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Global Trends in Regulations and Emissions Control Technologies for Near-zero Emitting Vehicles

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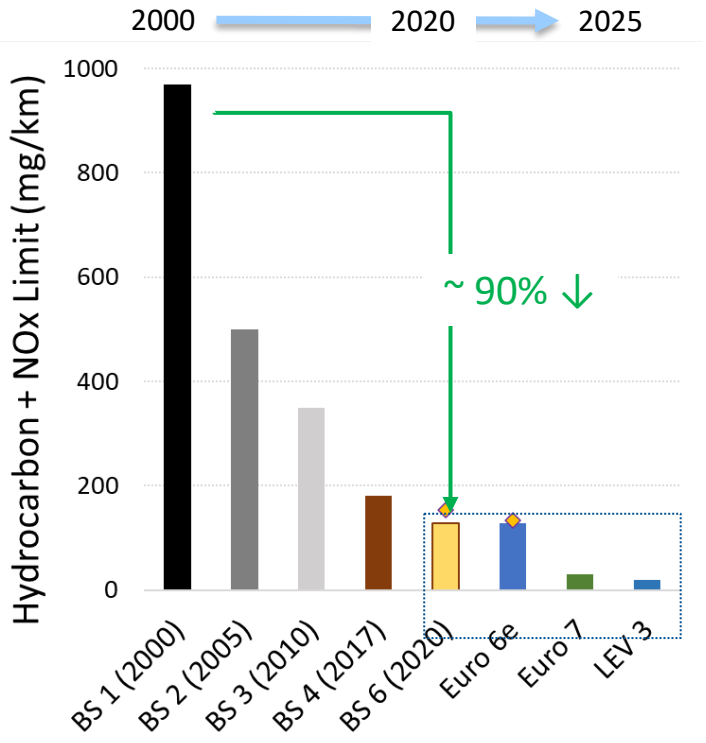
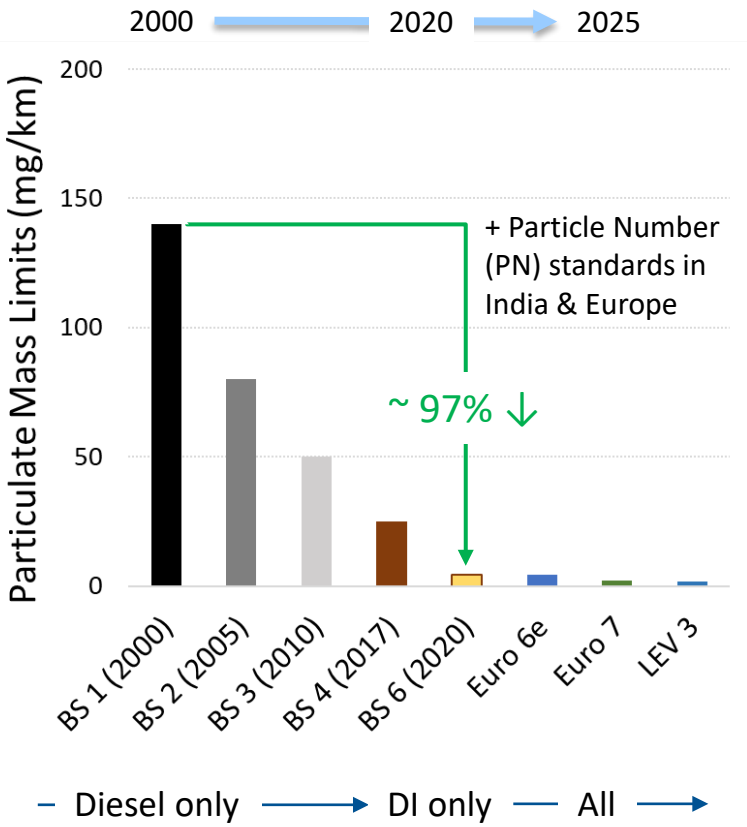
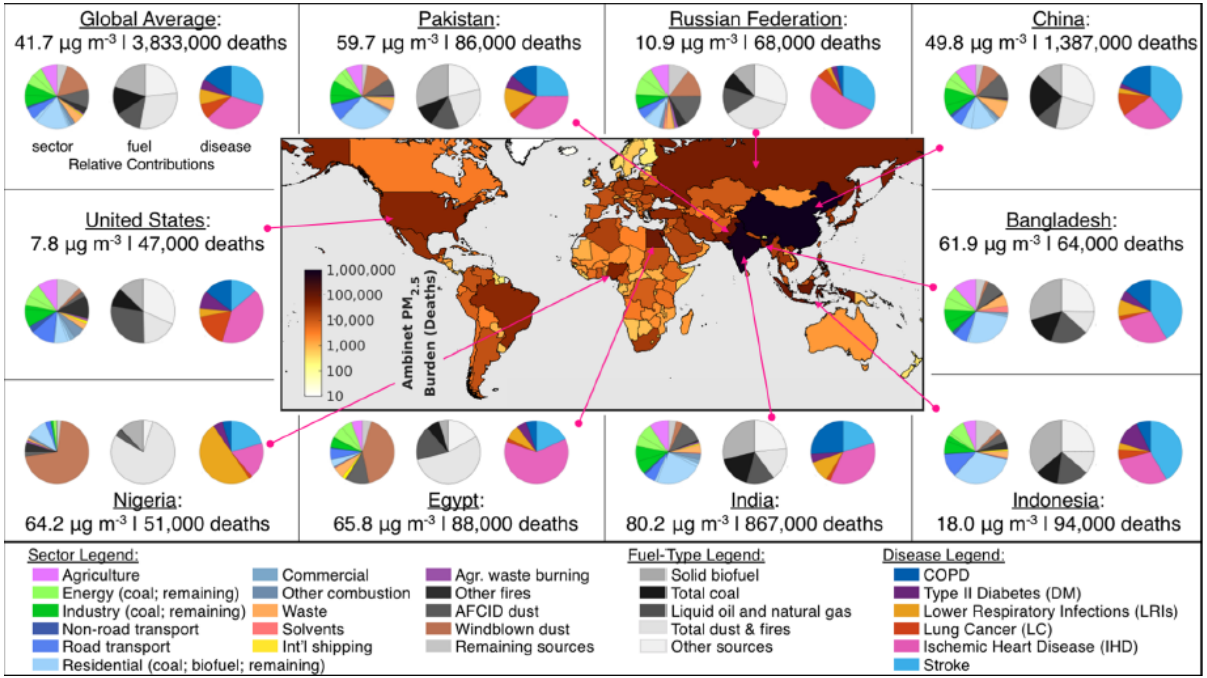
In the past 2 decades, NOx and particulate emission standards have tightened by > 90%

