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Design Profiles of EATS for Alternate Fuelled Combustion Engines

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ECOCAT India Pvt Ltd

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Contents

- Introduction & Alternate Fuels In India
- Emission Legislation Norms (BS VI & Onwards)
- H_2-ICE & Exhaust After treatment System
- Blended Ethanol Fuel
- Summary & Conclusion

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Introduction

- Emissions from the Energy sector more than doubled from ~1141 Mt CO_2e in 2005 to ~2455 Mt CO_2e in 2018.
- Transport sector accounted for 12 % of India's total emissions.

Road transport sector – One of the most energy intensive sectors.

- Total energy demand from road transport is projected to double from 2023 to 2050

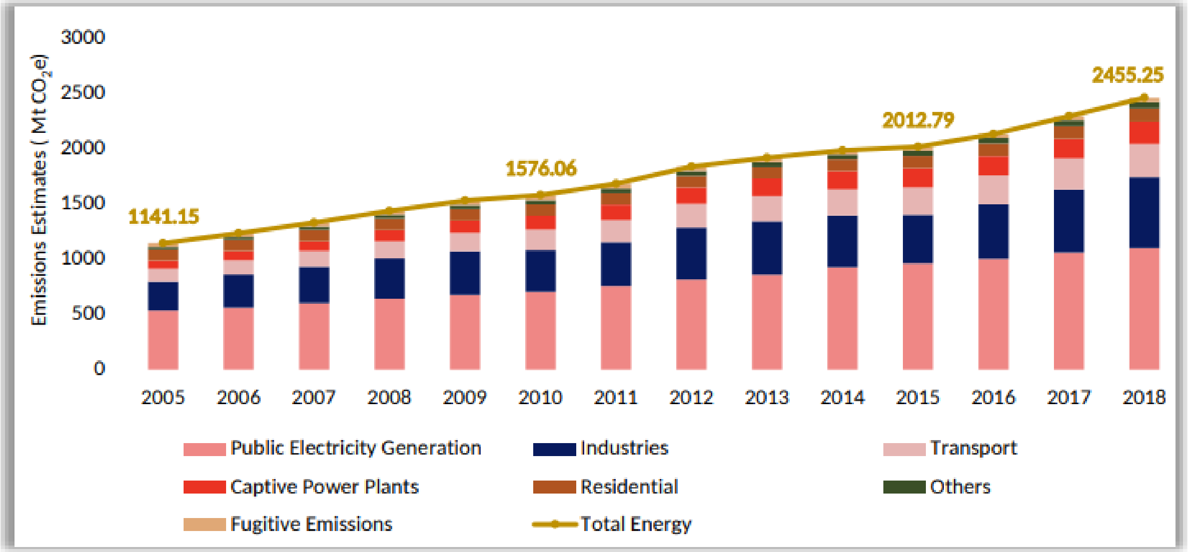
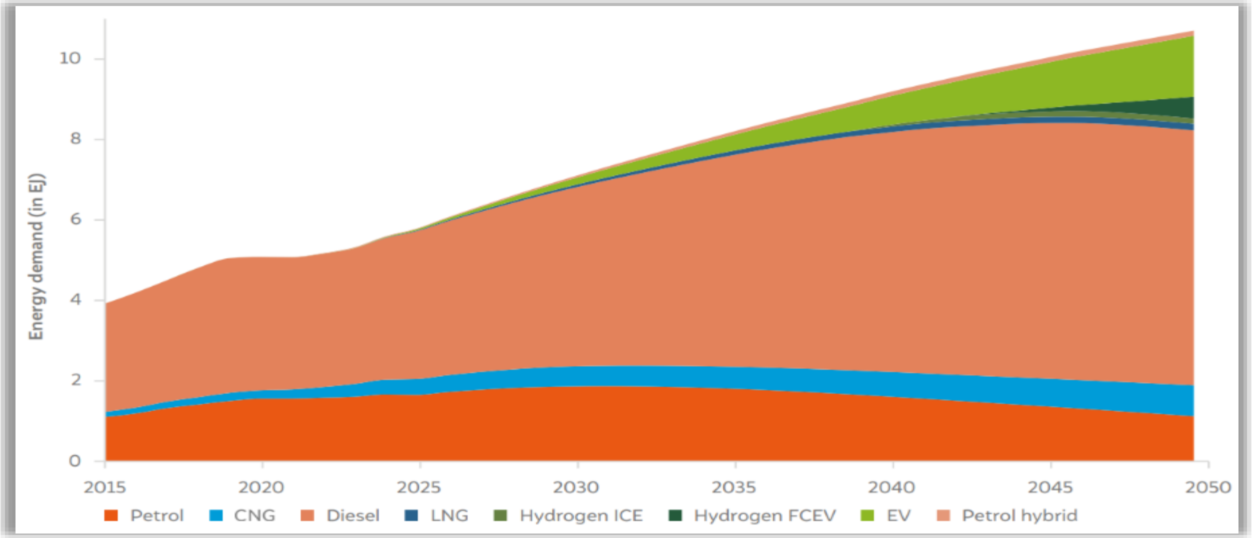


Fig 1: Category-wise Emissions (Mt CO2e) and Percentage Share in Total Energy Sector Emissions (2018)



"The need for Alternate Fuels arises from the urgent global demand to reduce environmental pollution, enhance energy security, and create a sustainable future beyond fossil fuels."

Source: CEEW (2025), What is Fuelling India's Road Transport Sector ?, : https://www.ceew.in/publications/how-will-fuel-demand-grow-with-changing-fuel-mix-in-different-vehicle-segments
GHG Platform India (2022), Trend Analysis of GHG Emissions of India, : https://www.ghgplatform-india.org/wp-content/uploads/2022/09/GHGPI_Trend-Analysis_2005-to-2018_India_Sep22.pdf

Alternate Fuels in India

Natural Gas Based Fuels → Hydrogen → Bio-Fuels → Synthetic Fuels

Alternate Fuels

- CNG
- LNG
- Bio-CNG
- H_2-ICE & Fuel Cell
- Bio-Ethanol
- Bio-Diesel
- Methanol
- DME, GTL, Fischer Tropsch etc.

Need for Alternate fuels in India

- Import dependency – Energy security risks.
- Environmental impact
- Resource depletion
- Energy Diversification
- Rural & Agricultural Linkages

Key Challenges in Adoption

- High Upfront Costs
- Technological Readiness
- Fuel Supply & Availability
- Vehicle Compatibility
- Consumer Awareness & Acceptance

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BSVI & Onwards

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🚧 Looking Ahead: BS7

Assuming BS7 adopts Euro 7 framework.

Key Changes

- Tightened Emission limits.
- Extended Lifetime (Up to 200,000 km for LDV & up to 875,000km for HDV)
- On-Board Monitoring system
- Brake & Tyre Emission limits.

Euro 7: Outcome of the final Trilogue(Council of the EU)-HDV

M2, M3, N2, N3	Euro-6	Euro-7	
mg/kWh (gas) kWh-1 (PN)	WHTC	WHTC(CI & PI)/ WHSC(CI)	RDE
NO_x	460	200	260
PM	10	8	10
PN	PN^{23} - 6×10^{11}	PN^{10} - 6×10^{11}	PN^{10} - 9×10^{11}
CO	4000	1500	1950
NMOG	160_{THC}	80	105
NH3	10ppm	60	85
CH4	500	500	650
N_2O	-	200	260

M2: busses<5 t,M3: busses>5 t, N2: trucks 3.5 t – 12 t , N3: trucks > 12 t

Light Duty Vehicles

- ➢ Alignment with Euro 6e (Emission limits &Test methods).
- ➢ PN10 instead of PN 23.

