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Global Perspectives on Transport Decarbonization - And Implications for Indian Context

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MOBILITY NOTES
On sustainable transportation

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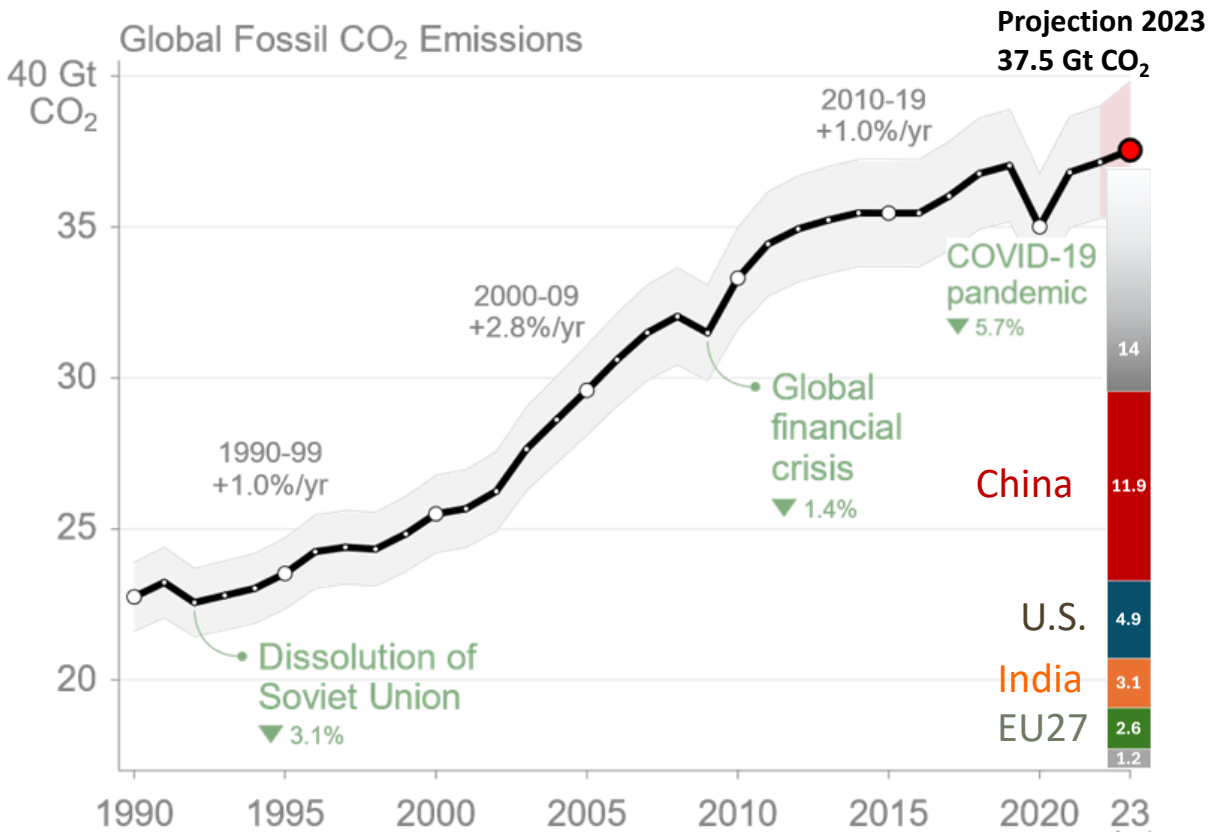
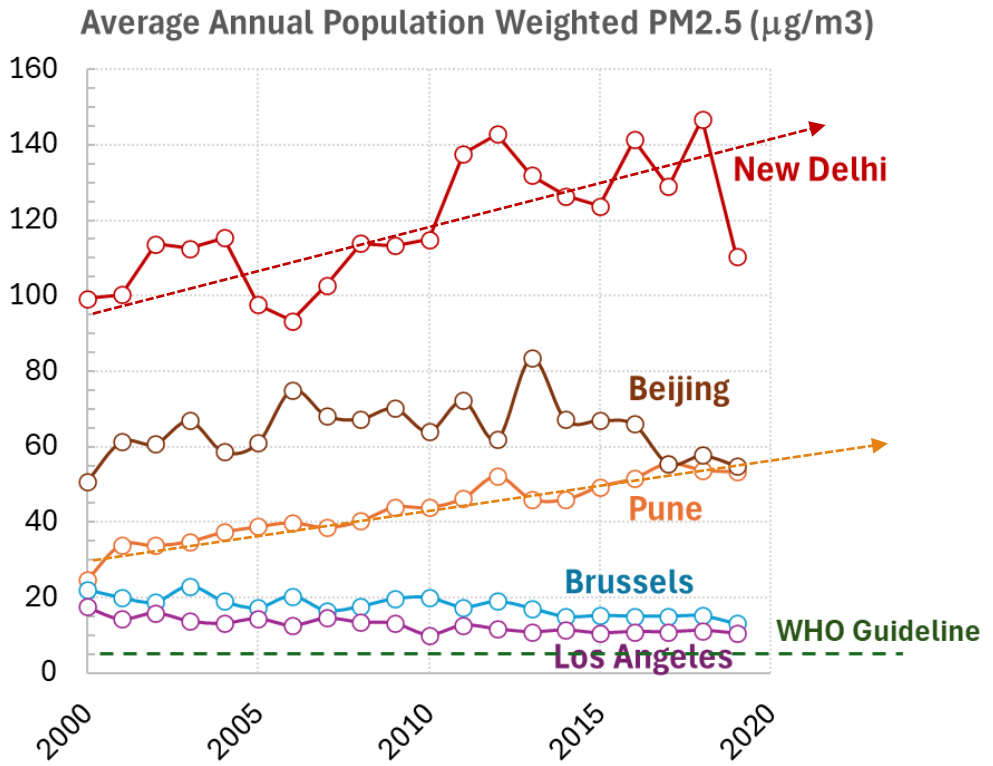
Reducing GHG and criteria pollutant emissions from road transport is a priority India is playing a major role in advancing the standards and technologies



Source: Global Carbon Project

Air quality in major cities in India is still far from the WHO guideline – and has deteriorated in the last two decades



Source: State of Global Air 2022

Emission Standards for Light-Duty Vehicles in Major Markets

Global Trends

US

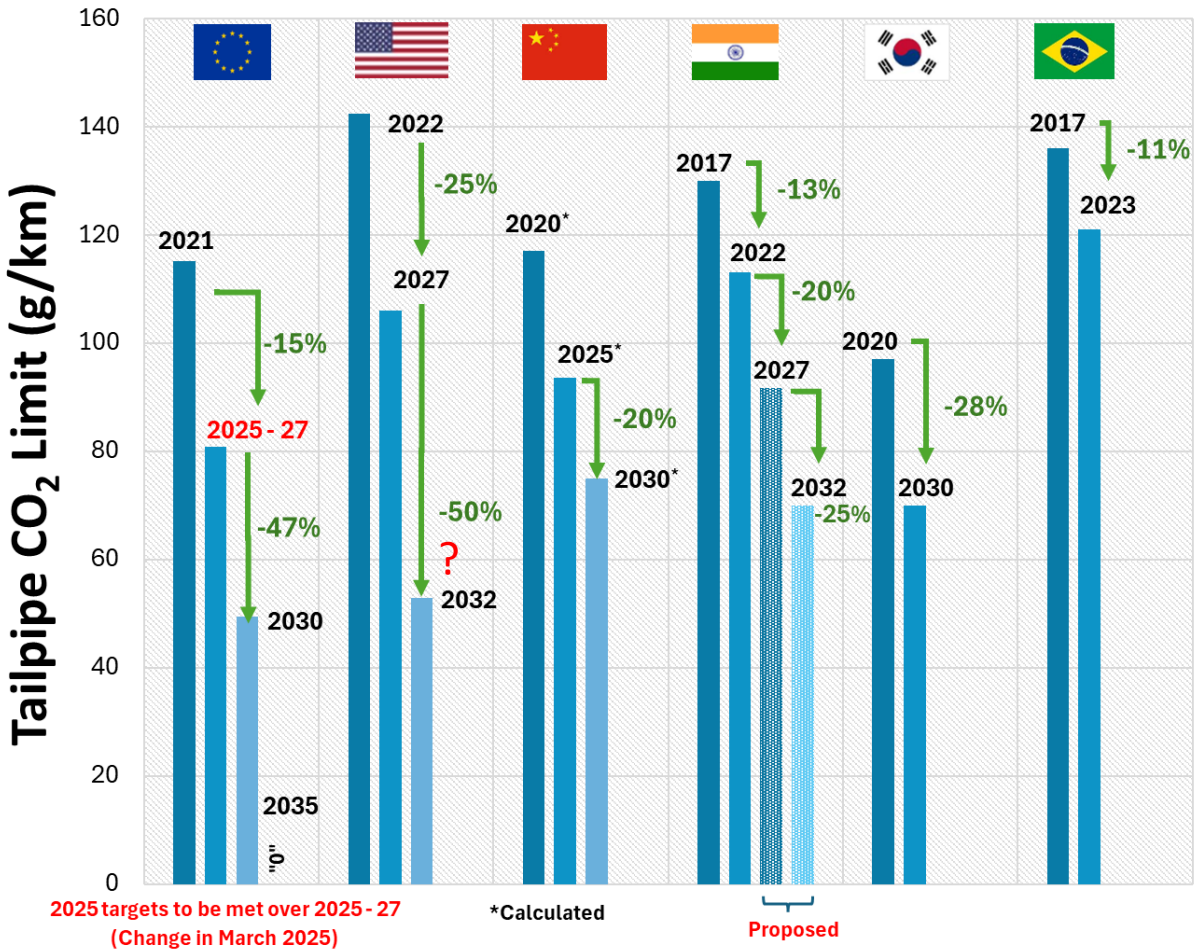
- MY 2027 CO_2 standards very likely relaxed / rescinded
- Future NHTSA CAFE standards will not include EV projections when setting standards

Europe

- 2025 standards to be met over 3 years (2025 – 2027)
- 2035 ICE phase-out hotly debated
- Role of e-fuels and renewable fuels explored
- UK - Hybrids allowed beyond 2030 (only ZEVs beyond 2035)

India

- New CAFE 2027 – 2032 standards proposed
- Concessions for smaller cars (3 g-CO_2/km)
- Carbon neutrality factor for alternate fuels and hybrids

