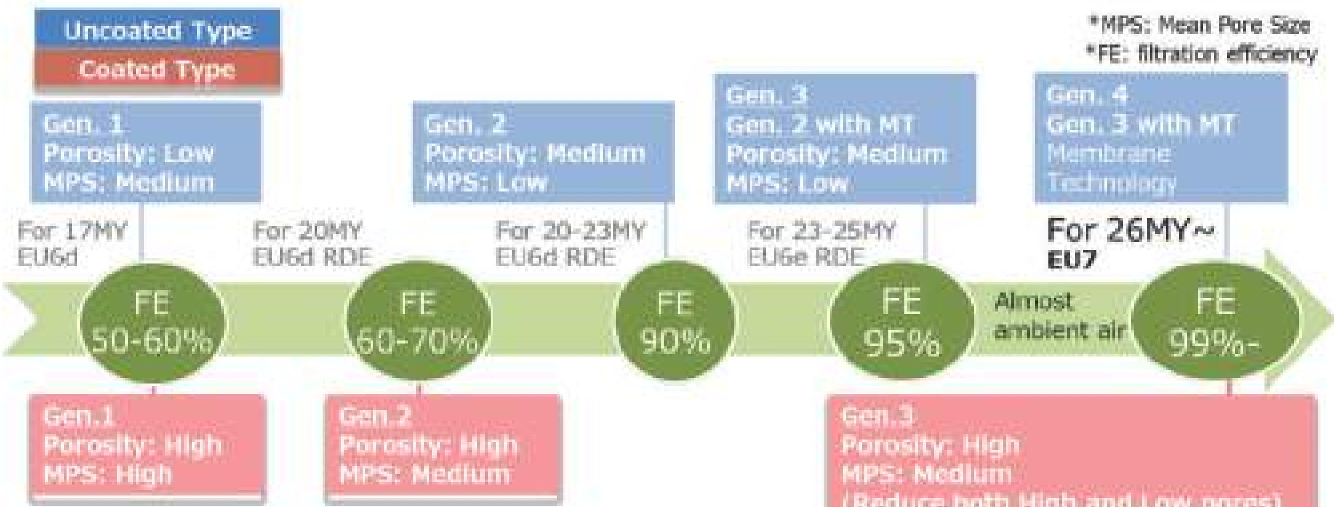

Fig.1: NGK GPF Development Roadmap

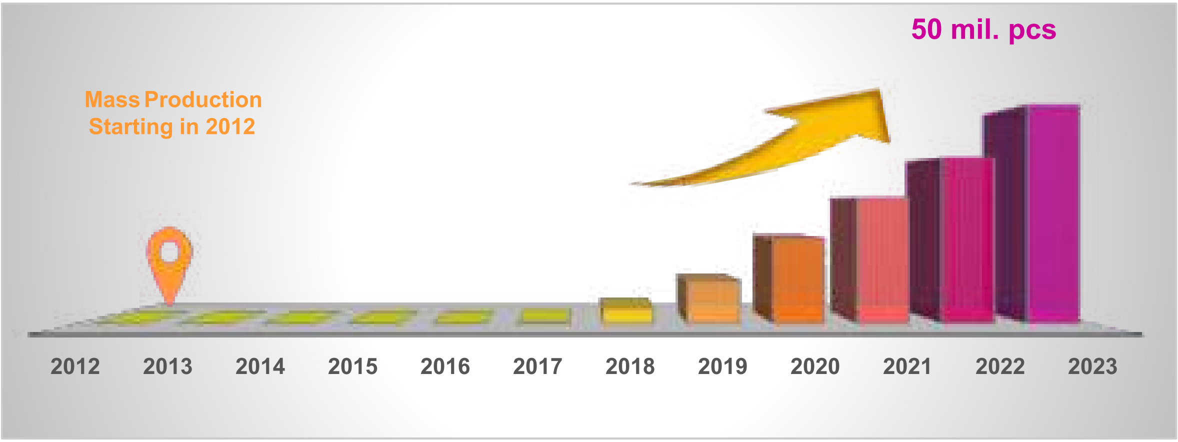

Fig.2: Accumulated GPF Deliveries

Investigation of PN impact for MIDC and WLTC

PN emission in PN23 was evaluated under MIDC and WLTC up to Phase 3. PN emission under WLTC was approx. 4 times higher and Filtration efficiency (hereafter F.E.) was approx. 5% lower than MIDC, because WLTC has higher speed and acceleration than MIDC. Even under such conditions, every GPF could fulfill 6.0E+11 #/km under both of MIDC and WLTC. Among the evaluated GPF, the Uncoated GPF had higher F.E. due to lower MPS.