Heavy Duty Vehicles

- ➢ NO_x emissions reduced by 56%
- ➢ CH_4, N_2O, PN_{10}, NMOG added to the regulated emissions
- ➢ New RDE requirements

Source: European Union (2024), REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,: https://data.consilium.europa.eu/doc/document/PE-109-2023-INIT/en/pdf

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H_2-ICE

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H_2 as fuel

H_2-ICE	**Fuel cell**
• Based on hydrogen combustion • Adaptation to existing ICE technology • Lower H_2 purity needed • NOx emissions, H_2 slip, and water vapor	• Based on electrochemical reaction • New Infrastructure needed • Hydrogen purity required • No other emission than water

H2-ICE technology is favoured for easier integration and lower cost than fuel cells.

- ➢ Sustainable Pathway to Zero Emissions and Decarbonization.
- ➢ ICE technology allows integration of this fuel.
- ➢ Better performance with lower emissions.

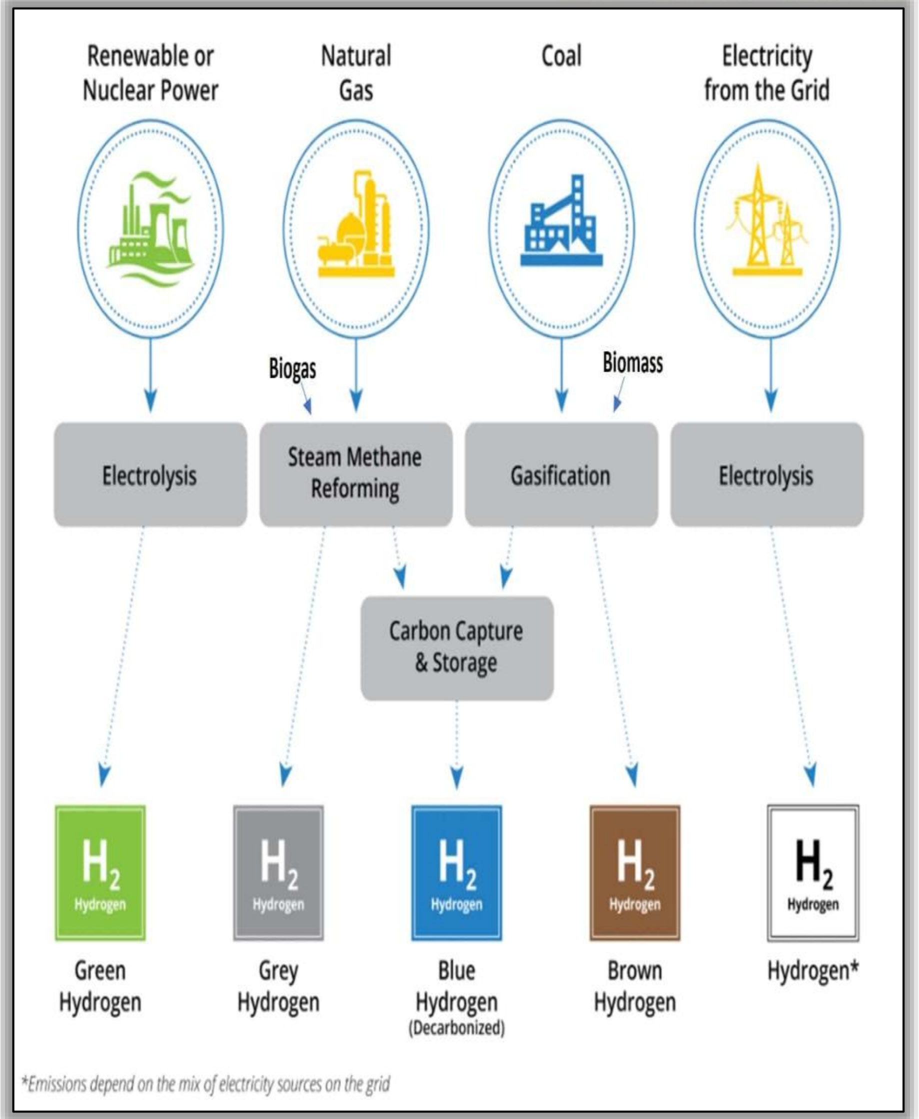

Fig 2: The different methods of hydrogen production and color-coding system (Hydrogen Power Partners)

Image: xylem (2023), Hydrogen from production to usage,: https://www.xylem.com/en-in/brands/sensus/blog/hydrogen-from-production-to-usage/

H_2 as fuel

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PROPERTIES	UNITS	HYDROGEN	GASOLINE	METHANE
Density gaseous	[kg m^{-3}]	0.08	4.4	0.65
Diffusivity in air	[cm2 s^{-2}]	0.63	0.08	0.20
Flammability in air	[volume %]	4.0 – 75.0	1.0 – 7.6	5.3 – 15.0
Minimum energy for ignition in air	[mJ]	0.02	0.24	0.29
Auto-ignition temperature	[K]	858	501-744	813
Flame temperature in air	[K]	2318	2470	2148
Burning velocity in NTP air	[cm s^{-1}]	265 – 325	37 – 43	37 – 45
Quenching gap in NTP air	[mm]	0.64	2.00	2.03

Fig 3: Hydrogen Properties

Favorable properties enabling high combustion efficiency

- **High Octane number**
- **Wide Flammability range & low ignition energy demand**
- **Fuel economy**
- **Good Diffusivity**
- **Lean Operation**
- **High specific energy & calorific value**

- Standalone fuel in both SI and CI engines.
- High stoichiometric air-to-fuel ratio (34.4:1)
- Lean operation due to wide flammability range allowing for NOx control.

- Low energy of ignition-Premature, Uncontrolled ignition
- High auto ignition temperature (SI over compression ignition)
- High Antiknock properties

Reference: Exhaust system for hydrogen fuelled combustion engines, Cecilia et al (2024)

H_2-ICE emission characteristics & challenges

- Significant amount of Hydrogen, Water & NO_X.
- Varying NOx emissions based on engine calibration.
- Exhaust Temperature slightly lower than Diesel ICEs.
- High amount of water production (~ 30%).
- CO, HC & PM from lube oil combustion.

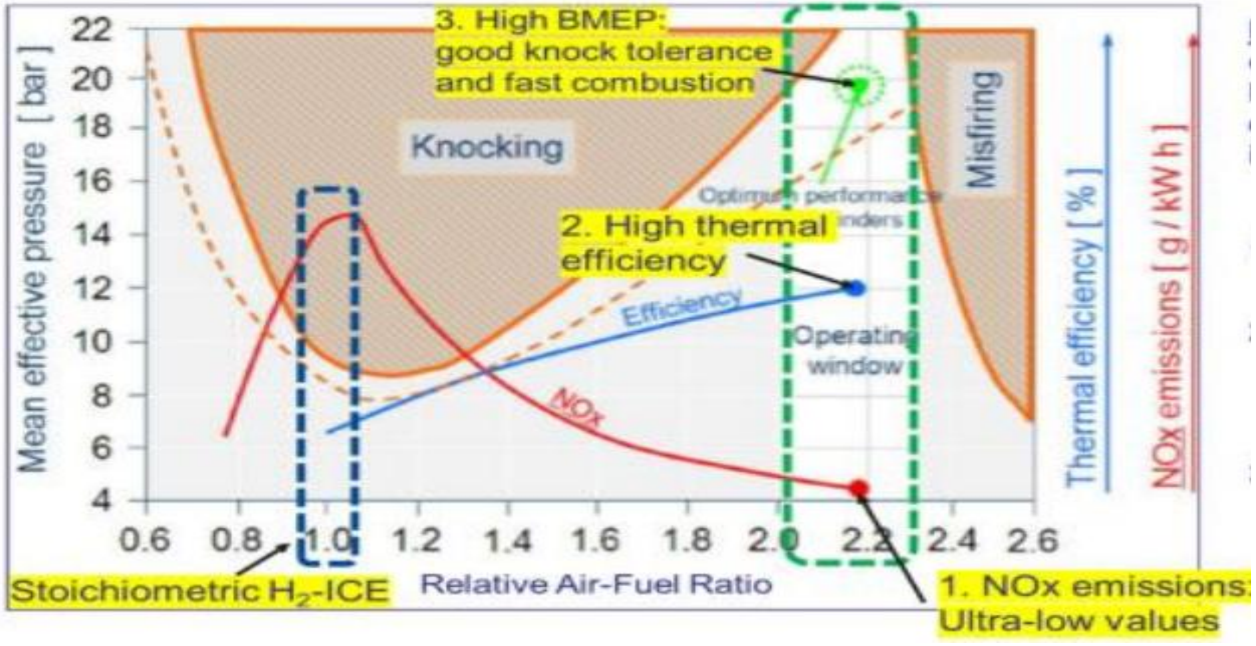

Fig 4: Relationship between AFR, mean effective pressure, thermal efficiency & NOx emissions