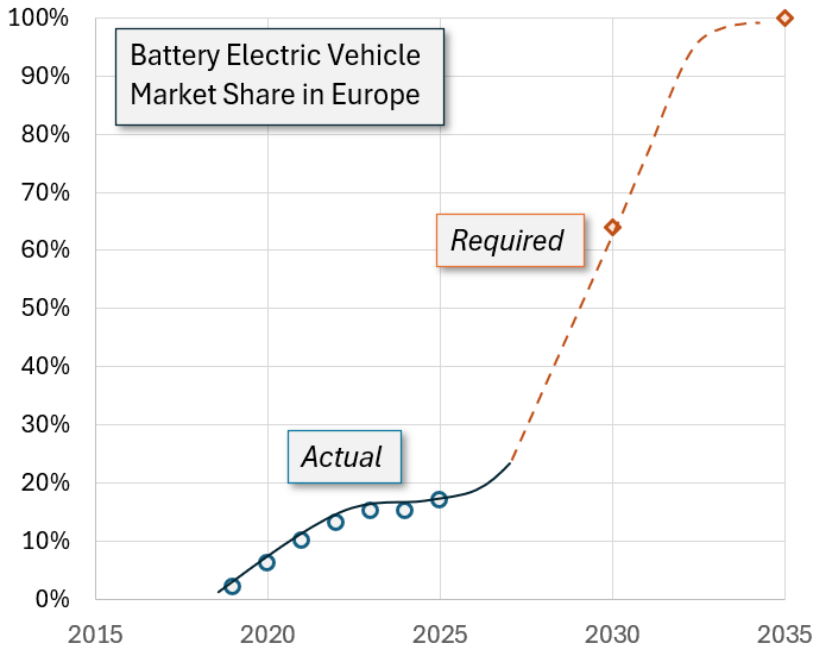


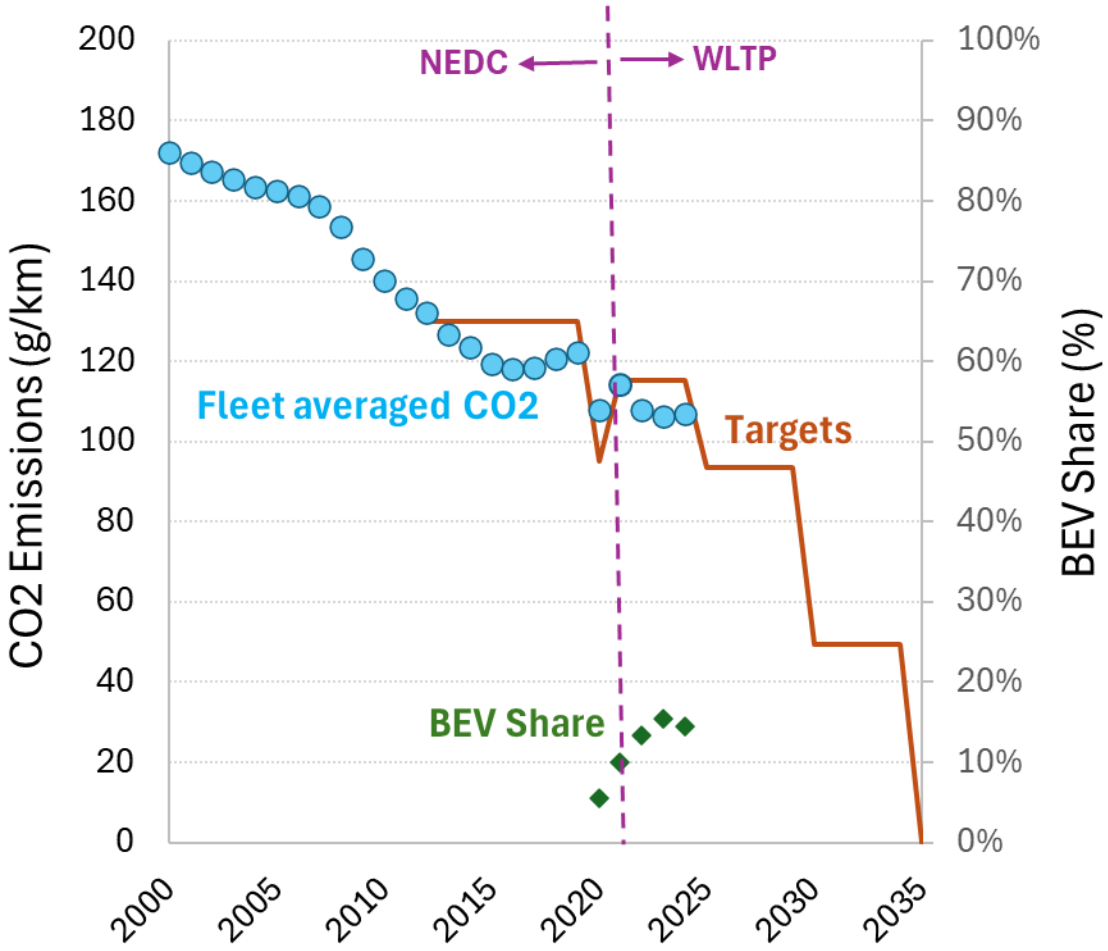
India should be wary of the “European experiment”
Pragmatic approach: Promote electrification while also upholding criteria pollutant standards

ACEA & CLEPA letter to EU Commission, Aug 27th

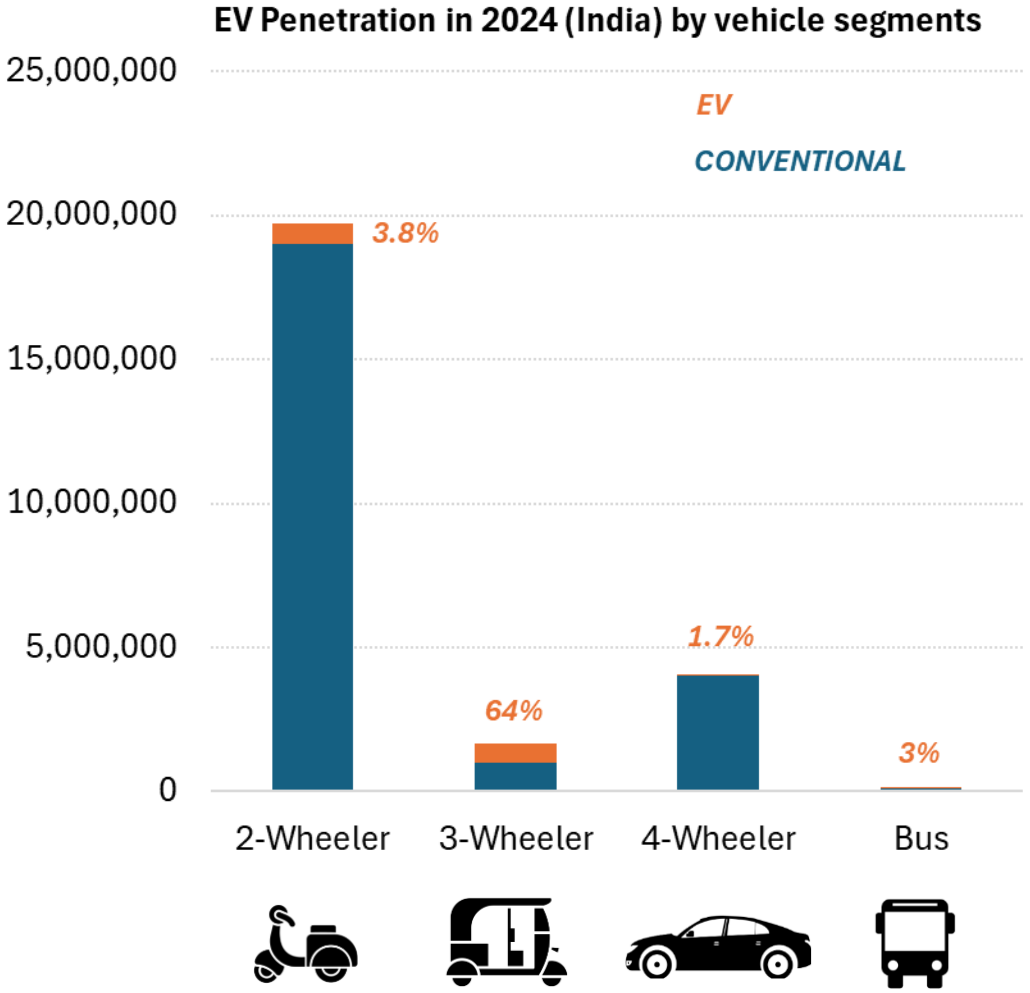
“Meeting the rigid car and van CO2 targets for 2030 and 2035 is, in today’s world, simply no longer feasible”

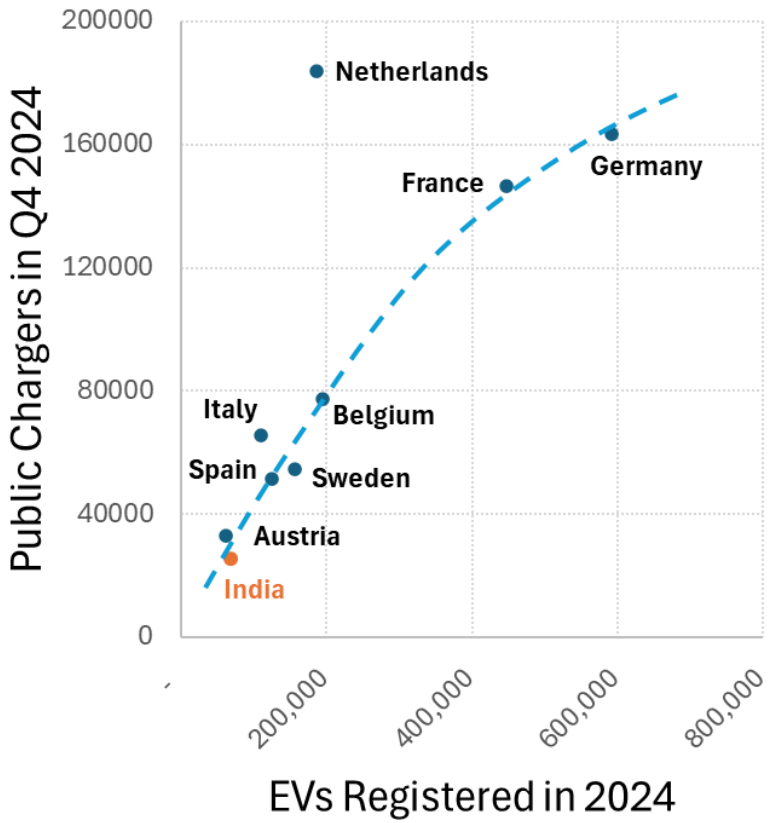
The EU risks missing the turn on its automotive transition – September’s Strategic Dialogue is the chance to correct course





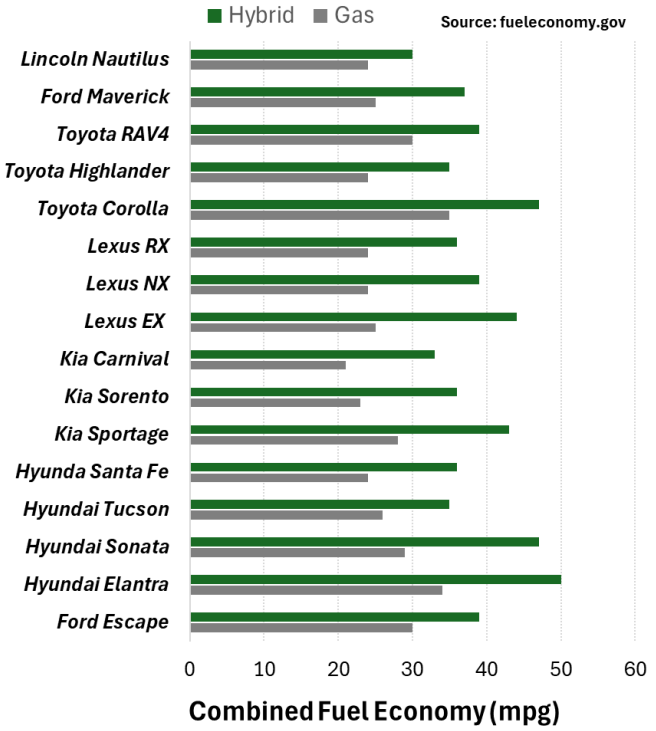
EV adoption in India is still in the early stage
Conventional vehicles expected to be around for decades and need to be improved