[Condition]

- **Vehicle**: 1.4L direct injection (Euro6), AFR: λ = 1
- **ATS layout:** CC-TWC + UF-**GPF**
- **GPF**: D132mm x 88mmL, **w/o catalyst**
- **WLTC:** Up to Phase 3

Color	Type		Cell density
	Coated GPF	Gen.1	300cpsi
		Gen.2	
		Gen.3	
	Uncoated GPF	Gen.2	200cpsi
		Gen.3	

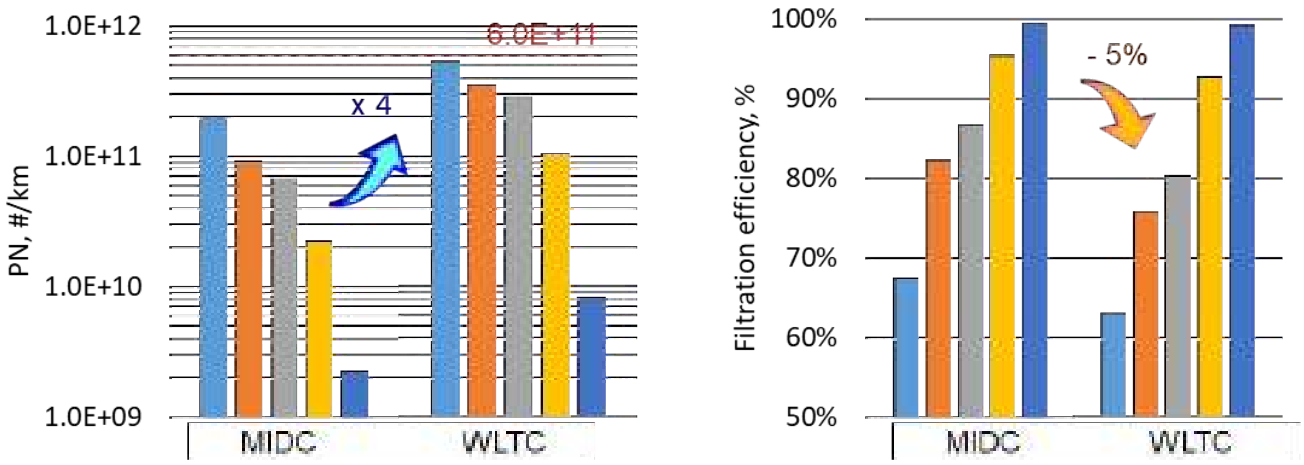

Fig.3 PN emissions and Filtration Efficiency under MIDC and WLTC

Investigation of PN impact for PN23 and PN10

PN emission in PN23 and PN10 were evaluated under WLTC. PN emissions increased approx. 44% by extending the measurement range of PN size from >23nm to >10nm. However, in the case of installing GPF, PN emissions were no big different between PN10 and PN23 because it was estimated PN of 10 to 23nm was collected by the diffusion effect of GPF. Both Coated and Uncoated GPF showed higher F.E. under >10nm measurement.

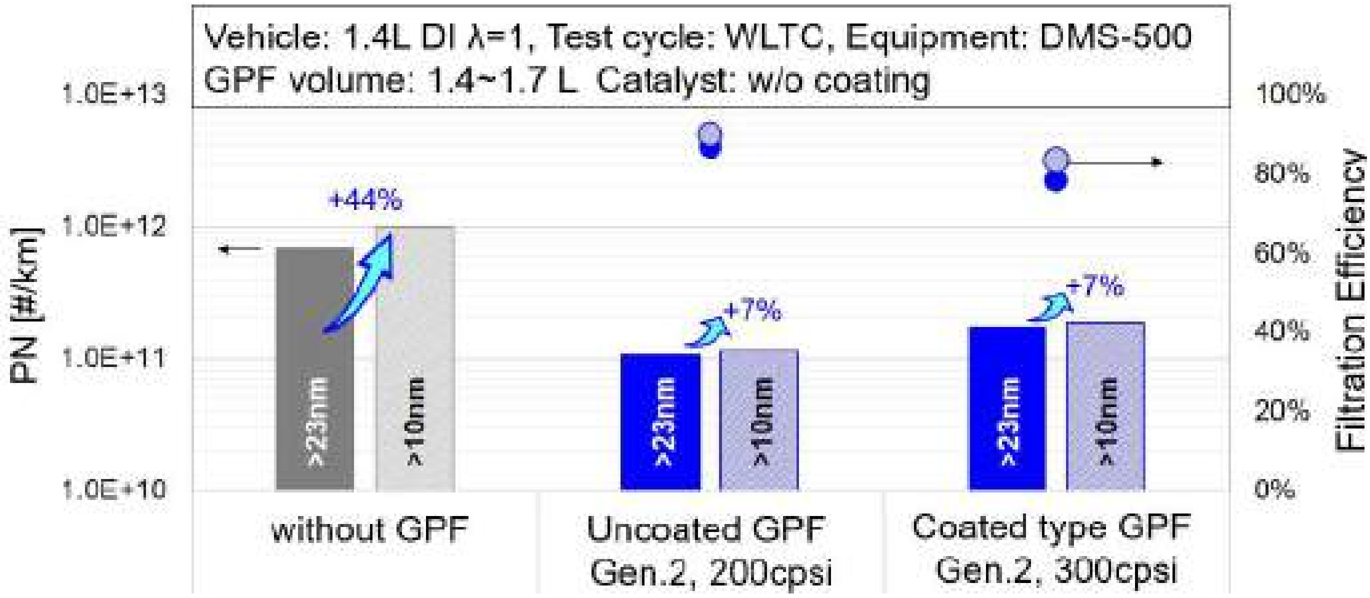

Fig.4：PN emissions and Filtration Efficiency in PN23(>23nm) and PN10(>10nm)

Technical Article 07

Pi GREEN INNOVATIONS PVT. LTD.