TECHNOLOGY	DIESEL ENGINE	PFI SI	LP DI SI	HP DI CI
Fuel	Diesel	H_2	H_2	H_2/Diesel
Injection/ignition type	DI/CI	PFI/SI	DI/SI	DI/CI
Air/fuel ratio	$1.1 < \lambda < 1.65$	$1.8 < \lambda < 2.7$	$1.8 < \lambda < 2.7$	$1.5 < \lambda < 2.4$
Engine-out NO_x	High	Low	Medium	High
After-treatment requirement(Euro VI)	Yes	No	Probably	Yes
H_20 in exhaust	Reference	3.1 times more	N.A.	2.6 times more
Exhaust temperature	Reference	Lower	Lower	Equal
Expected market Introduction	-	2027	2028	2025-2027
Power density	Reference	Lower	Equal	Higher
Efficiency	~45	~42	~42	>45

Fig 5: H2-ICE technologies compared with the traditional diesel engine

Challenges

- High thermal efficiency with reduced emissions.
- Stability of the combustion process.
- High specific engine power.
- Right Injection strategy (PFI, MPI or DI).
- Engine knock, pre-ignition & ignited mixture backdraft.

Reference: Analysis of the prospects for hydrogen-fuelled internal combustion engines, Stepien Z. et al (2024)

H_2-ICE Exhaust Aftertreatment system

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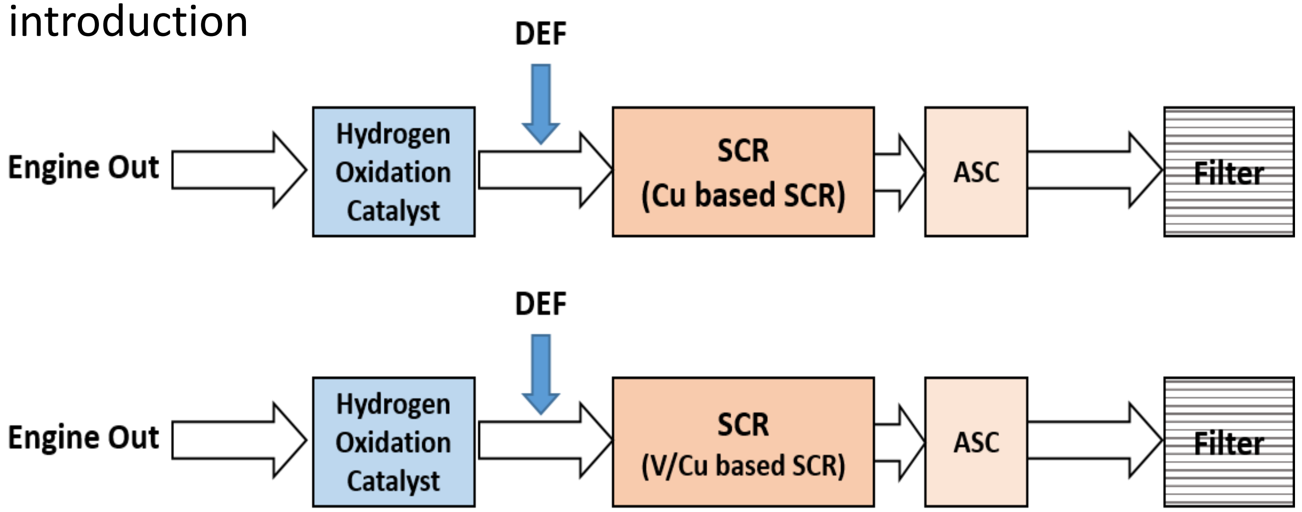
<u>OEM's perspective</u>: EATS development for quick market introduction



Ecocat H_2-ICE ATS configuration for lean operation

High $DeNO_x$ efficiency
Low N_2O formation
Wider Temperature Window

Reducing harmful emissions

- Existing SCR technology for efficient NO_x removal (0.25-6g/kWh)
- Oxidation Catalyst for H2-slip.
- ASC for ammonia slip

Temperature window – 200-500˚C
Water content-0-30%

Reactions in H_2-ICE Exhaust After treatment System

	$2\,H_2 + O_2 \Longrightarrow 2\,H_2O$	HOC catalyst
	$NO + O_2 \Longleftrightarrow NO_2$	
Hydrolysis	$CO(NH_2)_2CO + H_20 \Longrightarrow 2NH_3 + CO_2$	
Standard SCR	$4\,NO + 4\,NH_3 + O_2 \Longrightarrow 4\,N_2 + 6\,H_2O$	
Fast SCR	$NO + 2\,NH_3 + NO_2 \Longrightarrow 4\,N_2 + 3\,H_2O$	SCR catalyst
NO_2-SCR	$4\,NH_3 + 3\,NO_2 \Longrightarrow 3.5\,N_2 + 6\,H_2O$	
	$4\,NH_3 + 3\,O_2 \Longrightarrow 2\,N_2 + 6\,H2O$	ASC catalyst

H_2-ICE Exhaust Aftertreatment system

Key performance matrix

- **Oxidation catalyst:** High H_2 Oxidation performance, NO_2 formation & Exotherm.
- **SCR:** High NOx removal percentage
  Low N_2O formation
- **Hydrothermal durability of catalysts (0-30%).**

Right Sizing of Catalyst based on application meeting limits.

Influence Parameters

1. NH_3 storage capacity of SCR
2. Effect of H_2 on SCR Performance
3. Effect of NO_2 to NO_x ratio
4. Effect of water on oxidation catalyst & SCR performance
5. Effect of Space Velocity on catalyst performance

SCR Washcoat Technology– NO_x abatement

Copper based SCR
- Wide temperature operation
- High Thermal Durability
- High Temperature Conversion

Vanadium based SCR
- Low temperature range
- Low Thermal Durability
- Low Temperature Conversion

Challenges involving SCR technology for H_2-ICE

- **Low & high temperature NOx conversion**
- **Effect of moisture content on SCR durability**
- **Increased system complexity**