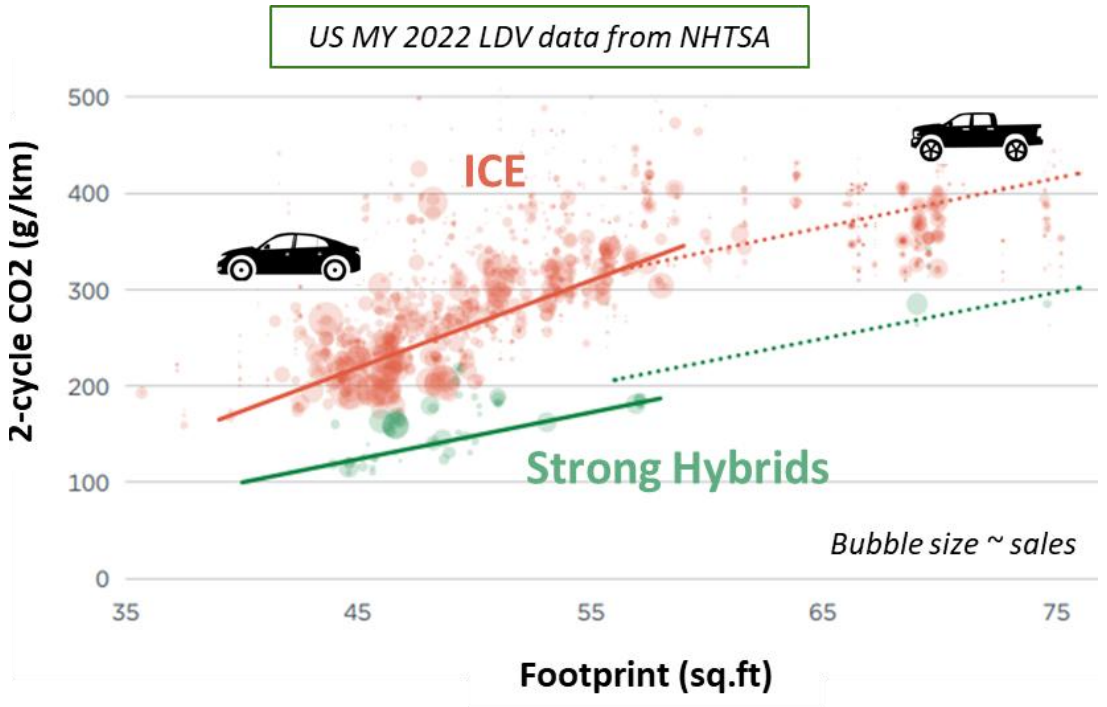


Hybrids are increasing market share – and are seen as a cost-effective choice for CO_2 reductions

Avg. fuel economy improvement: 12.5 mpg
Avg. MSRP difference = $1,800



Reduction in CO_2 emissions with strong hybridization
Cars ~ 43% | Light-duty trucks : 29 - 41%



Additional 15% reduced CO_2 expected at a modest price premium of $300 - $800

Future improvements in hybrid CO_2 emissions

- Dedicated hybrid engines with BTE > 45%
- Advanced engine oils
- Higher injection pressures
- Electric supercharging and intercooling
- Improved air handling
- In-cylinder fuel reforming
- Dedicated e-turbochargers
- Active pre-chamber ignition
- Variable compression ratios
- Waste heat recovery (e.g. e-turbo)
- Higher compression ratios
- Water injection
- Lean combustion
- Electrically heated catalysts
- Larger batteries

India should implement best elements of Criteria Pollutant Tailpipe Standards from other Major Markets

Light-Duty	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
US - CARB	LEV III					ACC 2.0 : Criteria + ZEV *						
US - EPA	Tier 3						Tier 4 * (NMOG+NOx = 15 mg/mi, PM = 0.5 mg/mi) + GHG (50% reduction from 2027 - 2032) ?						
Europe	Euro 6d		Euro 6e				Euro 7					
China	China 6a		China 6b (w/ RDE)					China 7 (~ Euro 7) +Tier 3 elements				
India	BS 6 Stage 1		BS 6 Stage 2 (w/ RDE)			WLTP			BS 7 (~ Euro 7)			
Brazil	L6	PROCONVE L7			PROCONVE L8							

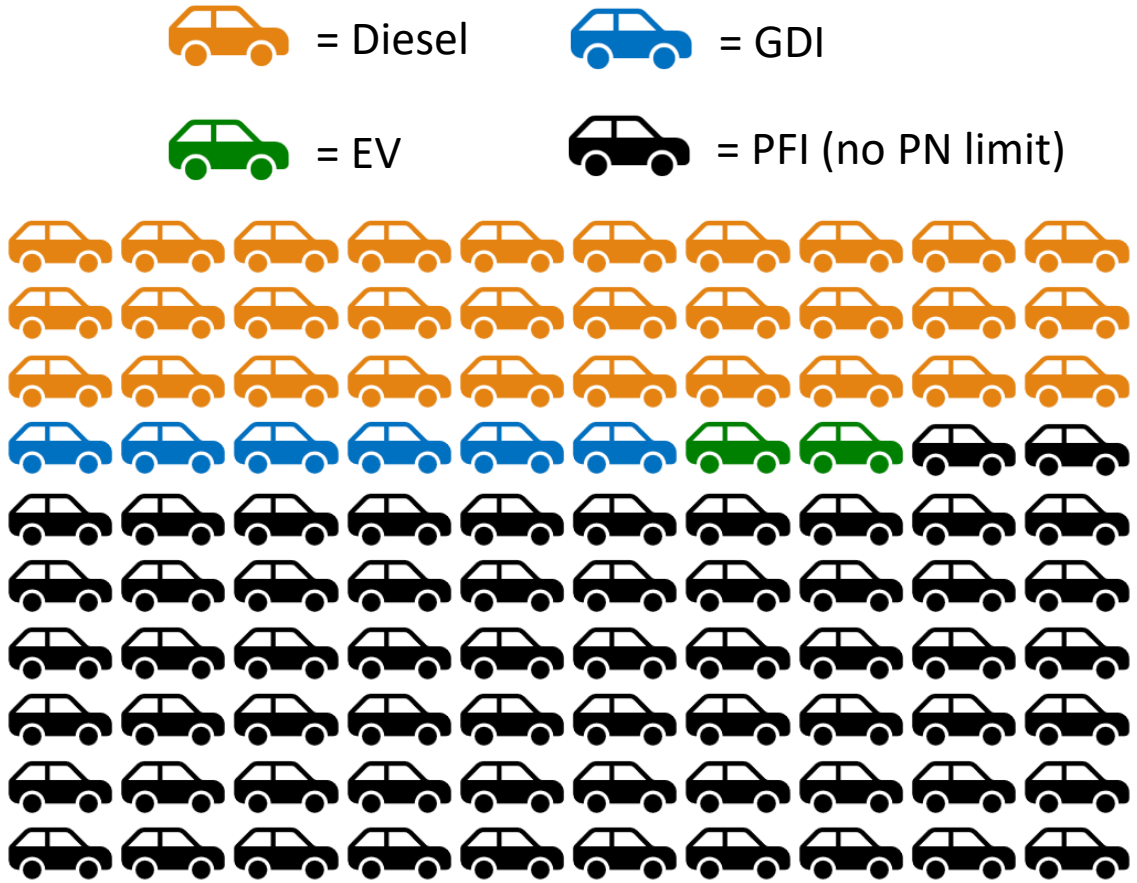
**EPA is reviewing Tier 4 standards, CARB authority for ACC 2.0 revoked – but work on ACC 3.0 starting*

Overall Approach in Europe and US for successive tightening --

- Ensure standards are set for pollutants at levels that can be measured (e.g. PN_{10} or 0.5 mg/mi)
- Ensure standards result in implementation of best available technology (e.g. GPFs, right sized canisters for evap)
- Ensure standards are met over all reasonable real-world ambient and driving conditions (RDE in Europe)
- Ensure standards are fuel and technology neutral (GDI = PFI = Diesel = Hybrids = …)

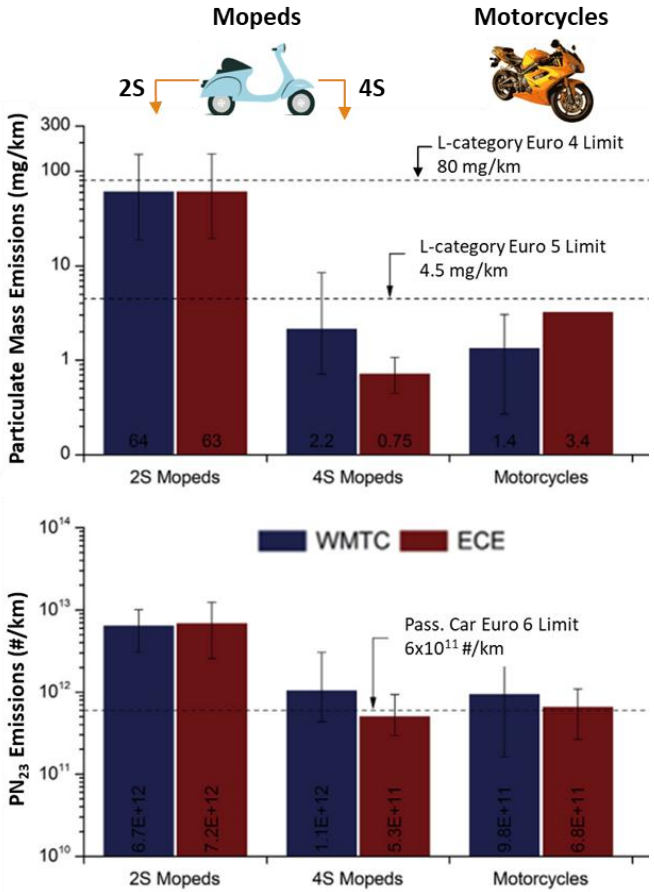
Upcoming standards must limit particulate emissions from all vehicle and fuel types

BS VI PN limit applies to direct injected engines only
→ ~ 60% of new light-duty vehicles without any PN standard !