Retrofitment: An Impactful Approach towards Reducing Emissions Inventory

-Team Pi Green Innovations

Clean air is need of every large populated town on planet Earth. It is ever growing challenge and every country with pledged to reduce environmental impact including controlling CO_2/GHG footprint has limited options - Moving to tighter emissions norms for automotive and off-highway powering solutions, curbing pollutions through better upkeep and compliances of engines including phasing out polluting older vehicles and equipment. Phase out option usually has socio economic impact and proven difficult to implement. Similarly, a greater renewable energy share along with energy storage, fuel economy norms and non-carbonaceous fuel/s introduction is a major path forward towards controlling GHG emissions

While newer vehicles and equipment introduction with stringent emission norms help cleaning up air, it takes longer time horizon to make impact as older engines keep polluting through their lifecycle. Economically and practically feasible retrofitment solutions is a definite solution that can help reduce emissions inventory faster.

In India, Hon. National Green Tribunal and in effect MoEF & Climate Change introduced a revolutionary initiative to reduce particulate matter emissions from Diesel Gensets, due to their proximity to the dense population. Enforcement of the same across states is a reality now and will contribute it's share to fight pollution. Such effort is unique in India and a model example of how policies can enforce right effect. Retrofitment Worldwide remains a mixed success however there are initiatives and successes those can be referred from China urban initiatives, EPA retrofit/repower programs, CARB DG retrofit mandate and efforts by VERT, UNECE.

Opportunity exists to provide retrofit solutions to curb particulate matter emissions from stationary sources, mobile sources such as off-highway equipment and vehicles, later being a big challenge due to packaging and weight requirements. As newer challenges are encountered, innovation in this space is key to make progress.

Retrofitting older engines has it's own challenges. Proven technology for particulate matter reduction such as DOC+DPF or CDPF are very capable solutions however with varying duty cycles encountered and old generation engines without active thermal management provision, such solutions can seldom be introduced as passively regenerated solutions. Alternate non-temperature dependent solutions, assisted-passive solutions without impacting TCO are key innovation requirements in this space to make a headway and not to lose end user's trust.

A renewed approach towards NO_x reduction is also a need of today. A solution that effectively combines PM and NOx reduction functions 'in a box' utilizing multi-zoning catalyst coatings and a unique and common reagent use is an innovation space.

Compact assisted PM control architecture for automotive application is a novel and economically attractive solution for retrofit that will make a large impact on air quality if such initiatives are explored by the ministry in collaboration with industry and research institutes with intent to bring mandatory retrofitment for passenger vehicles older than 15 years as a mandate for extending registration.

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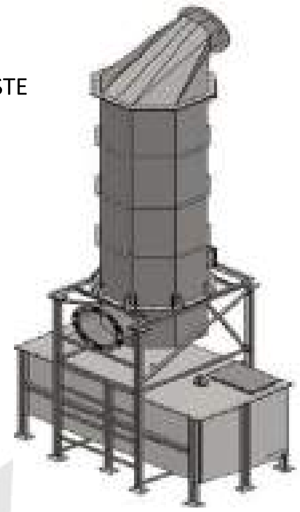

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- ASSISTED PASSIVE REGEN – PATENT APPLIED
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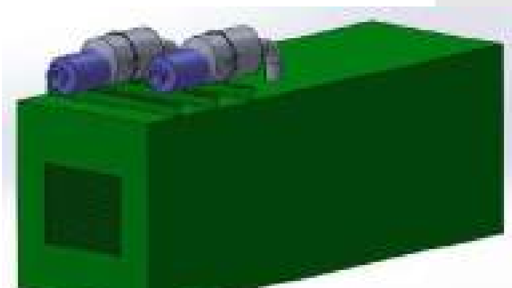

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Beyond mobility and IC engines those get prominent attention, boilers, incinerators (including crematoriums) are major source of pollution, particularly particulate matter. Environmental experts and scientists given an option choose PM as a major challenge to attack. These sources require different solutions for PM reduction as these are not Carbon particles/soot that can be regenerated but an ash in large proportion. CPCB has significantly lowered allowable PM emissions limits from most of these sources. A conventional cyclone separator and bag filters cannot fulfil such needs any more. Improvised electrostatic precipitation-based solutions and advance chemistry scrubbers are way to go. This space is still being innovated.

Retrofitment does not and shall not remain constrained to after treatment solutions. Apt dual-fuel retrofitments using CNG/LNG along with aftertreatment system to control Methane slippage is a need of today with economic advantages such retrofitment helps lowering TCO. Such initiative by NGO on DG sets has been one of the examples however due to lack of type approval or technical requirements policies such efforts did not leave good test with end users with damaged engines and false promise of 70% PM reduction. Market opportunities for a well-engineered solutions for heavy duty trucks, inland marine vessels, fishing trawlers and even off-highway equipment are enormous. Natural gas being a cleaner and cheaper transition fuel, Government shall promote such activities. Methane however has 20+ times more GHG effect than CO_2 and hence must use methane slip aftertreatment solution.

Solutions to capture variety of particulate matter closer to population also remains a potent solution to reduce exposure to the population where pollution form the source (even after stringent controls) is not adequate. Economical solutions such as ESP + Cyclone PM separators can be mass utilized for semi-closed and closed spaces running on green power to reduce exposure and achieve better population health results. Such solutions does not require expensive filtration media, are consistent and low maintenance.

In essence, retrofitment is a very impactful and innovative approach that still remains to be fully explored.

Pi Green Innovations Pvt Ltd, a company driven by vision of 'A Pollution Free Tomorrow' focuses on innovative solutions those target particulate matter reduction, CO_2 reduction and permanent sequestration solutions and much more. Our technology approach is driven by safety of the equipment, lower TCO, energy efficiency.