DeNOx & Catalyst Durability

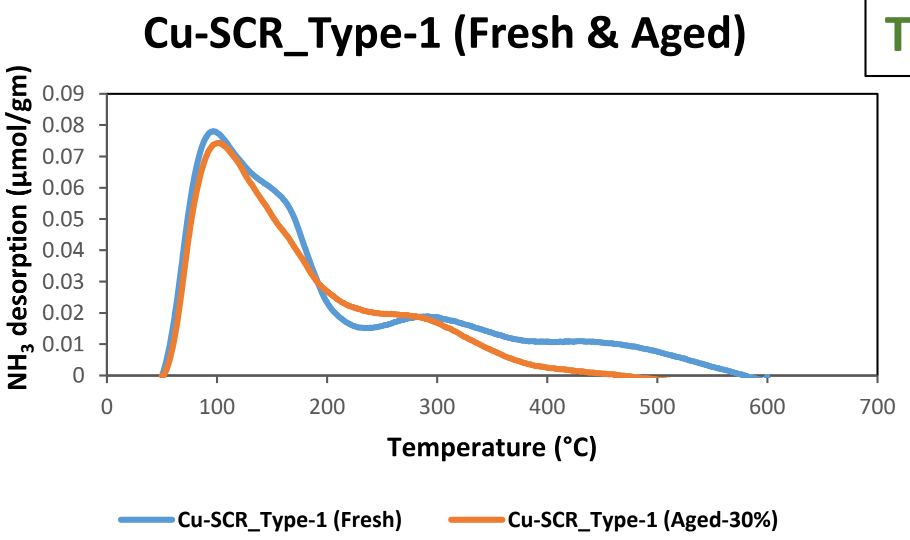
NH_3- Temperature Programmed Desorption Study
- Acidic properties crucial for NH_3 adsorption
- NH_3 adsorption capacity

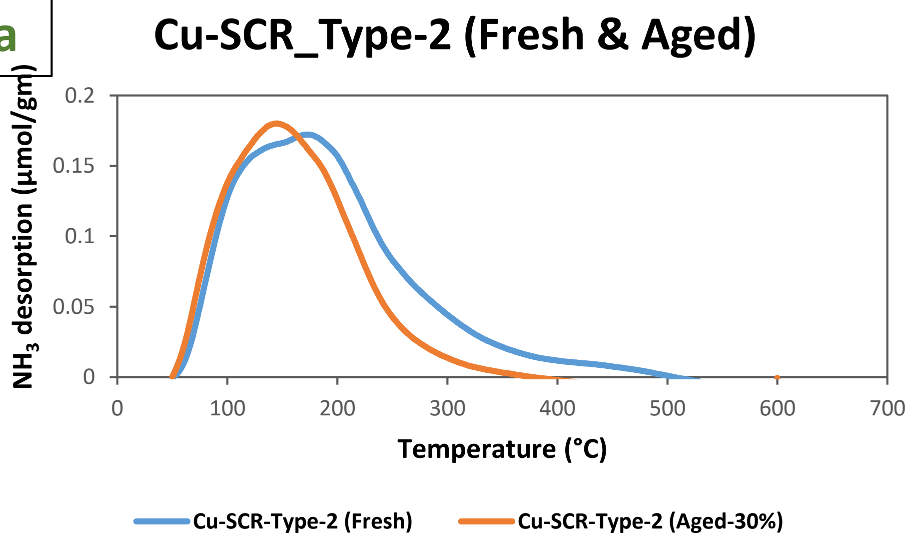
In SCR reaction, active site has a strong adsorption effect on the gas molecules

➢ **Directly relates to NOx conversion**

➢ **Hydrothermal Aging** - 650°C x 50hrs, 30% H_20

Type-1: High Silica
Type-2: Low Silica





Cu-SCR_Type-1
- High Temperature operating range.
- Reduced Low Temperature NH_3 storage capacity.
- Stable under severe Hydrothermal Aging.
- Good balance between activity & stability.

Cu-SCR_Type-2
- Low to mid temperature operating range.
- High low Temperature NH_3 storage capacity.
- Tends to suffer from Hydrothermal aging

DeNOx & Catalyst Durability

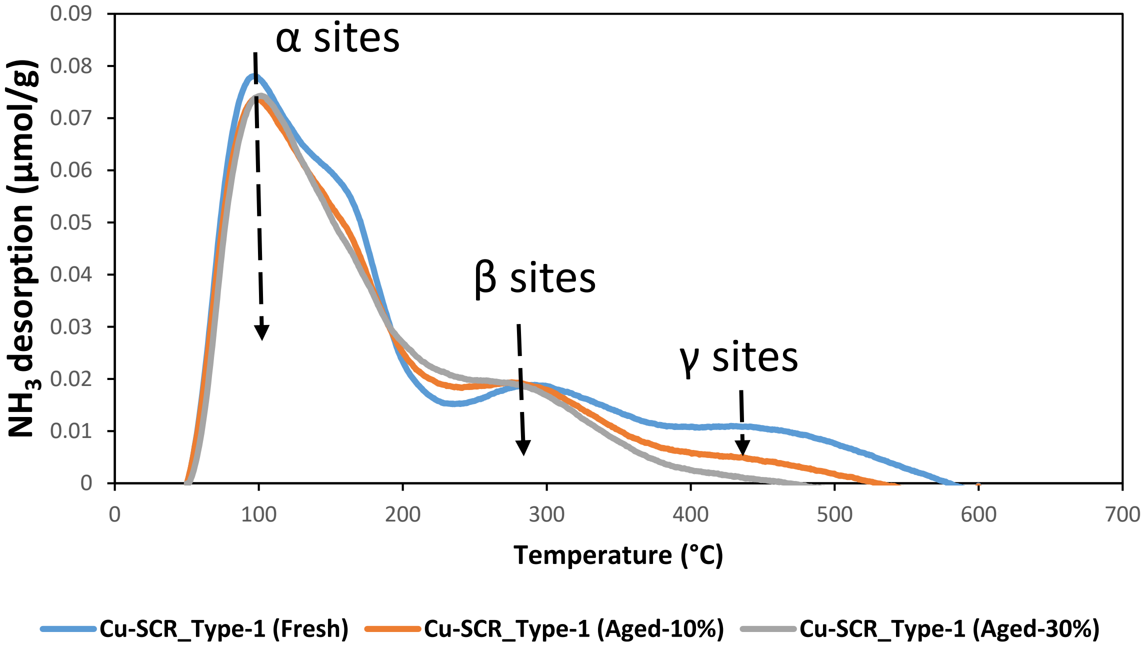
NH_3- Temperature Programmed Desorption Study

- Acidic properties crucial for NH_3 adsorption
- NH3 adsorption capacity

NH_3 adsorbs on **1. α sites-Weak Lewis acid sites**
2. β sites-Strong Lewis acid sites
3. γ sites-Bronsted acid sites

- **HT Aging-** 650°C x 50hrs, 10% H_20 – **Diesel Aging**
- **HT Aging-** 650°C x 50hrs, 30% H_20 – **H_2-ICE Aging**

Cu-SCR Type-1 (Fresh vs Aged)