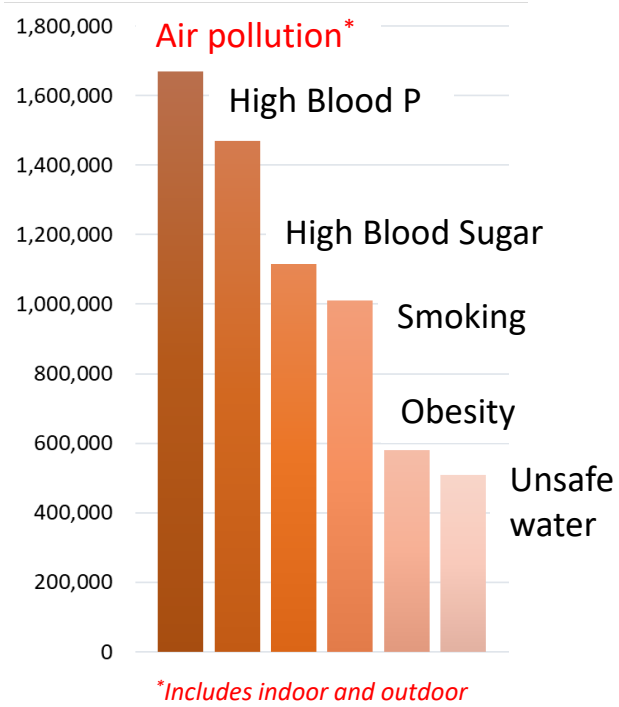




However, further reductions in air pollution are crucial

Fine particulate* pollution associated with ~ 850,000 premature deaths annually in India