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Sustainability in Transportation: Challenges, Prospect and Role for Conventional IC Engines Enveloped by Other Solutions

Neelkanth Marathe
Executive Director, Emissions Controls Manufacturers Association (ECMA India)

[the views expressed by the author in this article are purely owned by him and not essentially represent the views of ECMA organisation]

Sustainability in mobility and energy supply is becoming a critical concern for the transport sector. as the transport sector accounts for a significance portion of global greenhouse gas emissions. The shift towards sustainable mobility involves reducing environmental impact while maintaining efficient transport solutions. Advances in the technology are pl aying a pivotal role in driving this transformation, with emerging trends and best practices paving the way for a greener future in transportation. Global demand for mobility is growing rapidly especially in the developing world. About 97 percent of transport fuels currently come from petroleum, a large fraction of which is imported by the countries where it is used. Rising prices of conventional crude oil face economic, technical, and environmental challenges. Direct combustion of fossil fuels accounts for a significant fraction of global primary energy use, air pollutant emissions and greenhouse gas (GHG) emissions.

Approaches to Sustainable Transportation

Following are some of the considerations to reduce transport-related energy use and emissions, towards realising sustainable solutions for the future transportation system.

• shifting to more efficient modes of transport, such as from cars to mass transit (bus or rail), or from trucks to rail or ships. Further efficiency improvements could be achieved by reducing vehicle weight, streamlining, and improving designs of engines, transmissions, and drive trains, including hybridization.

• replacing petroleum-based fuels with low-carbon and/or zero-carbon alternative fuels, including renewably produced biofuels, and electricity or hydrogen produced from low-carbon sources such as renewables, fossil energy with carbon capture and storage (CCS), or nuclear power.

• reducing vehicle miles travelled, which can be realised by encouraging greater use of carpooling, cycling, and walking, combining trips, and telecommuting. In addition, city and regional planning can be made smarter so that people do not have to travel as far to work, shop, and socialize. This practice could have direct impact on GHG emissions reduction.

Alternative Fuel and Vehicle Pathways

It is needless to state that current transportation system is based almost exclusively on petroleum and the internal combustion engine. However, now there are many other possibilities emerging to address the control on climate changes, such as –

hybrid drive trains
battery electric drive trains
fuel cell based drive trains
alternative fuels based drive trains (compressed natural gas, ethanol, methanol, DME, F-T diesel, electricity, and hydrogen) energy security concerns.

While many of these pathways offer potential societal benefits in terms of emissions or energy security, there is no clear path yet visible.

SUSTAINABLE TRANSPORTATION

Energy sustainability has been defined as "providing for the ability of future generations to supply a set of energy services to meet their demands without diminishing the potential for future environmental, economic and social well-being." Life-cycle analysis (LCA) is a powerful method for evaluating and comparing fuel/vehicle pathways with respect to a set of sustainability metrics. These could include primary energy use, greenhouse gas emissions, air pollutant emissions, water use, land use, materials requirements, and other factors that might be harder to quantify such as reliability and resiliency. Life-cycle analysis for transportation analyzes all the steps in producing and using fuels. Emissions, energy use, and other factors can be estimated at each step and added up to give a "well-to-wheels" total.

LCA can also be used as a basis for estimating the societal costs of different fuel/ vehicle pathways including externalities, such as health damage from air pollution, climate impacts of greenhouse gas emissions, and economic costs of oil insecurity. When these costs are added to the direct cost of owning and operating the vehicle, low-emission options become more competitive with conventional fuels.

Sustainability in mobility, therefore, requires a multifaceted approach, driven by technological innovations and best practices that promote cleaner and more efficient transportation. As technology continues to evolve, the transformation of the mobility sector will play a significant role in combating climate change and ensuring a greener and more sustainable future for generations to come.

Challenges for IC Engine Technology

Despite the growing focus on electric vehicles and other alternative fuel technologies, Internal Combustion Engines (ICEs) will continue to play a significant role in the automotive industry, particularly in the regions where feasibility of a full electrifications is not yet feasible. Forthcoming stricter emission regulations, like Euro 7, compels ICE technology to further evolve to meet stringent standards while maintaining performance, efficiency and sustainability.

The challenge for ICE technology lies in achieving ultra-low emission levels across a wide range of real-world driving conditions, which requires substantial improvements in combustion efficiency and exhaust after-treatment systems. Under RDE, emissions must be controlled not only in laboratory conditions but also in complex and varied real-world driving conditions such as extreme temperatures, varying altitudes, and stop-and-go urban traffic. ICE vehicles must meet these requirements consistently and with good margins making the engine design and emission management quite complex. Hybrid powertrains that combine an ICE with an electric motor can significantly reduce emissions. Mild hybrids and plug-in hybrids allow the ICE to operate more efficiently by using electric motor to handle low-load conditions such as idling and stop-start traffic, where emissions are typically higher from ICEs.

While gasoline and diesel will still remain the dominant fuels for ICE Vehicles in short term, alternative and future-brand fuels can offer meet ultra-low emission targets. Improved thermal management can help ICE vehicles operating efficiently under all conditions. Electrically heated catalysts has potential to reduce cold start emissions while advanced cooling systems ensure lower emission during both warm-up and regular driving. Continuous real-time monitoring of emissions will play a strong role to help ensure that ICE vehicles remain compliant to emission standards over their entire life span.