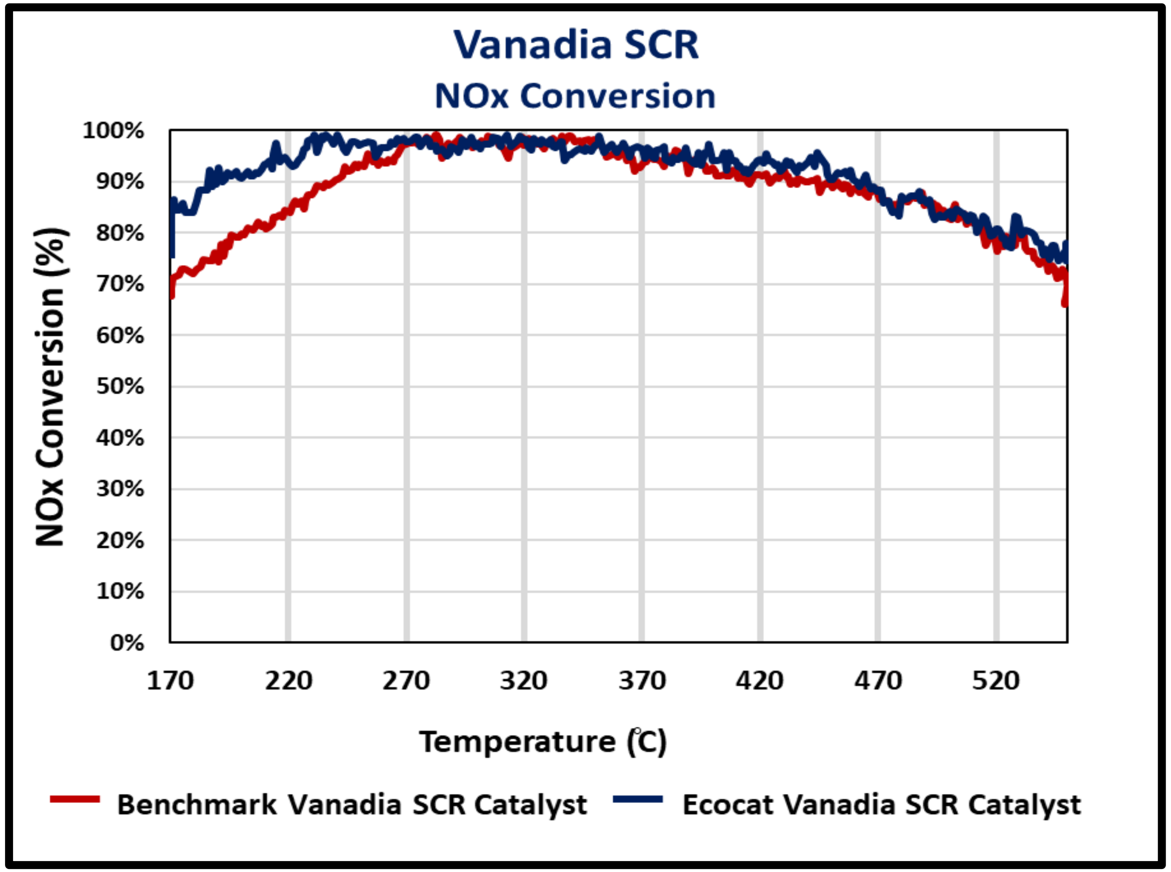
Effect of Hydrothermal Aging (Fresh, 10%, 30%)

- NH_3 adsorption capacity is retained.
- Unstable ZCuOH active sites ↔ more stable Z_2Cu sites.
- Lewis Sites maintained even after severe aging.
- Significant loss of γ-sites (Bronsted acid sites).
  Dealumination of the framework
- Catalyst performance remains the same.

SCR Washcoat Technology – High & Low Temperature NOx conversion

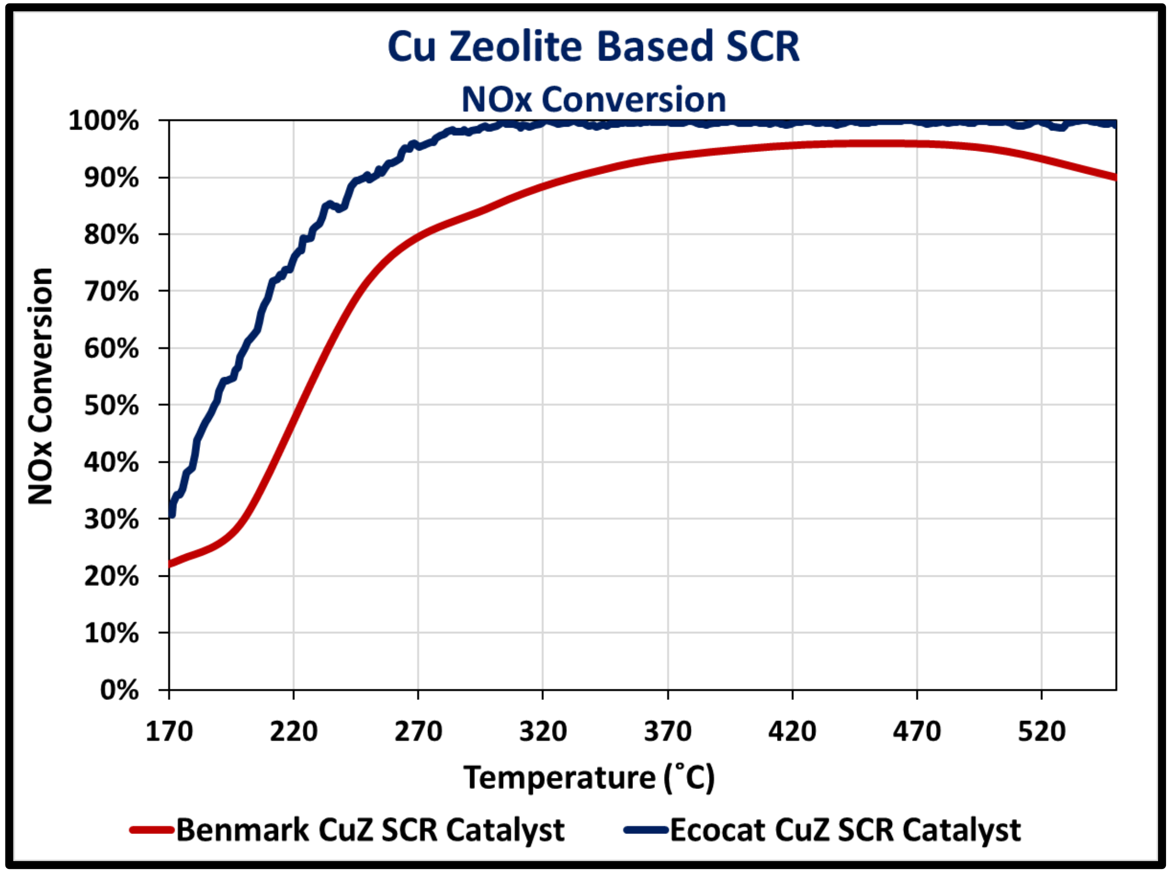
Low & Medium Temperature Technology

Vanadia SCR



Wider Temperature Technology

Cu-Zeolite SCR



- SCR washcoat chemistry shows efficient NOx conversion at wider temperature range with lower LOT.