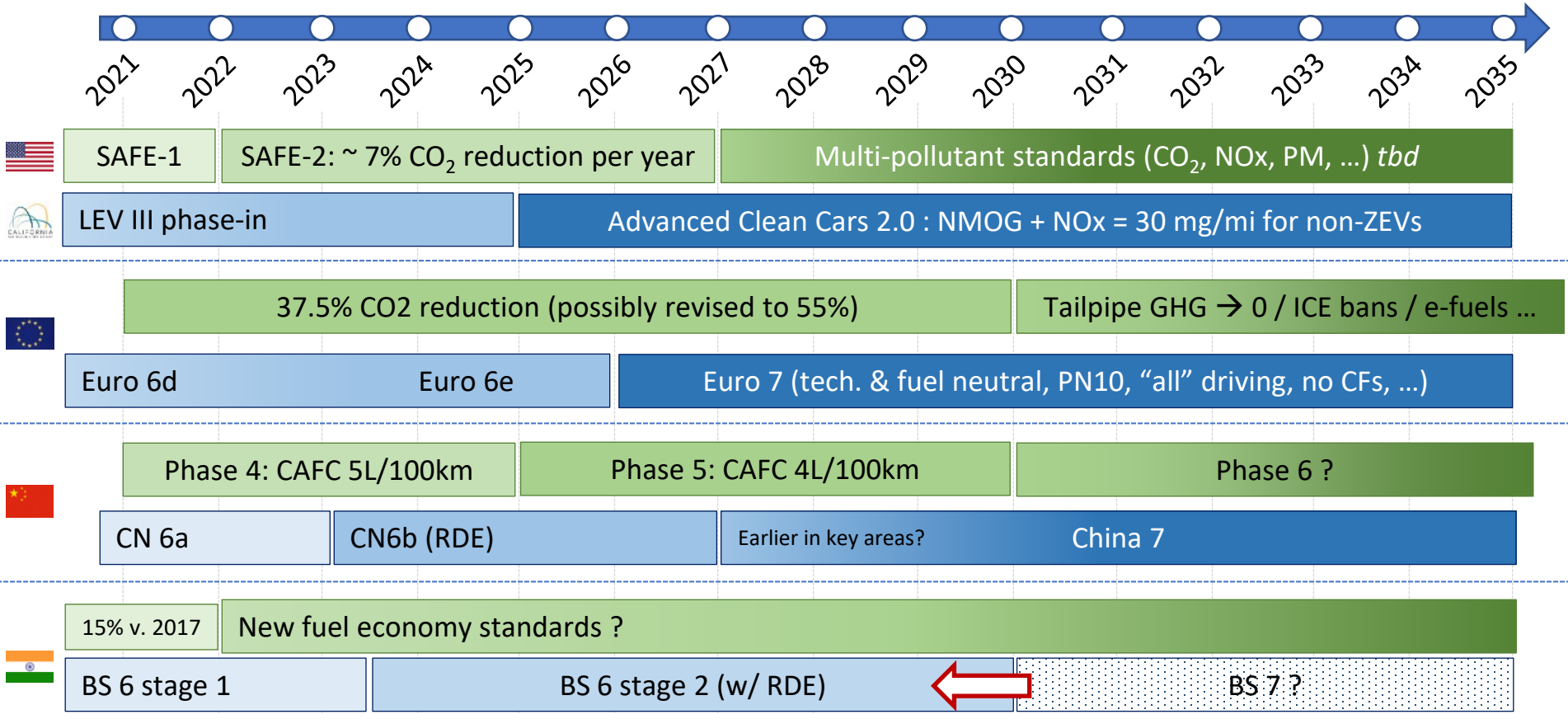


Nature Comm. 2021, 12:3594 https://doi.org/10.1038/s41467-021-23853-y

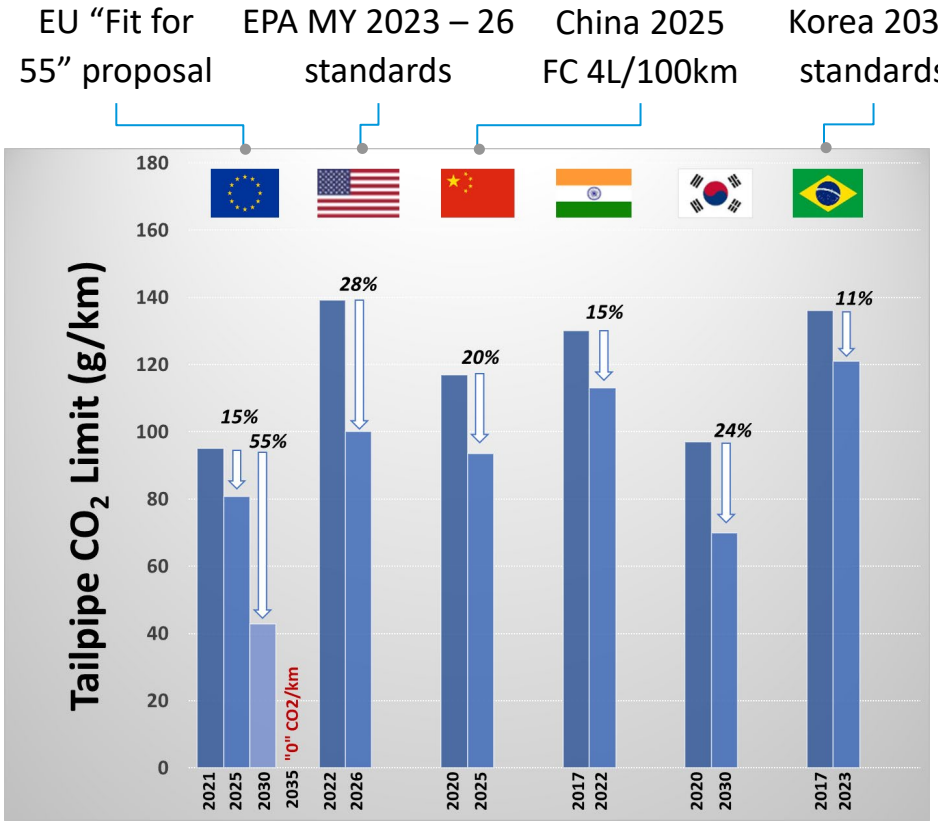
Source: OurWorldInData.org

*Also known as $PM_{2.5}$ = Fine particles with diameter < 2.5 μm

Light-duty regulations in major markets
India is well-poised to adopt best practices for the next standards



Stringent CO_2 standards increase emphasis on electrification



European Union