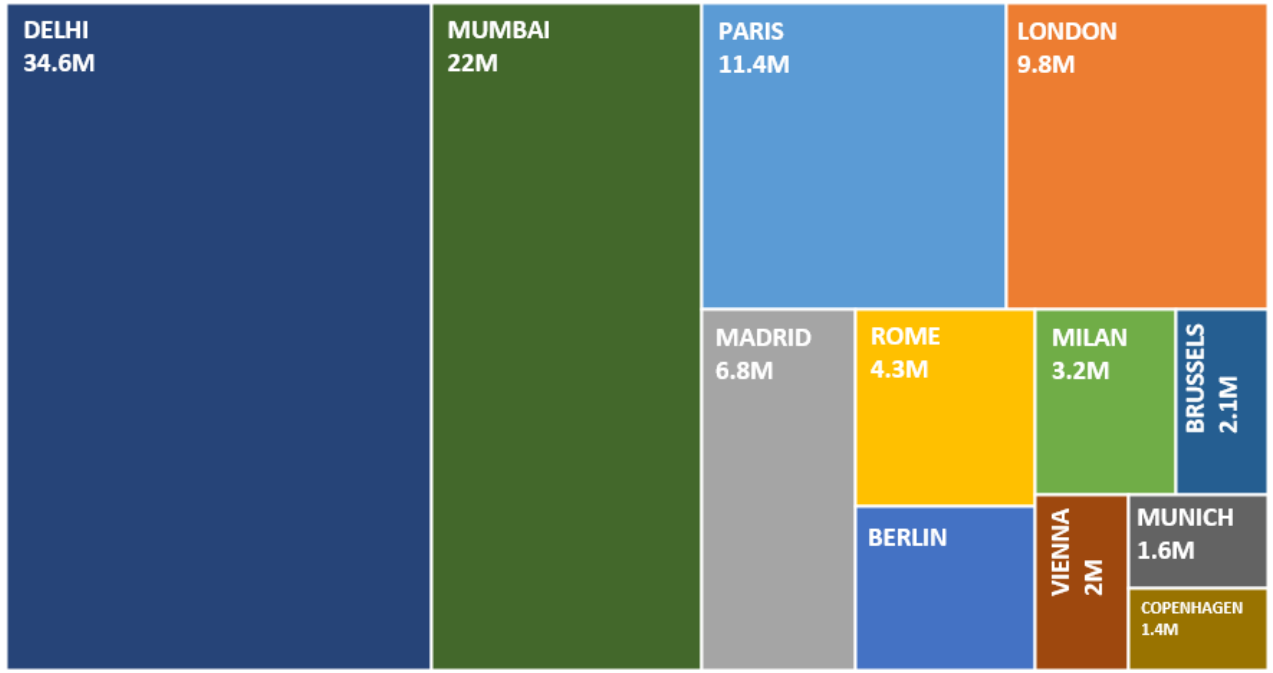
X 18 - 20 million sold each year

Particulate emissions from 2W can be higher than Euro 6 pass. car PN limit



India is NOT Europe
It's time for setting standards that relate to local conditions

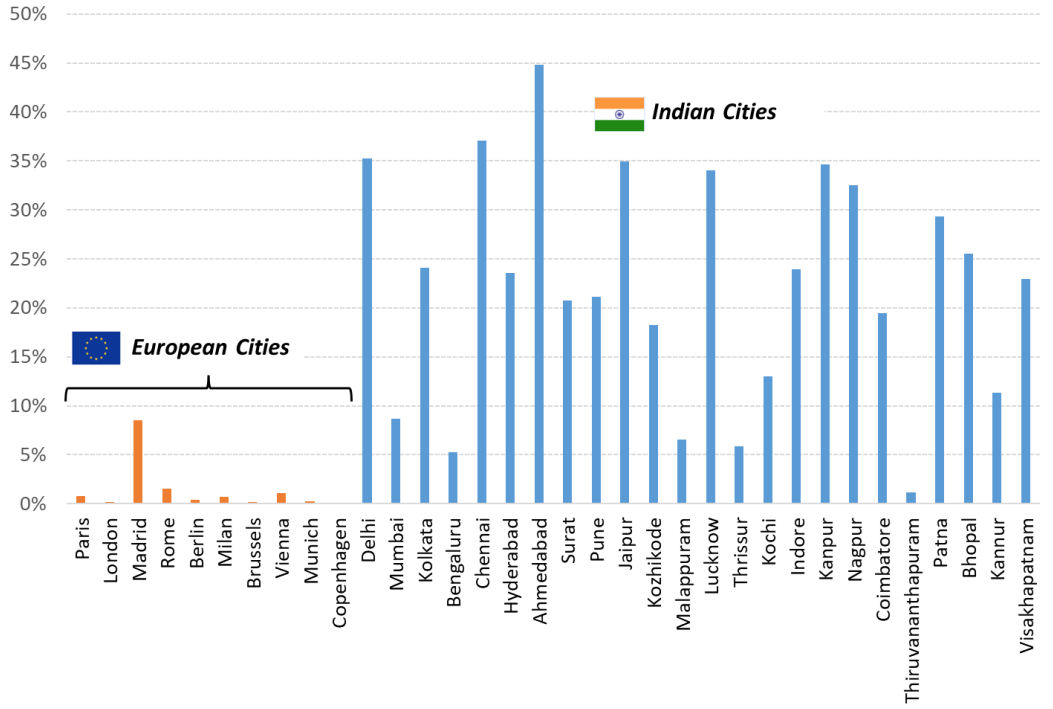
Indian urban density is much higher than Europe → higher population at health risk for breathing polluted air



Population of Delhi and Mumbai is greater than that of 10 European cities combined !

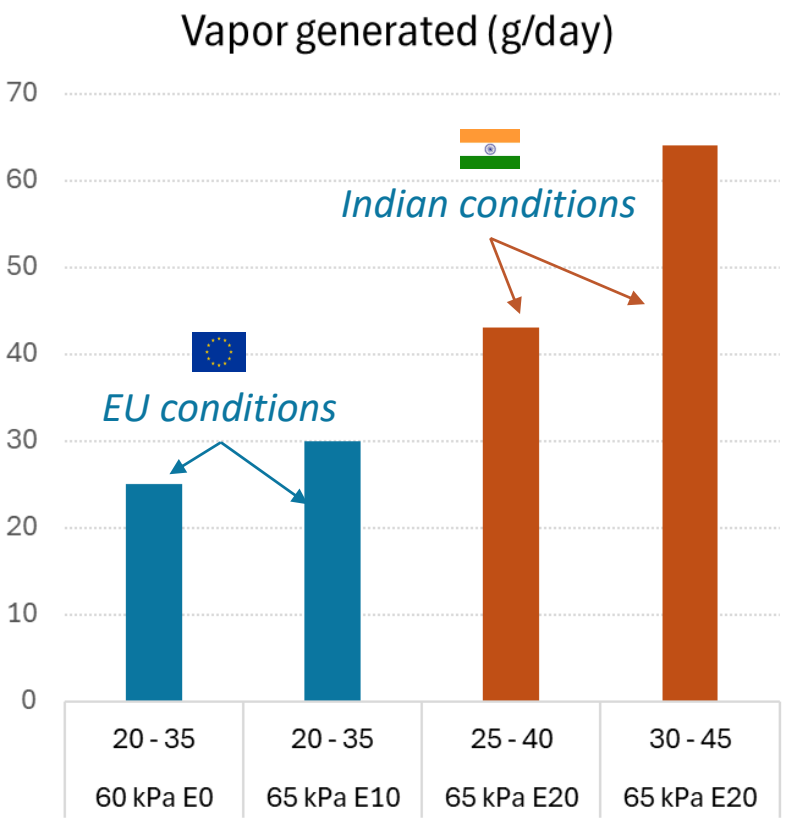
Upcoming test protocols should reflect Indian ambient and driving conditions

Comparison of % days > 35 C in major cities in India & Europe



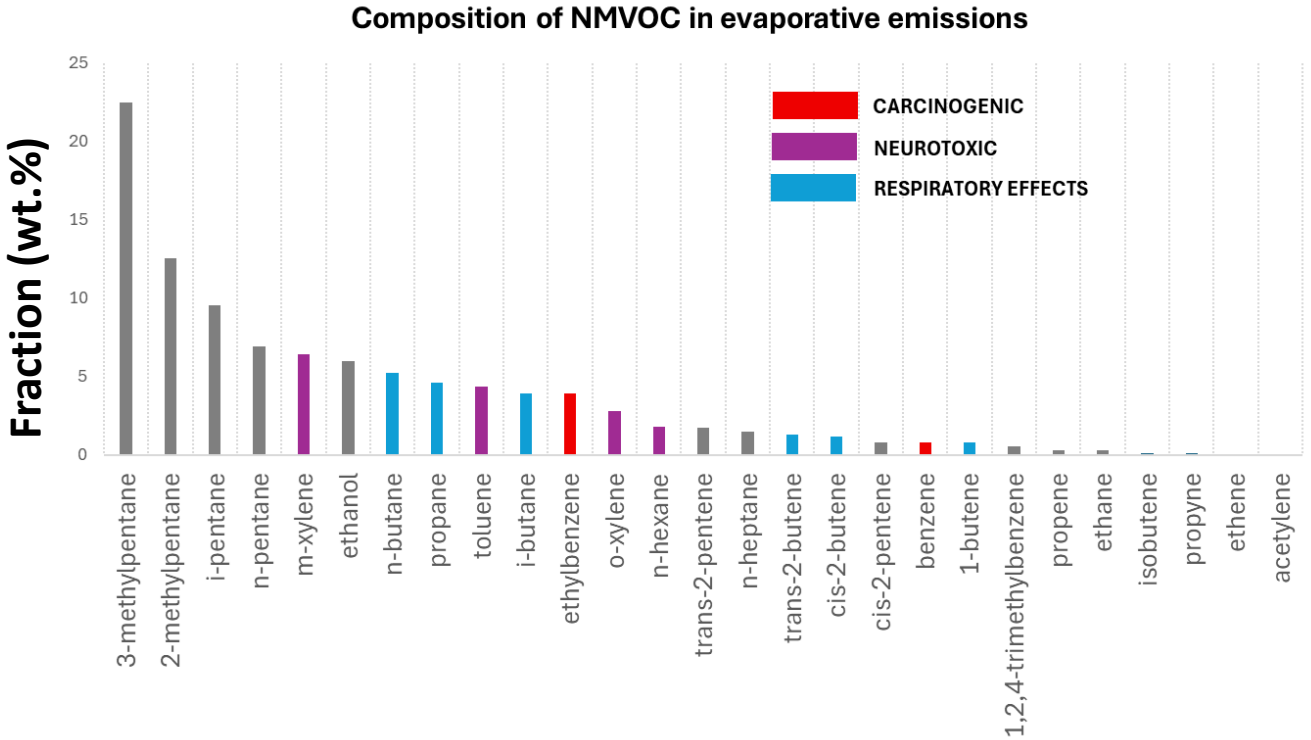
Need to address higher evaporative emissions in India and their impact on human health

Vapor generation depends strongly on diurnal temperature profile and fuel



Source: ECMA webinar, June 2025

Some of the constituents from the emissions are hazardous to health



Source: EMEP/EEA air pollutant emission inventory guidebook 2019

And it's a win-win …

Evaporative emission control system will save fuel (and $$) for the consumer

On-road and Non-Road Heavy-Duty Emission Standards in Major Markets

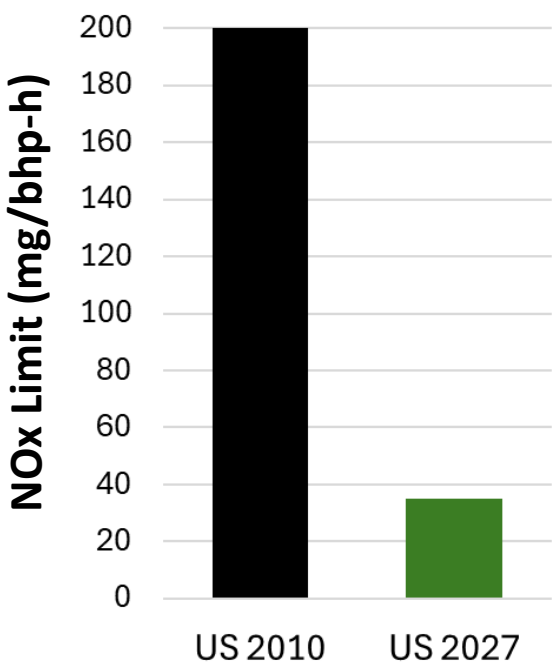
US / California standards for MY 2027+ uncertain

Heavy-Duty On-Road	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
US - CARB	US 2010			Low NOx Omnibus : 75% NOx redn.			EPA Low NOx (350 mg/bhp-hr) + GHG Ph. 3					
US - EPA	US 2010, GHG Phase 3											
Europe	Euro VI-E (PN 6e11 #/kWh, cold-start, ...)							Euro VII NOx 90 - 350 mg/kWh, PN (10nm) 2e11 #/kWh				
China	China VIa		China VIb (w/ RDE)					China VII ~ Euro VII + US LLC?				
India	BS VI Stage 1		BS VI Stage 2 (w/ RDE)						BS VII (~ Euro 7)			
Brazil	PROCONVE 7 (~Euro V)		PROCONVE 8 (~ Euro VI-C)									