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Ethanol

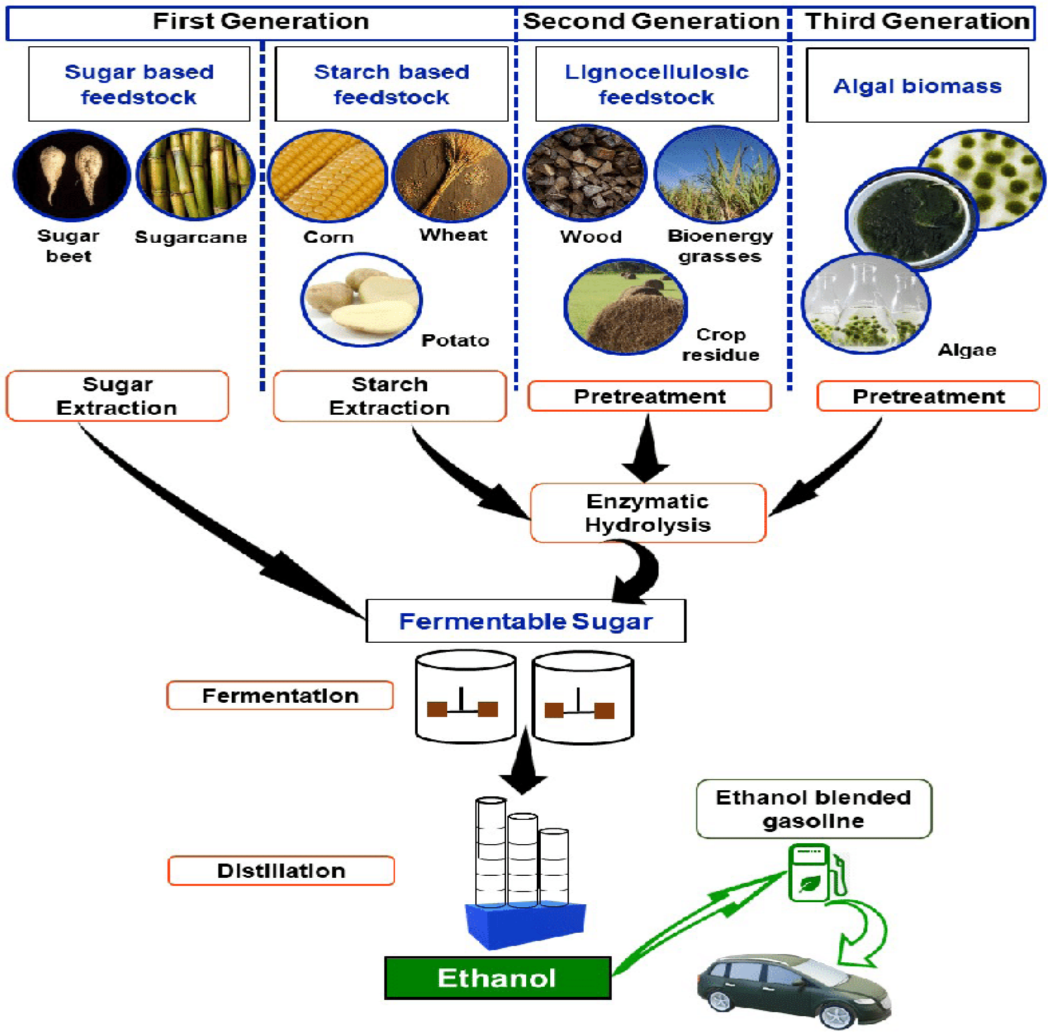


Fig: 6 Schematic pathways of first, second and third generation ethanol production

India's Focus

India mainly uses **1G ethanol**

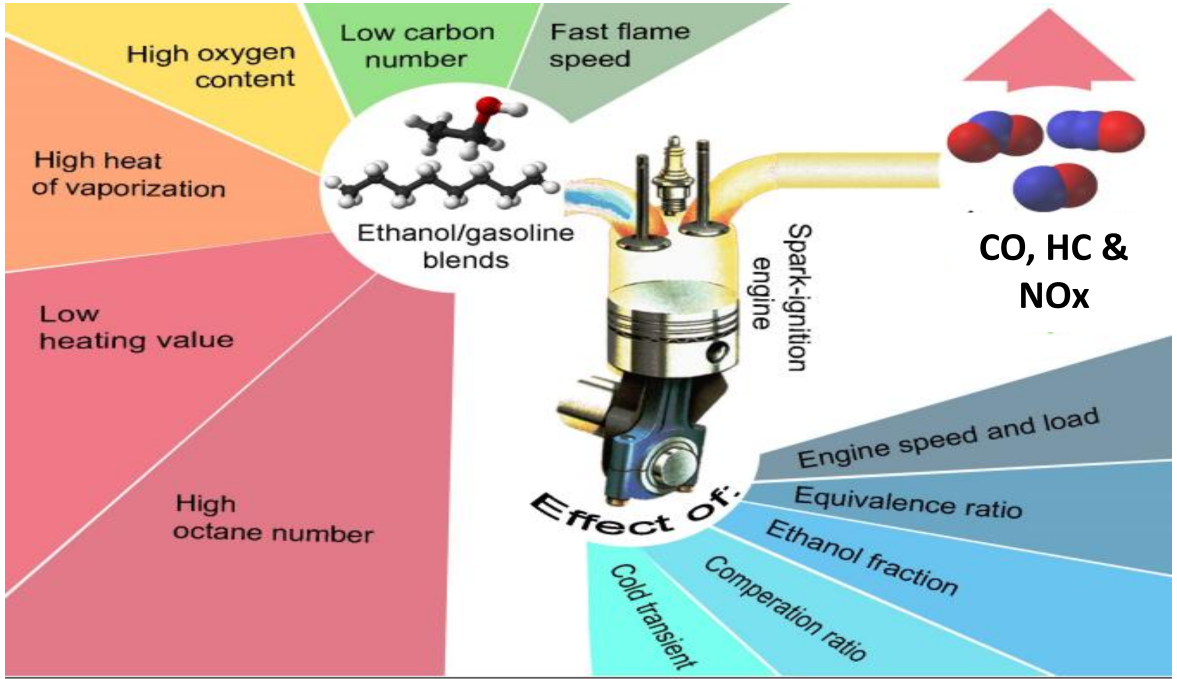
- ➢ The National Policy on Biofuels is now promoting **2G ethanol**
- ➢ **BPCL's first integrated 2G plus 1G Bio Ethanol refinery at Bargarh**
- ➢ **IOCL:2G Ethanol Plant set up using rice straw & 3G Ethanol Technology with Lanzatech gas fermentation technology at Panipat Refinery**

- ➢ Ethanol blended gasoline in SI engines is accepted worldwide.
- ➢ Measurable GHG emissions benefits as vehicular fuel.
- ➢ Favorable Exhaust Emission reducing properties.
- ➢ Flex fuel vehicles with E-85 in Brazil & USA currently in use.

Image: Biofuel: Concepts and Considerations (2023), : https://edis.ifas.ufl.edu/publication/SS688

Ethanol

Fuel Characteristics	Effect on Exhaust Emissions	Engine Characteristics



Property	Gasoline	Ethanol	Remarks
Stoichiometric AFR[-]	14.2-15	9	More Power Potential
O-fraction [mass%]	0	34.7	More complete combustion
Research octane number	91-100	110	High compression ratio, High thermal Efficiency, More Power
Reid vapor pressure [kPa]	53-60	17	Difficulty In cold start, High HC & CO during cold start
Lower Heating value [MJ/kg]	44	27	Higher Fuel Consumption
Latent Heat vaporization [kJ/kg]	380-400	910	Faster combustion and higher volumetric efficiency

Fig: 7 Physiochemical properties of Gasoline & Ethanol

- Ethanol blending increases the oxygen content.
- Increase in octane number & the volatility of gasoline.
- Lower Energy density – Fuel consumption.
- Minor tailpipe CO_2 reduction.

Reference: A review on the effects of ethanol/gasoline fuel blends on NOx emissions in SI engines, Paolo et al (2021)

Effect of Ethanol-gasoline blends

Based on literature

Regulated gasoline(RF) compared with E15 & E30 blended fuels

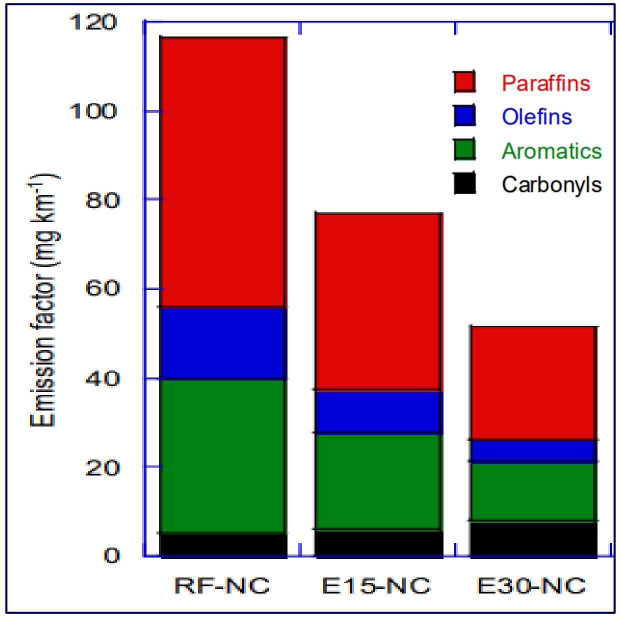


Fig: 8 VOCs emission factors for RF, E15, E30

RF- 116mgkm^{-1}, E15- 76.8mgkm^{-1}, E30- 51.5mgkm^{-1}

- **Regulated gases emissions**

CO, THC, NMHC, NOx, CO_2

- **Unregulated gases Emissions**

Air toxics emissions: HCHO, CH_3CHO, NH_3, CH_3CH_2OH

GHG emissions: N_20, CH_4

An analysis of the VOC species in the tailpipe exhaust

- **Addition of ethanol**

Paraffins ↓, Olefins ↓, Aromatics ↓, Carbonyls ↑

- **Carbonyls emissions:** acetaldehyde, acetone, formaldehyde, and benzaldehyde
- **HC emissions tend towards low molecular weight compounds.**
- **Low exhaust temperature-cooling effect of Ethanol**