To suffice, ICE technology still has significant role to play in the transition towards cleaner mobility; by adopting advanced emissions control technologies, improving combustion efficiency, hybridising powertrains and exploring alternative fuels.

CHALLENGES for THE BIOFUELS PATHWAY

Biofuels are generally compatible with internal combustion engine vehicle (ICEV) technologies and can also be used in hybrid electric drive trains. Many ICEVs already use liquid biofuels, whereas only a small fraction has been adapted to run on gaseous fuels or hydrogen. However, most of the existing fleet of gasoline and diesel ICEVs can only operate on a relatively low biofuel blend to avoid adverse effects on vehicle operation and durability. The percentage of ethanol that can be blended into gasoline for conventional vehicles is currently under exploration. All vehicles in Brazil must be capable of accepting blends of up to 25 percent ethanol. In India too, 20 percent ethanol blend in gasoline is going to be mandatory from year 2025. Safeguards must be exercised in place to prevent older vehicles and small off-road engines from mistakenly using high ethanol blends.

An increasing number of flexible-fuel vehicles (FFVs) can use higher blends of ethanol (up to 85 percent) or 100 percent gasoline. FFVs vary the engine operation depending on the ethanol content of the fuel, measured by the oxygen sensor in the exhaust. In addition, they use larger fuel injectors and different materials in the fuel system to guard against the corrosive nature of ethanol. In Brazil 17 percent of vehicles are FFVs. Biodiesel can legally be blended at any percentage with petroleum diesel. However, some engine manufacturers do not honor warranties if biodiesel blends are used. The most common blend is B20 (20 percent biodiesel by volume) to avoid issues with cold weather.

“Drop-in” biofuels are hydrocarbon fuels produced from biomass that can be blended freely with petroleum gasoline or diesel and used in conventional vehicles without modification. These fuels provide a seamless transition to alternative fuels as the vehicles and infrastructure require no modification. These fuels will not be an exact match for petroleum fuels and will require refining to get the fuel properties in line with specifications for gasoline and diesel.

Since liquid biofuels blended in limited amounts are similar to neat gasoline or diesel in terms of vehicle performance and refuelling time, and do not require new vehicle types, they can be relatively transparent to the consumer. Fuel costs may therefore be the main factor determining consumer acceptance. In Brazil, for example, FFV users select their fuel based on price. Reduced range and reduced fuel economy with ethanol and, to a lesser extent, biodiesel, can also be a factor in consumer acceptance.

Blending biodiesel with conventional diesel fuel (B7, B20) reduces CO2 and PM emissions. Higher biodiesel blends, such as B20 (20% biodiesel), can further reduce emissions while maintaining performance in diesel engines.

Synthetic fuels, also known as e-fuels, are produced using renewable energy to synthesize hydrogen and carbon dioxide into liquid fuels such as synthetic gasoline and diesel. These fuels have potential to drastically reduce tailpipe emissions and provide a near-zero carbon alternative to conventional fossil fuels.

Blending future fuels with conventional gasoline and diesel provides an immediate solution for reducing emissions while allowing for the continued use of existing ICE technology. Fuel blends can reduce CO2, NOx, PM and HC emissions, helping vehicles comply with forthcoming stricter emission regulations such as Euro 7 standards.

Clean Air Today, Cleaner Air Tomorrow

Challenges for The Plug-in Electric Vehicle Pathway

While biofuels seem to represent the nearest-term answer to the demand for alternative fuels, electricity is closing in as a viable choice. Electric-drive technology continues to pique the imagination of motorists with its promise of clean skies, quiet cars, and plentiful fuel produced from non-polluting domestic sources. In the designs they have dangled before us, automakers have shown us variations in plug-in electric vehicle (PEV) size, performance, and definition in efforts to overcome the fundamental challenge of electric drive: how to store energy and supply power. PEVs (a category that includ es plug-in hybrid electric vehicles or PHEVs as well as battery electric vehicles or BEVs) are powered at least in part by electricity from the grid—a fuel that under certain conditions is less costly and more environmentally friendly than gasoline. Because vehicle electrification can improve the total energy efficiency (MJ/mile) of the vehicle and may allow lowering of the carbon intensity (gCO2 /MJ) of the fuel used in vehicles over time, PEVs offer a form of transportation with the potential for very low greenhouse gas (GHG) emissions.

The Hydrogen Fuel Pathway

Hydrogen-powered Internal Combustion Engines (H2-ICEs) offer a promising solution to the challenges posed by ultra-low emission regulations. Combination of conventional ICE technology with clean-burning characteristics of hydrogen is showing an excellent future especially for heavy-duty and long-haul applications segment, where electrification is found to be not feasible and operable even in long term.

H2-ICEs offer cleaner combustion leveraging existing ICE technology. Combustion of hydrogen yield water vapour as the primary by-product in the tail-pipe, which is practically a carbon-free emission and near-zero CO2, meaning heavily reduced greenhouse gas emissions. However, H2-ICE may generate NOx due to high combustion temperatures, however, advanced combustion such bas lean-burn and exhaust after-treatment techniques can minimise NOx emission substantially. H2-ICE does not produce PM like gasoline or diesel combustion does. However, some traces of PM emission is possible because of lubricant oil burning. Robust design of piston-ring-cylinder liner combination and quality of lubricant oil will be essentially required to control the PM emissions. Another important aspect of hydrogen usage in ICE is that it does not essentially require very high purity level of hydrogen. ICE combustion can tolerate some impurities in the hydrogen fuel, which makes it relatively affordable in cost and handling.