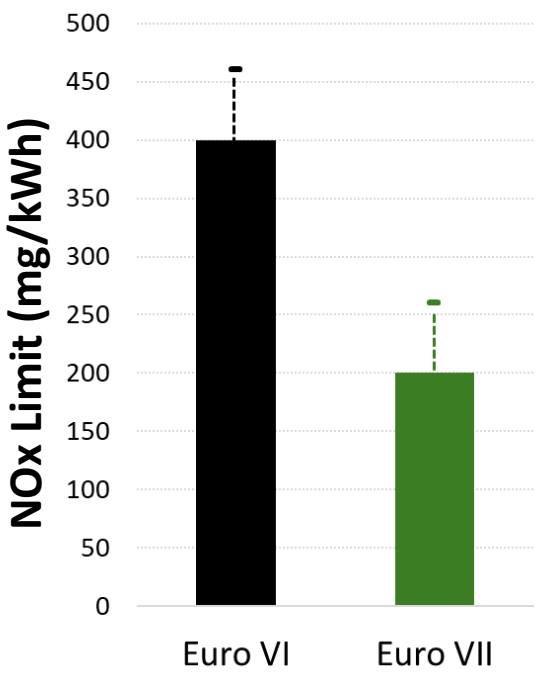
Heavy-Duty Non-Road	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
US - CARB	Tier 4 Final								Tier 5 ? (NOx 90% redn., First GHG rule)			
US - EPA				SORE : Zero emitting < 19 kW (25 hp)						Tier 5 ?		
Europe	Stage V				REVIEW					Stage VI ?		
China	China III ~ EU III A		China IV (~ EU III B) + PN limit					China V				
India	CEV IV (Apr '21)		TREM IV (Apr '23)		CEV V 1/25		TREM V Agr. (4/26)					
Brazil	Proconve MAR-I ~ US Tier 3 / EU III A							MAR - II				
Japan	Tier 4 Final									Tier 5 ?		
Korea	Tier 4 Final	Stage V								Stage VI ?		

Low NOx Standards in US and Europe & Advanced Control Technologies

US EPA Low NOx Rule

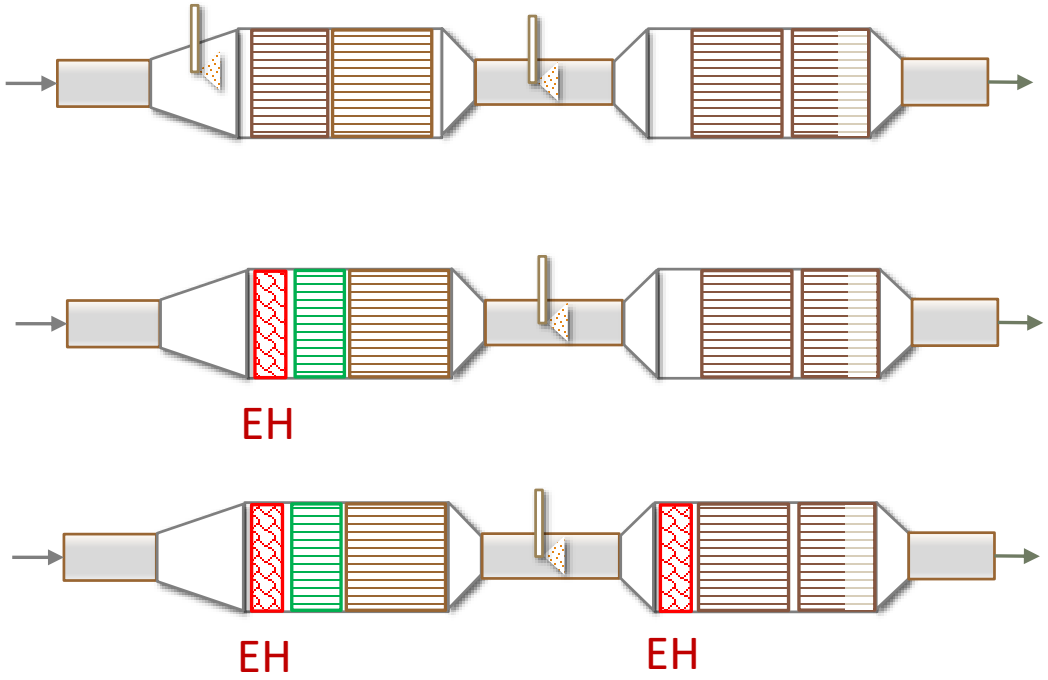


Euro VII



Low NOx System (MY 2027+)

Electric heater(s), Added SCR, Dual dosing



+ Low load cycle – Important for India !

PM Limit reduced by 50%

PN Limit reduced to 9×10^{11} #/km on RDE

Includes particles down to 10 nm

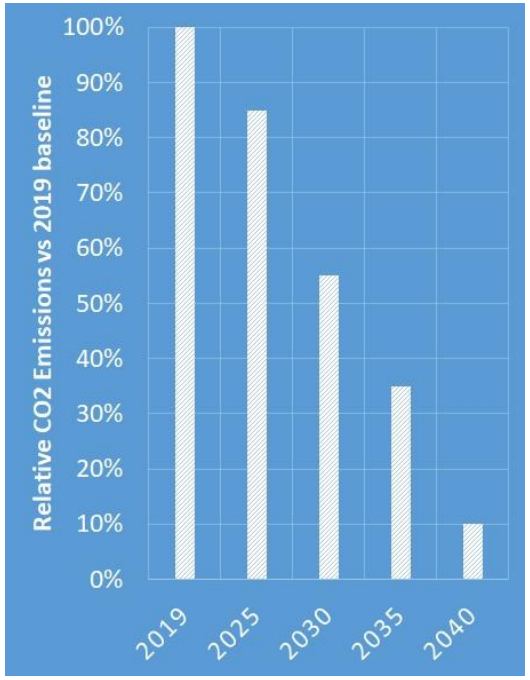
Heavy-Duty Engines are meeting Low NOx standards
(while emitting lower GHG & particulates)

Engine	 Navistar S13	 PACCAR MX-13	 Volvo D13	 Cummins 2027 X15	 Cummins X15N	 Cummins X10	 Cummins B6.7 Octane (gasoline)
Engine Peak Power, Max. Torque	13L, 6-cyl. 515hp-1450 lb.ft	13L, 6-cyl. 405hp-1,650 & 510hp-1,850 lb.ft	13L, 6-cyl. 455 hp-1,650 lb.ft	15L, 6-cyl. 605hp-2,050 lb.ft	15L, 6-cyl. 500 hp-1850 lb.ft	10L, 6-cyl. HD: 450 hp-1650 lb.ft MD: 380 hp-1250 lb.ft	6.7L, 6-cyl. 300 hp, 660 lb.ft
After-treatment System	 Hot, uncooled EGR SCR + DPF + SCR with dual dosing No DOC	 48V EH in cc-position DOC/DPF/EH/SCR Longer SCR, 70% ↑ vol.	 48V EH in uf-position DOC + DPF + EH + SCR	  Closed CV, c-EGR Two 48V 5 kW EHs 1st can: EH + DOC-DPF 2nd can : EH + two SCRs in parallel. 7% higher cat. vol., 44% lower ΔP	Closed CV TWC	c-EGR 48V EH Twin-module	TWC

Heavy-Duty CO_2 standards

EU HD CO_2 Standards

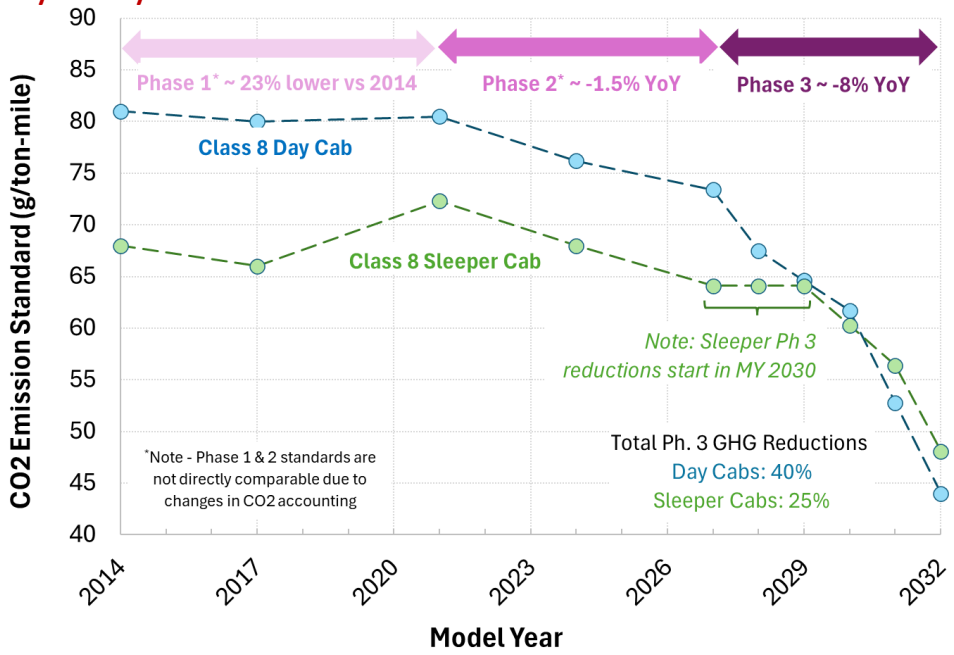
- 90% CO_2 reduction by 2040
- ZEV mandate for city buses
- Incentives for ZLEVs
- Penalty of €4,250 per vehicle per gCO_2/t.km exceeded from 2025+
- ZEV defined as vehicle emitting < 3 g/(t·km)



Commission will review regulation by 2027 to assess appropriateness, role of e-fuels, and development of methodology for the assessment and reporting of lifecycle CO_2 emissions.