Reference: Effect of blending ethanol with gasoline on the performance of Motorcycle Catalysts & Airborne Pollutant Emissions, Jiun et al (2019)

Effect of Ethanol-gasoline blends

Based on literature

Regulated gasoline(RF) compared with E15 & E30

CO emission- ↓ 30%(E15), ↓ 37%(E30)

HC emission- ↓ 19%(E15), ↓ 28%(E30)

NO_x emission- ↑ 8.1%(E15), ↓ 2.7%(E30)

- Ethanol blended gasoline reduces CO & HC emissions from tailpipe exhausts
- Aldehydes (formaldehydes & acetaldehydes), unburned ethanol emissions increases
- NOx emission depending on operating conditions and other parameters

Aging effect on TWCs with gasoline-ethanol blend

Conventional TWC: PGM on Al_2O_3, CeO_2-ZrO_2 & other dopants (5000 → 16200km)

CO: (RF-6.1→25%), (E15-5.3→12%), (E30-81→104%)

HC: (RF-9.4→25%), (E15-13→52%), (E30-4.8→29%)

NOx: (RF-14→43%), (E15-33→83%), (E30-14→57%)

Increase in fuel consumption with Ethanol blending due to low energy content of Ethanol

Effects on the performance of motorcycle catalysts & emissions

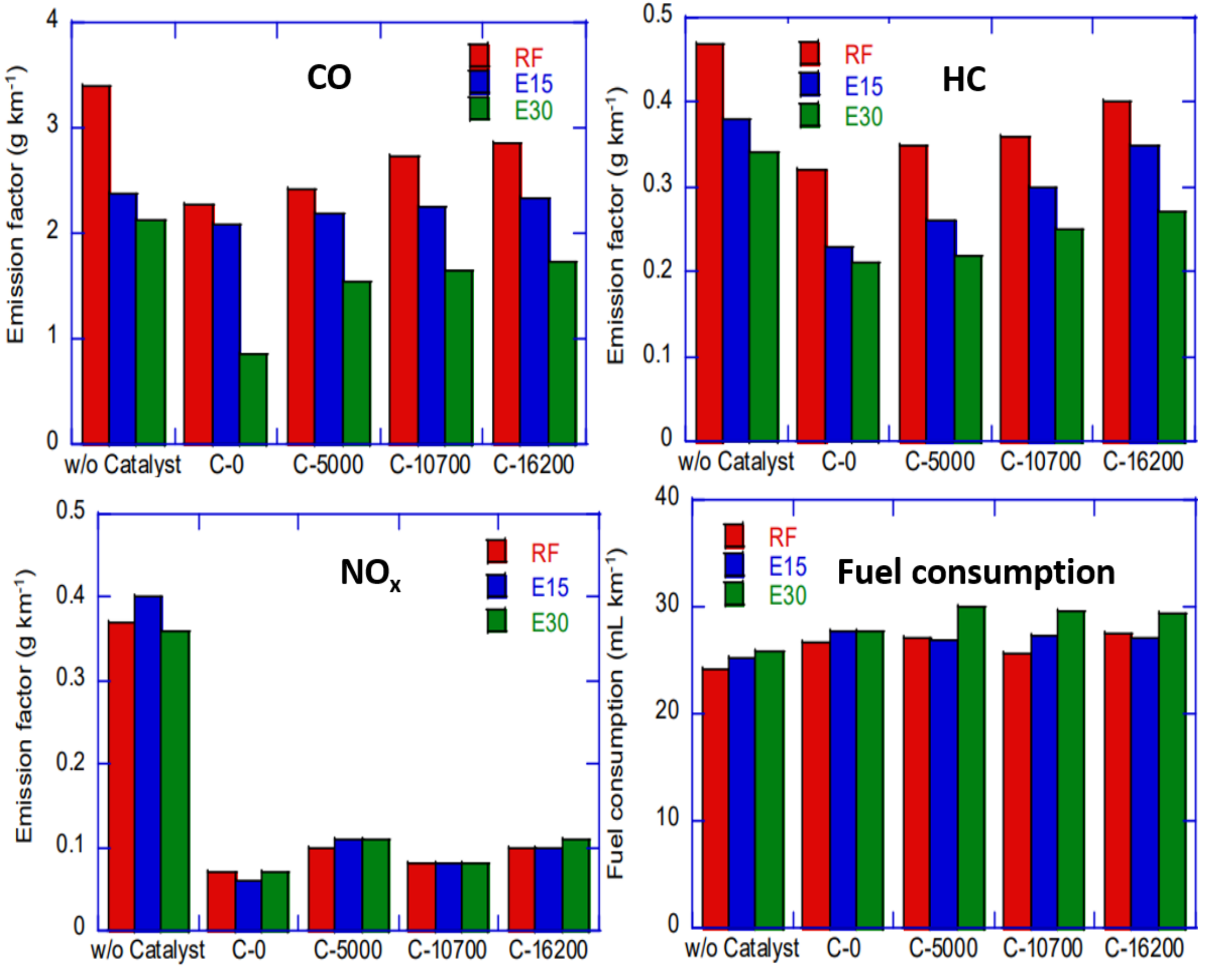


Fig 8: CO, HC, NO_x emission & fuel consumption for different ethanol blending with & without catalyst.(running mileage: 0, 5000, 10700 & 16200km)

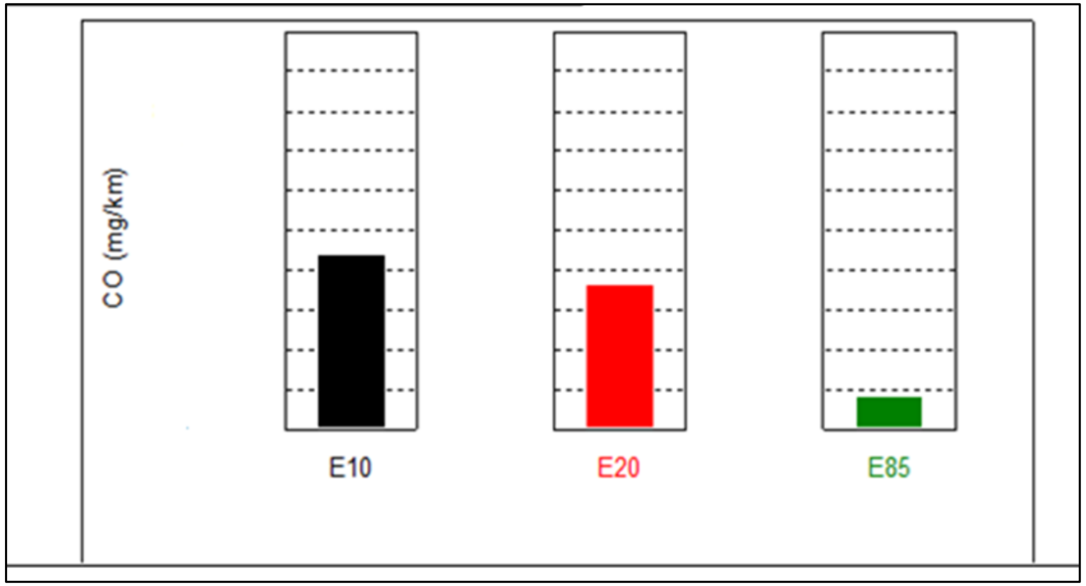
Reference: Effect of blending ethanol with gasoline on the performance of Motorcycle Catalysts & Airborne Pollutant Emissions, Jiun et al (2019)