To reach stringent long term goals for cutting greenhouse gas emissions from transportation, it appears likely that the light duty fleet is required to be largely electrified in next 2 – 3 decades. Hydrogen fuel cells are an important enabling technology for this vision. Automakers foresee a future electrified light duty fleet with batteries powering smaller, shorter range cars and hydrogen fuel cells powering larger vehicles with longer range. To electrify all segments of the light duty market, fuel cells are a necessary complement to batteries.

Recent assessments affirm the long-term potential of hydrogen to greatly reduce oil dependence as well as transportation emissions of greenhouse gases and air pollutants —far beyond what might be achieved by energy efficiency alone. They also highlight the complex technical and logistical challenges that must be addressed before a hydrogen-based transportation system can become a reality.

Although internal combustion engines can run on hydrogen, it is the higher-efficiency, zero emission hydrogen fuel cell that has largely captured the attention of automakers. Several automakers have embraced fuel cells as a superior zero-emission technology and have large development and commercialization programs. Hydrogen and fuel cells represent a logical progression beyond efficiency and increasing electrification of cars with hybrid and electric drive trains. As noted above, many automakers see complementary roles for hydrogen fuel cells and battery electric vehicles and are pursuing both technologies.

Fuel cells are highly efficient electrochemical “engines” that combine hydrogen and oxygen in air to produce electricity to power the vehicle. Fuel cells operate without combustion or emissions of pollutants or greenhouse gases; the only tailpipe emission is water. FCVs use electric drive trains but have a longer range, a faster refuelling time, and the potential for lower cost than battery electric cars. In addition to the fuel cell stack, other key components of a hydrogen FCVs include hydrogen storage, electric motors and power controllers, and batteries for hybrid operation and cold start support. Most of the fuel cell vehicles today are hybrids.

Mobility is central to human wellbeing: It enables access to opportunities and fosters prosperity, quality of life, and social connections. Today, billions of people around the world enjoy a level of personal mobility that would have been unimaginable just a few generations ago. But the technologies and infrastructure that have evolved over the last one hundred years to deliver personal mobility fall short of satisfying the demands of the 21st century. In many countries, access to transportation remains highly unequal, reflecting and perpetuating larger socio-economic disparities. At the same time, traffic congestion plagues millions of commuters and impacts the economies of large metropolitan areas around the world. Private motor vehicles, despite significant advances in performance, comfort, and safety, remain a major source of negative externalities. They cause millions of road injuries and fatalities each year and contribute to both unhealthy levels of local air pollution and rising emissions of planet warming greenhouse gases.

Sustainable transportation entails a healthy balance between humans, transportation and natural systems. To make transportation sustainable, city roads and streets must become accessible to everyone. Naturally, consideration should also be directed towards the environment, which should always remain as close to how it is without transportation or urban structures as possible (or at least experience minimal impact).

Future fuels and fuel blends are essential tools in meeting the forthcoming stringent demands. As the automotive industry transitions towards zero-emission mobility, the development and widespread adoption of these fuels will be key to achieving sustainability goals and reducing the environmental impact of transportation. This also carries a potential for a continued use of conventional fuels like gasoline and diesel in the internal combustion engines. Improving the fuel efficiency of conventional engines and then gradually introducing alternative engines is also one of the promising solution.

The adaptability of ICE technology, combined with the scalability of new fuel types like biofuels and e-fuels, makes it a crucial part of a diversified strategy to achieve near-term emissions reductions while the world is transitioning to fully renewable energy sources. It is feasible to move towards a lower-carbon future without compromising on the present-day energy needs, by optimising ICEs and integrating them into the broader ecosystem of sustainable transportation.

Internal Combustion engine engineering is still having an excellent potential that is developing to address current issues as well as future expectations. ICE remains an essential part of the transportation system, even with the increasing push and popularity of EVs. ICEs continue to be vital for powering automobiles, providing infrastructure for global transportation and advancing efficiency and sustainability even as the automotive sector is aligning with the changing scenario. In order to ensure that the pulse of mobility resonates with both the legacy of combustion engines and demands of a fast changing automotive market, ICE roadmap is required to ensure a careful balance between the history and innovation. ICEs are advancing the transition to a more efficient and sustainable future, whether through promoting hybridisation or using cleaner fuels or integrating with intelligent systems.

It is quite likely that future of modern diesel engines, particularly those with advanced emission control technologies, is not going to be entirely overshadowed by EVs. Instead, there is a potential for a complementary role, especially in applications where diesel advantages in energy density, range and adaptability to low-carbon fuels provide unique benefits. While EVs are likely to dominate in passenger cars, urban transport and other light duty applications; modern cleaner diesel engines remain relevant and preferred choice for commercial and heavy-duty transport, long-haul transport, off-road applications, marine usage, and also in the areas where electricity grid is either has underdeveloped infrastructure or less sustainable.

Modern cleaner diesel engines, leveraging advanced after-treatment systems, potentially demonstrates a near-zero ultra-low emissions of NOx and PM in the tailpipe making it substantially cleaner over its previous generation products. Therefore, modern cleaner diesel engines have a significant role to play in the near and medium term, especially as part of a diverse strategy to achieve global emission targets.