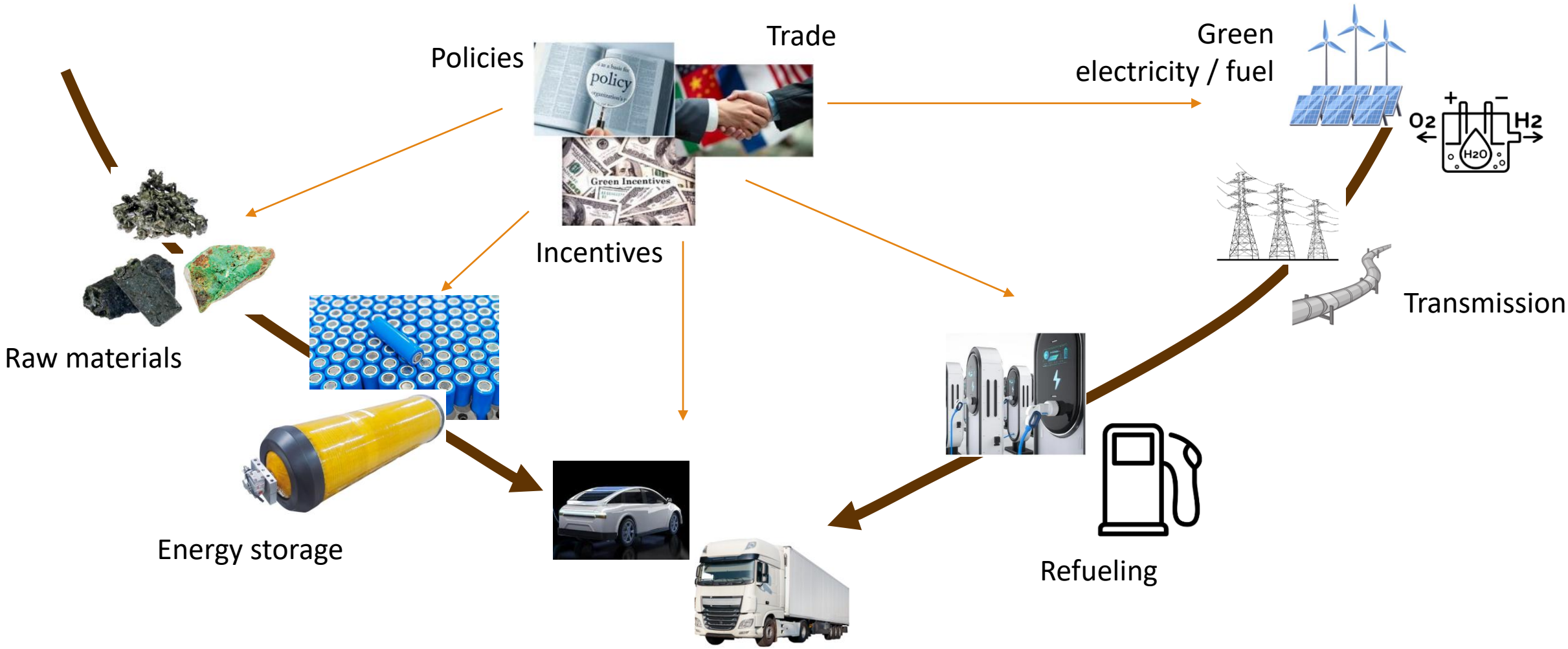
U.S. Tractor CO_2 Standards

Very likely to be weakened to avoid effective ZEV mandate



- Technology neutral standards
- H_2-ICE is NOT a ZEV: Default CO_2 emission value = 3 g/hp-hr
- Vehicles with H_2-ICE and neat H_2, CO_2 = 0

Various factors affect the growth and sustainability of alternate fuels



Hydrogen is getting increased attention
H_2-ICE seen as pathway to utilize H_2, while FC trucks can offer higher fuel efficiency

Press release

Volvo to launch hydrogen-powered trucks

2024-05-23

08-04-2024

MAN expands its zero-emission portfolio

hTGX Range 600 km

KEYOU Truck "ALL-INCLUSIVE" starts from € 0.58 / km

Truck as a service model

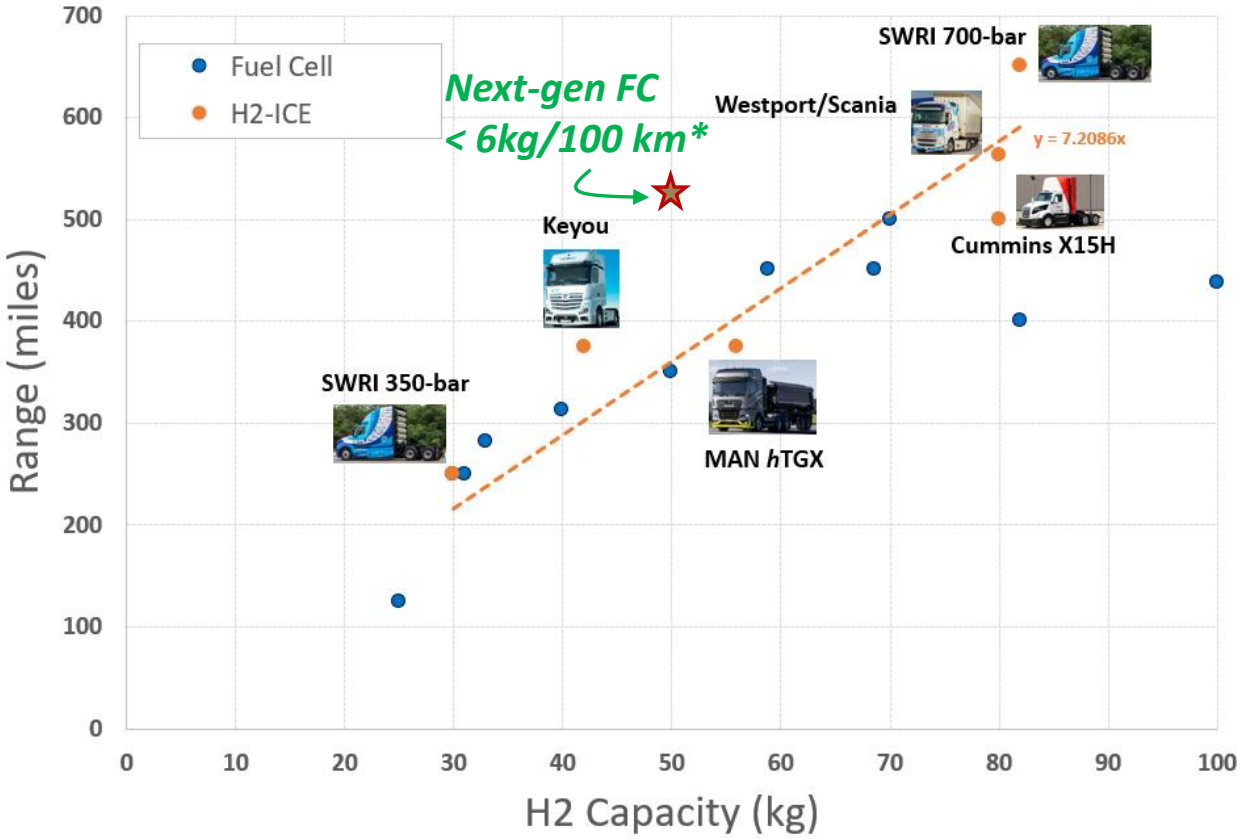
Tata Motors rolls out hydrogen trucks for India

January 30, 2025

40 tonnes of IKEA products hauled by hydrogen ICE-powered truck in Sweden

Holcim H_2 hybrid: On-board H_2 generation, 15% ↓ fuel consumption

Several H_2 trucks announced
- Utilizing both H_2-ICE and Fuel cell technology

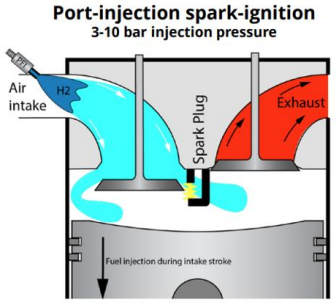


*cellcentric, SAE HD Sustainable Transport Symposium, Gothenburg

Hydrogen ICEs will require a simplified after-treatment system to meet low NOx standards

Spark Ignited

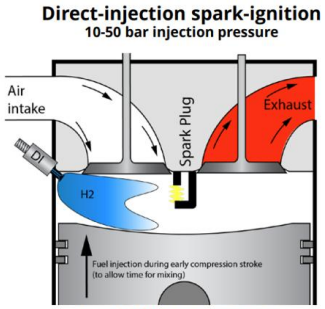
Port Injected



Key challenges: power density, abnormal combustion, efficiency

"Generation 1" H2ICE technology
~2025 market introduction, retrofits

Direct Injected

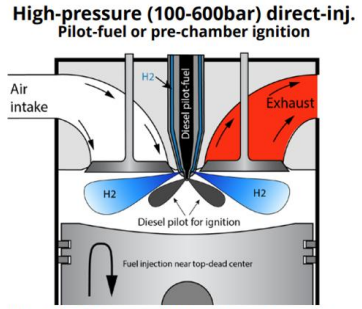


Key challenges: injection technology, abnormal combustion

"Generation 2" H2ICE technology
~2025-2030 market introduction

Pilot fuel / Pre-chamber

Direct Injected



Key challenges: High-pressure pump, NOx, fuel compression energy

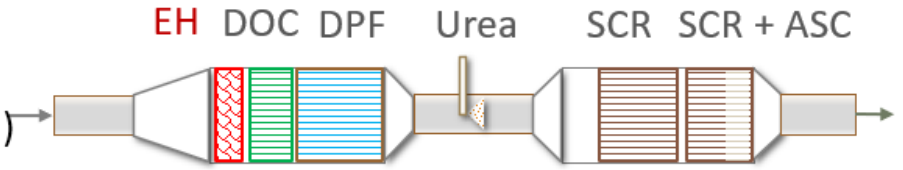
"Generation 2+" technology, best efficiency
Market readiness ~2025-2030

Volumetric Efficiency

Market readiness, Complexity, NOx

- No HCs / CO in exhaust : DOC → HOC
- Ultra-lean: Low engine-out NOx, low DEF consumption
- Filter only oil-based particulates
- Need to understand impact of water in exhaust

Diesel, 2027+
(Example system)



H_2-ICE
(EU system)

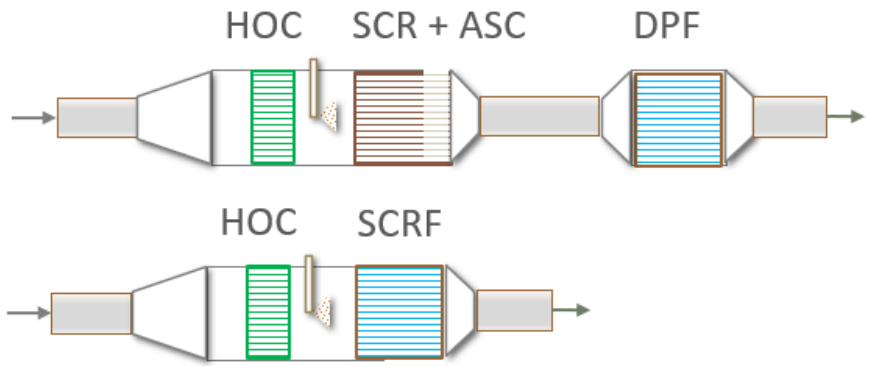
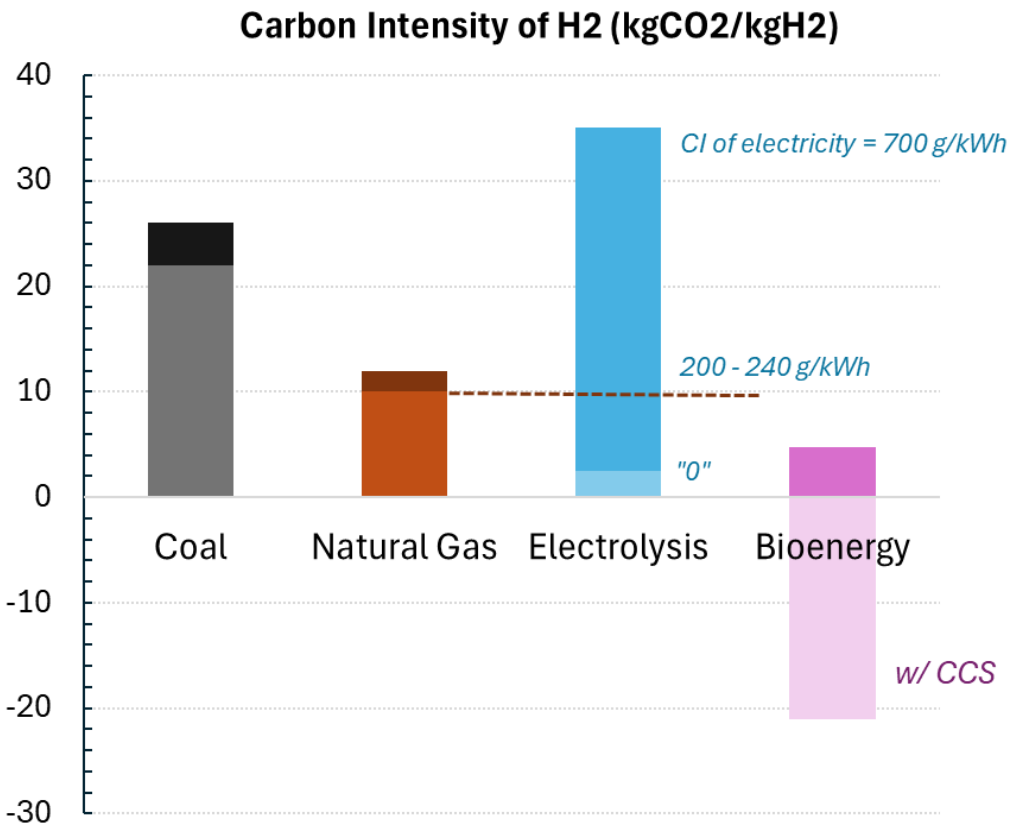