Effect of Ethanol-gasoline blends

Effects on the performance of motorcycle catalysts & emissions

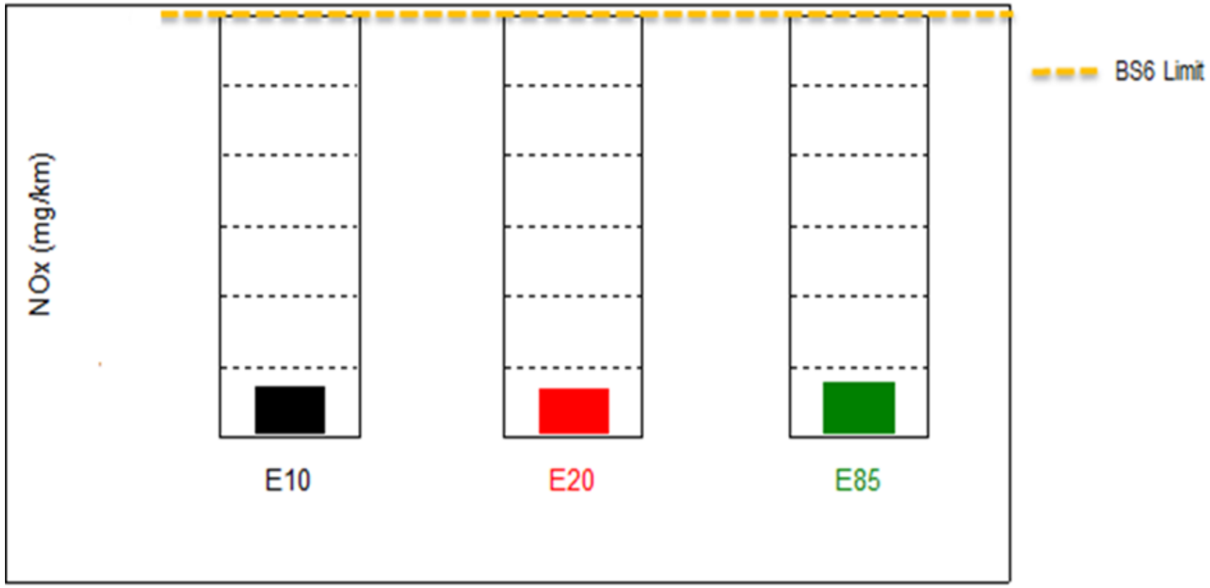
Experimental: All comparisons are between E20 and E85.

Impact on emissions: CO



- Significant reduction in CO observed with increase in ethanol % in blend.
- Overall CO reduced by 77% from E20 to E85.

Impact on emissions: NOx

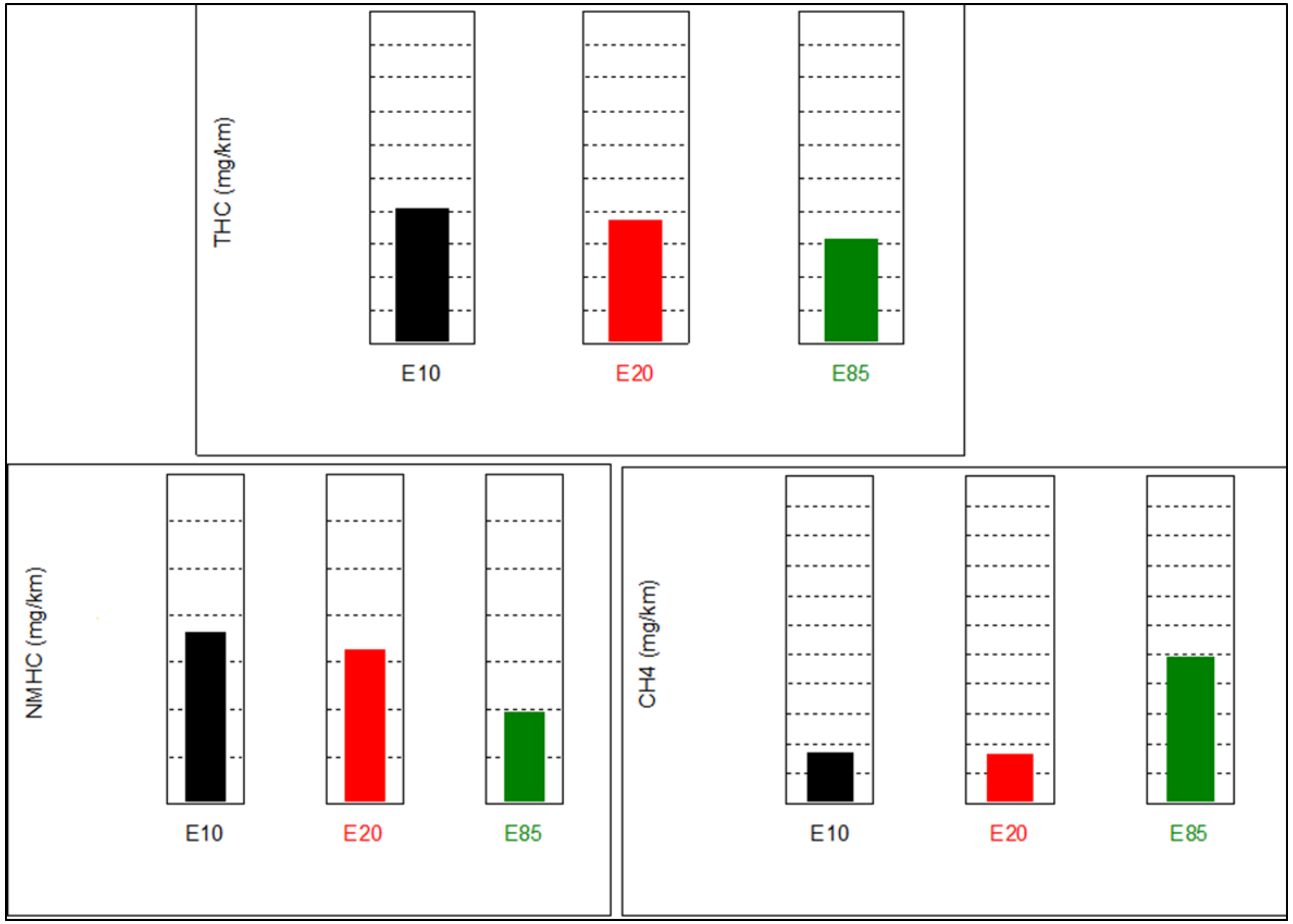


- NOx emission is in similar level with all the tested fuel blends, with the help of the calibration refinement.

Effect of Ethanol-gasoline blends

Effects on the performance of motorcycle catalysts & emissions

Experimental: All comparisons are between E20 and E85.



Impact on emissions: THC / NMHC

- Improvement to the extent of ~15% in THC emissions observed with higher blend.
- Significant improvement, up to ~40% in NMHC emissions observed with increasing ethanol % in blend.

Key Takeaways

1. NH_3 Desorption studies conducted to understand retention of acid sites, which directly relates to NO_x conversion on SCR.

2. After Hydrothermal aging with 30% steam, Cu based SCR sustained its performance.

3. SCR washcoats cover a wide range of temperatures for NO_x conversion.

4. Emission trends for Ethanol blended Gasoline fuel is discussed.

THANKS

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