Technical Article 09

Exhaust Aftertreatment Solutions for EURO7/BS7 Vehicles

Introduction

The automotive industry is entering a new era with stringent emission norms such as EURO 7 and Bharat Stage 7 (BS7). These regulations aim to reduce pollutants like nitrogen oxides (NOx) and particulate matter to minimize the environmental impact. As vehicle manufacturers work towards meeting these standards, the role of advanced thermal management systems, particularly in exhaust aftertreatment, becomes crucial. One of the most effective methods for controlling the extreme temperatures associated with exhaust systems in these vehicles is the integration of advanced insulation solutions.

At PBM Insulations Pvt. Ltd., we provide Glasswool insulation products specifically designed to address the high thermal demands of EURO 7 and BS7 vehicle engines. Our insulation technologies play a critical role in enhancing exhaust aftertreatment systems, ensuring efficient thermal management while maintaining vehicle performance.

The Challenge: High-Temperature Exhaust Systems in EURO7/BS7 Vehicles

EURO 7 and BS7 engines will operate at much higher temperatures compared to their predecessors due to the intensified requirements to reduce emissions. These elevated temperatures are necessary to improve catalytic reactions, reduce tailpipe emissions, and meet stricter pollutant limits. However, with such high operating temperatures, there are several challenges:

- Thermal Degradation: High exhaust temperatures can accelerate wear and tear on engine components, reducing their lifespan.
- Heat Management: Excess heat can affect surrounding components, leading to performance issues and potential safety hazards.
- Emission Control Efficiency: Maintaining optimal exhaust temperatures is essential for the proper functioning of aftertreatment systems like selective catalytic reduction (SCR) and diesel particulate filters (DPF).

The Solution: PBM's Glasswool Insulation for Exhaust Aftertreatment

At PBM Insulations, we offer a wide range of insulation products tailored to the demanding needs of modern exhaust systems. Our Glasswool insulation solutions are specifically engineered to withstand high-temperature environments and provide exceptional thermal performance. By effectively managing heat, our products ensure that exhaust aftertreatment systems operate efficiently without affecting vehicle performance.

Technical Article 09

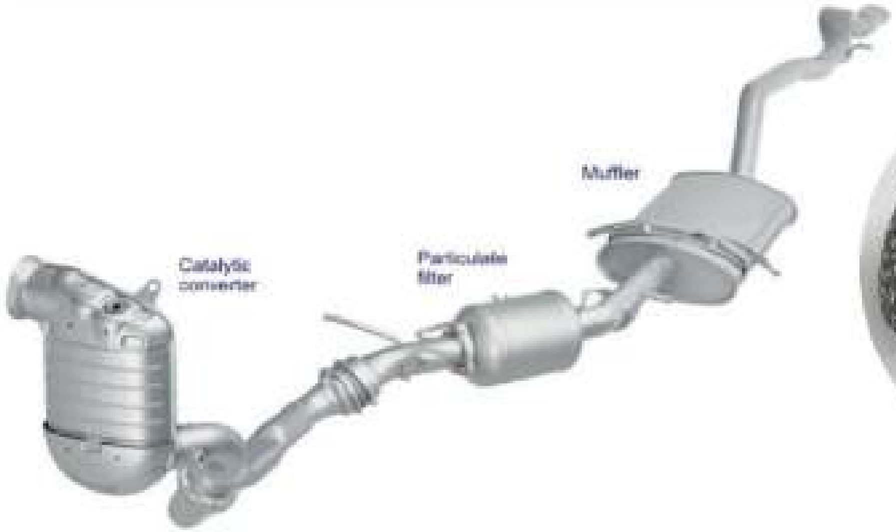
Key Features of PBM's Glasswool Insulation:

1. High Thermal Resistance:
PBM's Glasswool Insulation is engineered to withstand temperatures of up to 1600°C, making it the ideal solution for EURO 7 and BS7 vehicles. Its exceptional thermal resistance ensures reliable performance even under extreme conditions.

2. Enhanced Durability:
Designed for long-term performance, our insulation materials resist thermal degradation, extending the lifespan of exhaust system components. This durability is crucial for vehicles operating under high heat loads, as it minimizes the risk of component failure or reduced efficiency over time.

3. Lightweight and Flexible:
Our insulation products are lightweight and easy to integrate into existing exhaust designs. This flexibility allows vehicle manufacturers to incorporate our insulation solutions without adding significant weight, which is essential for maintaining overall vehicle performance and fuel efficiency.

4. Noise Reduction:
In addition to thermal management, PBM's Glasswool insulation offers excellent acoustic damping properties, reducing noise levels in vehicles. This added benefit enhances the overall driving experience by minimizing the sound generated by the exhaust system.



Comprehensive Insulation Solutions for Different Applications
PBM Insulations offers a variety of product categories to manage the high temperatures associated with EURO 7 and BS7 exhaust systems:

1. Hot Insulation for Exhaust Manifolds and Turbochargers:
Our high-temperature Glasswool insulation is used in critical areas such as exhaust manifolds and turbochargers, where heat needs to be contained and managed. This ensures the protection of surrounding components and optimizes engine performance.

2. Engine Insulation for Thermal Control:
Engine compartments in EURO 7 and BS7 vehicles are subjected to intense heat due to tighter emission controls. Our insulation solutions help in managing the thermal environment within the engine bay, preventing heat transfer to sensitive components and improving engine efficiency.