Image: February H2IQ Hour(energy.gov)

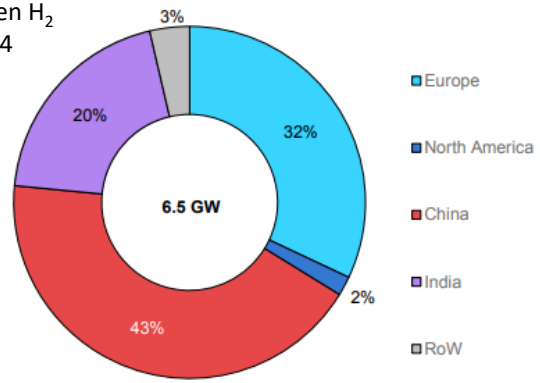
Will the H_2 produced reduce the GHG & criteria pollutant emissions?

Carbon intensity of H_2 depends on the feedstock and use of carbon capture

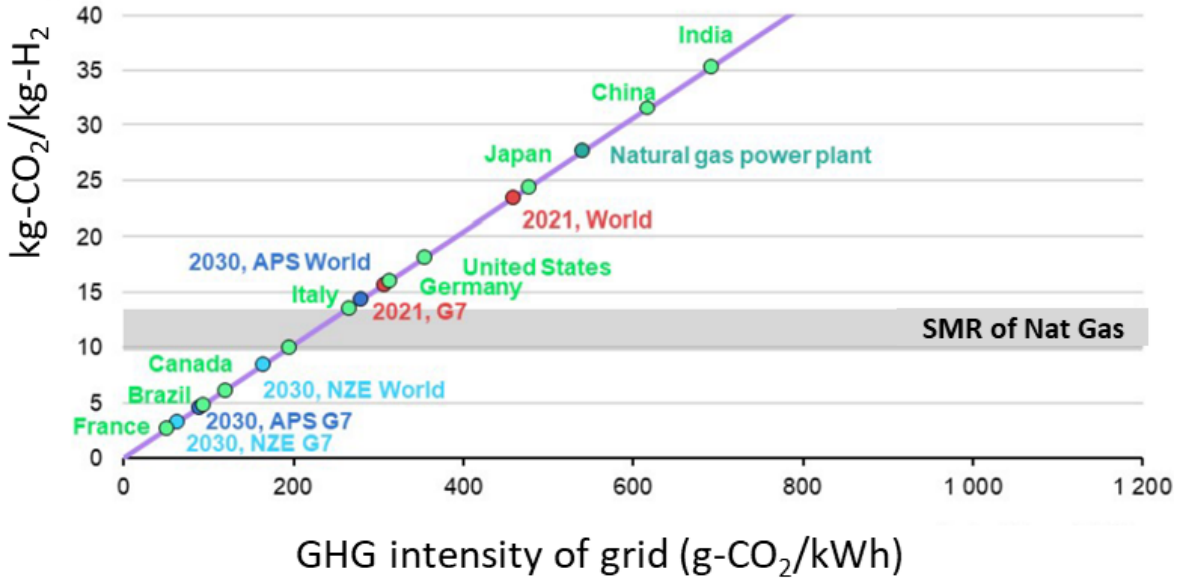


Investment in green H_2 in 9/2023 – 8/2024

India has a significant share of investment in green H_2

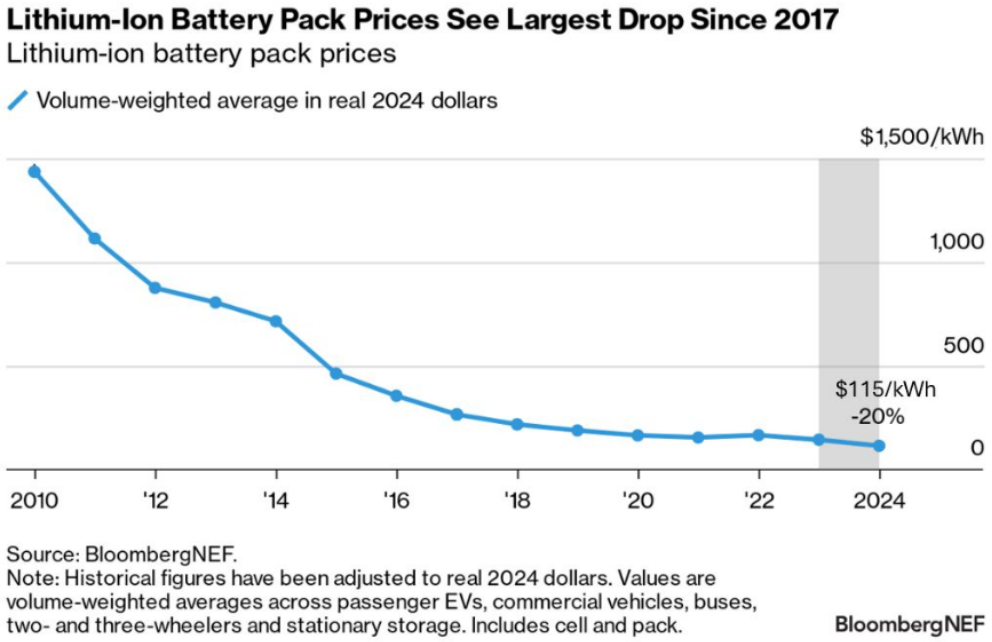


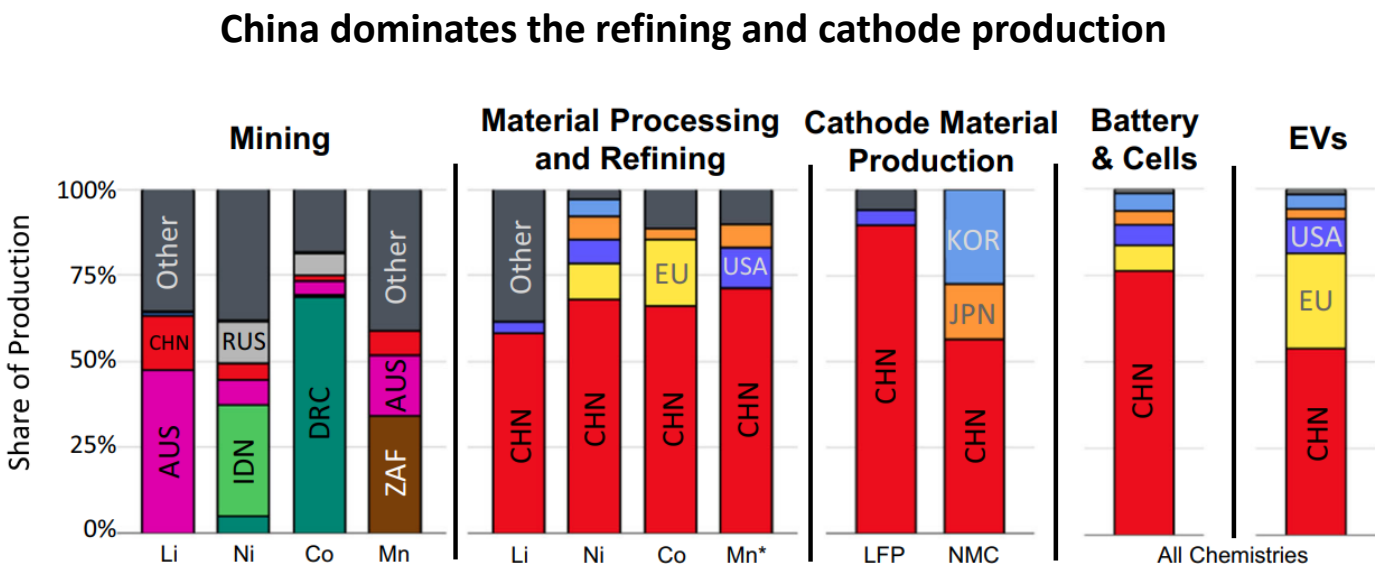
CI of Green H_2 – depends on CI of electricity and therefore location



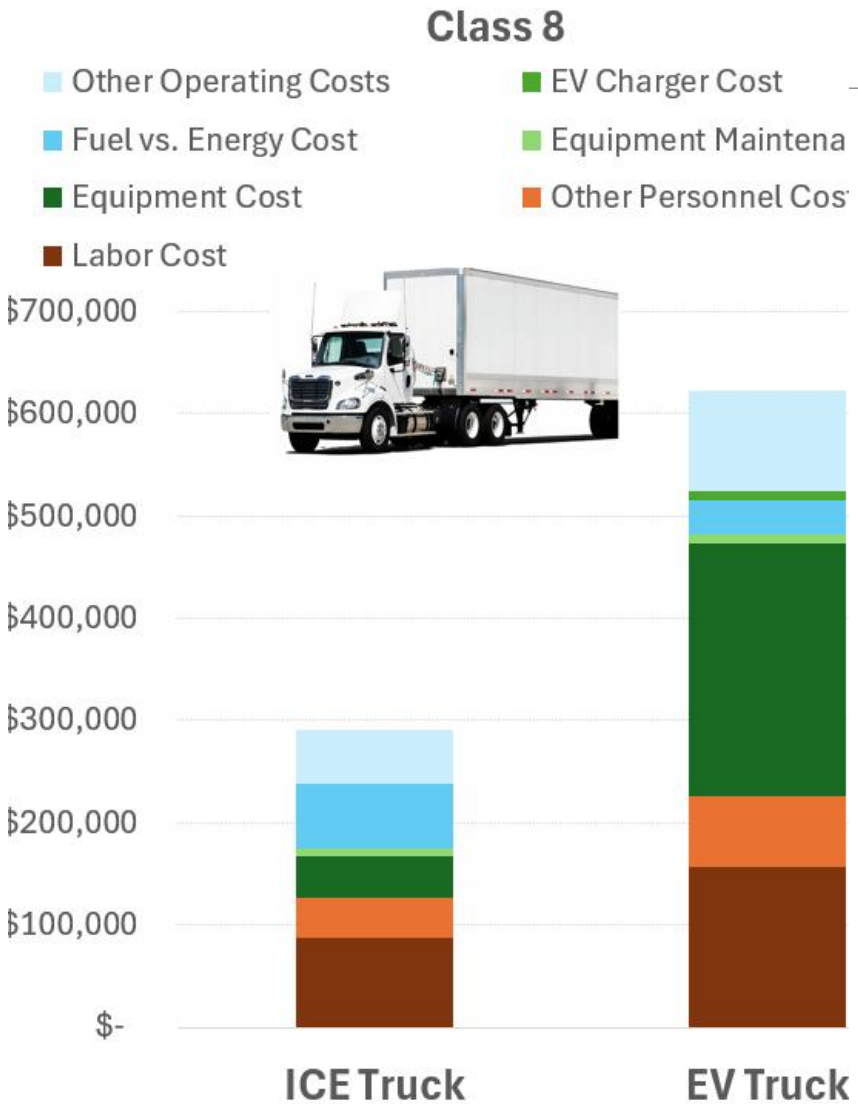
Source: IEA Global H2 Review (2024)