3. Exhaust Insulation for Aftertreatment Systems:
Exhaust aftertreatment systems like catalytic converters and DPFs must operate at specific temperatures to be effective. PBM's Glasswool insulation ensures that these systems retain the necessary heat to perform optimally, enhancing emission control while preventing heat loss.

Technical Article 09

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The Impact of Proper Insulation on Vehicle Performance

The integration of advanced insulation solutions in EURO 7 and BS7 vehicles is not just about meeting regulatory standards; it's about ensuring overall vehicle performance and longevity. By effectively managing the high temperatures generated in modern exhaust systems, PBM's Glasswool insulation helps:

- Improve Fuel Efficiency: By maintaining optimal engine and exhaust temperatures, our insulation solutions ensure that the vehicle's fuel efficiency is not compromised by excessive heat.

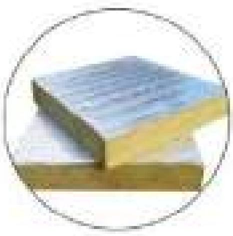
- Enhance Safety: Proper thermal management reduces the risk of overheating and thermal damage to surrounding components, increasing the safety and reliability of the vehicle.

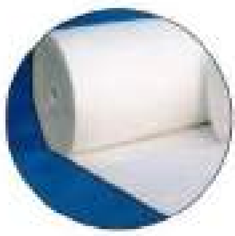
- Extend Component Lifespan: Our durable insulation materials prevent thermal degradation, extending the lifespan of critical components such as turbochargers, exhaust manifolds, and aftertreatment systems.

Conclusion

As the automotive industry moves toward stricter emission regulations with EURO 7 and BS7 standards, the need for advanced thermal management solutions is more important than ever. PBM Insulations Pvt. Ltd. is at the forefront of this effort, offering high-performance Glasswool insulation products designed to withstand the high temperatures associated with modern exhaust systems. Our solutions ensure that vehicle manufacturers can meet regulatory requirements without compromising on performance, safety, or durability.

With PBM's insulation, you can trust that your exhaust aftertreatment systems will operate efficiently, helping you stay ahead in the race toward cleaner and greener transportation.



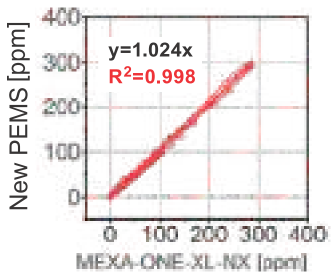


PBM INSULATIONS PVT. LTD.
Manufacturer & Supplier of Hi-Tech Insulation Products

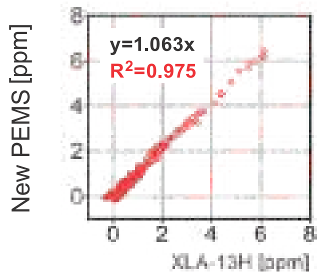
www.pbminsulations.com

Includes new components and improves testing efficiency through high lab analyzer correlation*2

NH3



HCHO

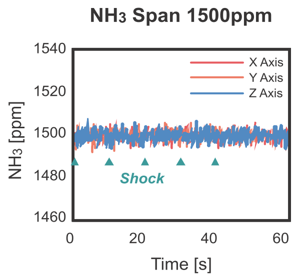


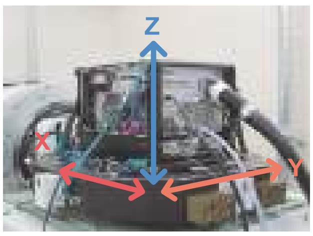
Principle	Component	Range
QCL-IR (IRLAM)	CO	0 - 5000 ppm, 0 - 12 vol%
	CO2	0 – 20 vol%
	NO	0 – 2000 ppm
	NO2	0 – 800 ppm
	N2O	0 – 1000 ppm
	NH3	0 – 1500 ppm
	HCHO	0 – 50 ppm
Same configuration as LDV and HDV	CH4	0 – 2000 ppm, 0 – 10000 ppm
FID	THC	0 – 10000 ppm

- Sampling temperature: 190°C
- Size: Approx. 490 (W) x 640 (D) x 385 (H) mm
- Weight: Approx 45 kg

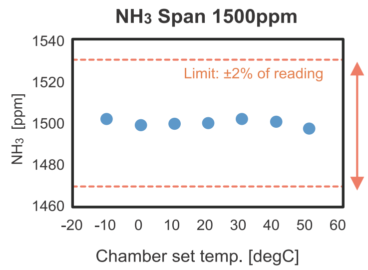
High robustness enables stable RDE testing

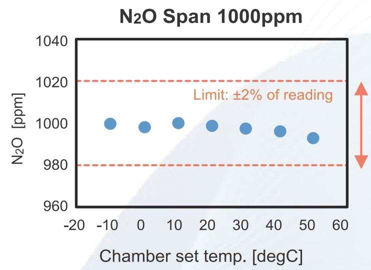
High stability even with shocks around 5G





Can be used stably at -10 ~ 45°C





*1 : IRLAM is a registered trademark or trademark of HORIBA, Ltd.
*2: The HORIBA QCL-IR PEMS is equipped to measure NH_3, N_2O, HCHO, but also CO, CO_2, NO, NO_2 and CH_4. A FID for total hydrocarbon measurement is also included.

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Please read the operation manual before using this product to assure safe and proper handling of the product.

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