Batteries continue to get cheaper
But supply chain is dominated by China





"Lithium-Ion Battery Roadmap – Industrialization Perspectives Toward 2030", published by Fraunhofer Institute



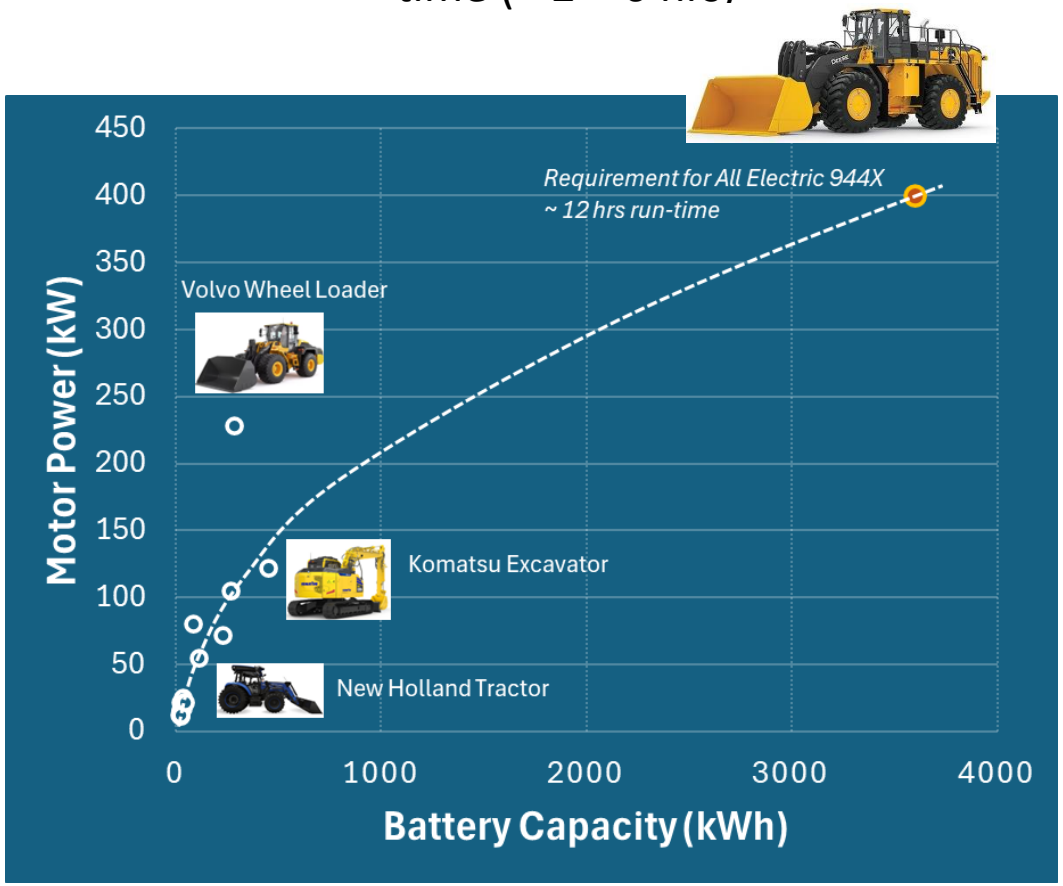
Total Cost of Transportation for a Heavy-Duty Fleet
Electric long-haul trucks cost > 2X that of diesel

- The total cost of transportation for an electric truck increases by over 2X
  - ~ $290K for diesel
  - ~ $620K for an EV
- The EV effectively requires almost 2 drivers to deliver the same payload as the diesel, due to limited range
- A mixed realistic fleet of 25 vehicles including Class 4 & Class 6 trucks would require an additional $3.7M or a 56% increase in cost to convert to electric.
  - That is a non-starter for most small and mid-sized fleets despite any incentives.

Source: Ryder, May 2024

For high-power, continuous operation, electrics are impractical given current battery energy densities India must continue to implement non-road emission norms given the longevity of diesels here

Electric machines are increasing, but mostly limited to compact size – and with limited run time (~ 2 – 6 hrs)



Fully electrifying a wheel loader operating for 12 hours will require 3.6MWh energy, 27 EV batteries, adding 54,000 lbs weight

<u>Diesel – electric solution</u>

13.5L engine works in limited speed range, similar to genset, to power electric drivetrain & batteries

~30% reduction in fuel consumption

Renewable fuel can further reduce WtW GHG

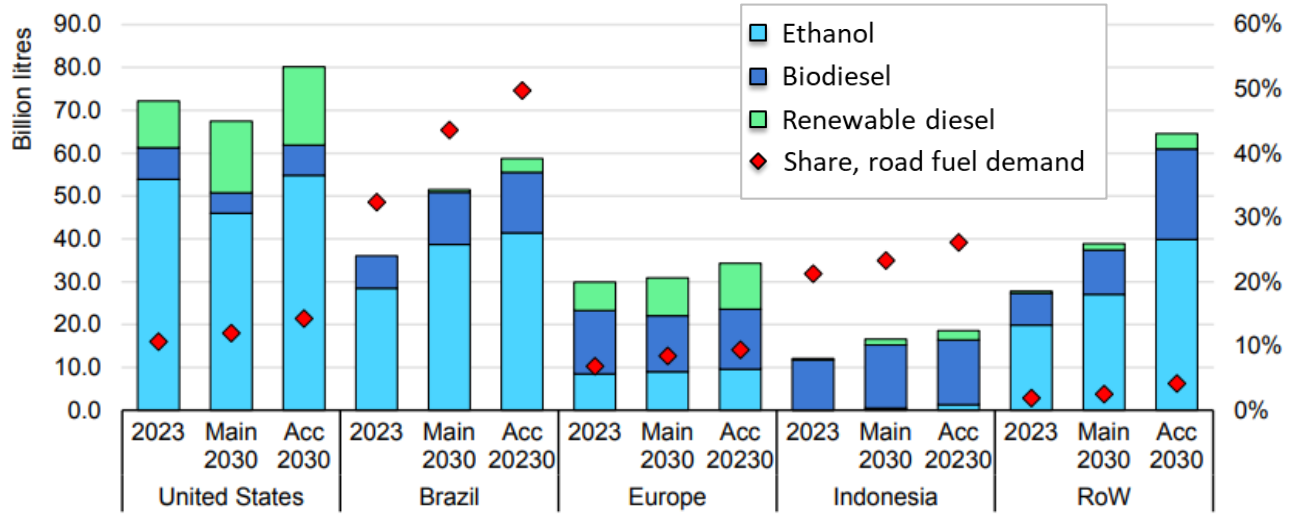
Savings of up to 50% on tire wear

10% cost savings on maintenance

Biofuels growth is a mixed picture across the world

Source: International Energy Agency, Renewables 2024

Road biofuel consumption by country and fuel, main and accelerated cases, 2023-2030



US

Road biofuel use is forecast to fall 5B liters by 2030:

- 8B liters of ethanol due to light-duty electrification
- 3B liters of biodiesel, replaced by renewable diesel

\+ 6B liters of renewable diesel

Brazil

Road biofuel use forecast to increase by >15B liters by 2030:

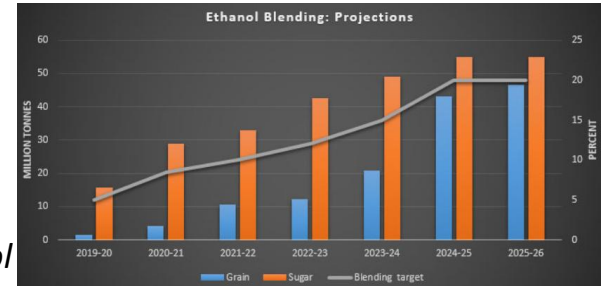
Biofuel blending rate of almost 45%

Growth driven by Fuel of the Future Program

→ Increase ethanol blending to 35% and biodiesel to 20%

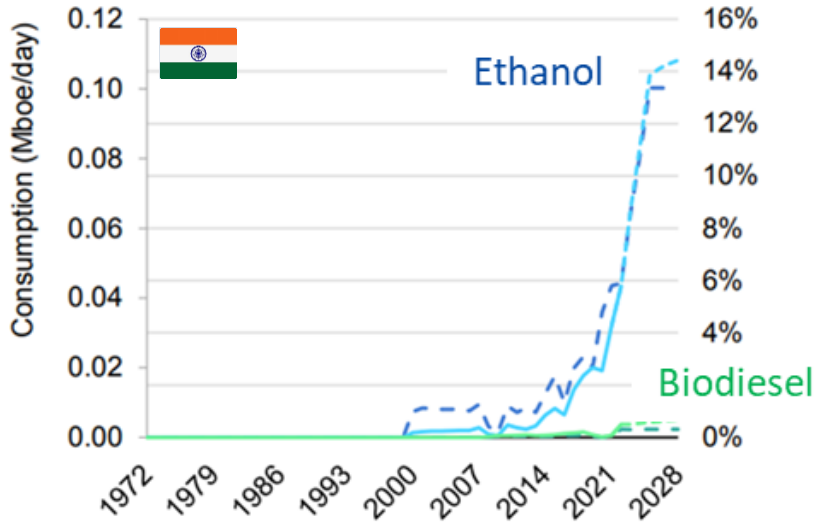
India

Target 20% ethanol blending by 2025



Source: *Roadmap for Ethanol Blending, Govt of India*

India biofuels consumption (Mboe/day)



Notes: Acc = accelerated case. RoW = rest of world.

Source: Road transport demand from IEA (2024), Oil 2024.

Various technologies being pursued for emission reductions. All have some strengths and weaknesses

Only low carbon fuels, retrofits, and scrappage can decarbonize existing fleet

	IC Engine	Hybrid	BEV	H_2 Fuel Cell	H_2 ICE	Low C fuels
GHG Reduction	Ref.	+	++ Depends on electricity	+ Depends on H2 "color"	+ Depends on H2 "color"	++
Fueling Infrastructure	Ref.	o	---	---	---	o
Refueling Time	Ref.	o	--	o	o	o
Range	Ref.	o	-	o	o	o
NOx/PM emissions	Ref.	+	+++	+++	+	+
TCO *Total cost of ownership*	Ref.	+	++/-- Sensitive to battery, electricity prices	++/-- Sensitive to H2 price	-- Sensitive to H2 price	++
Critical materials	Ref.	-	--	--	o	o
Applies to legacy fleet?	-	No	No	No	No	Yes

What matters is CO_2 entering the atmosphere, not what's emitted at the tailpipe → need policies based on lifecycle analysis

FUEL

Production

Transport

Fueling

OTHER

Land-use change
Impact on environment
Environmental Justice

CO_2 capture

Impact on market

VEHICLE

Raw material

Components

Assembly

In-use
(Regulated today)

Maintenance

Export

Recycle

Disposal

Thank you !

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MOBILITY NOTES
On sustainable transportation