- 2030 target changed from 37.5% → 55% reduction vs. 2021
- Confirmed ICE ban beyond 2035
- But considering allowing ICEs running on carbon neutral fuels

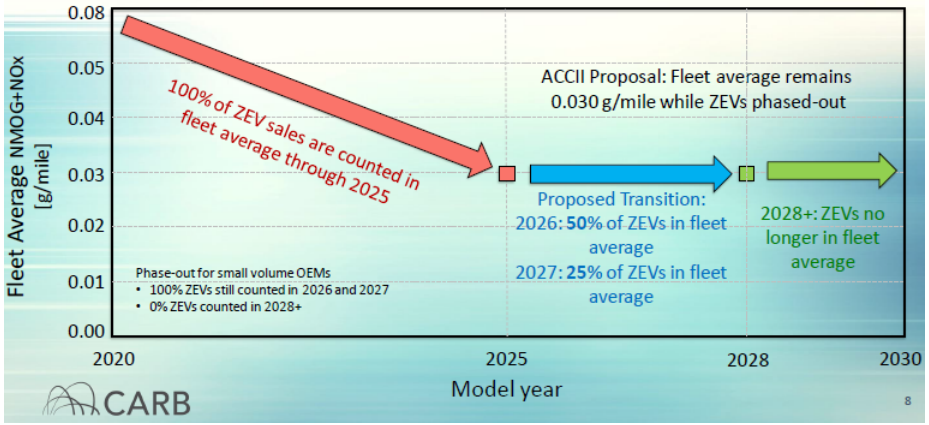
US

- MY 2023-26 limits revised and significantly lowered vs "SAFE"
- MY 2027+ standards being developed and will be part of multi-pollutant rule to be proposed by March 2023
- California has a ZEV sales mandate in place, with 100% EVs by 2035

California Advanced Clean Cars II

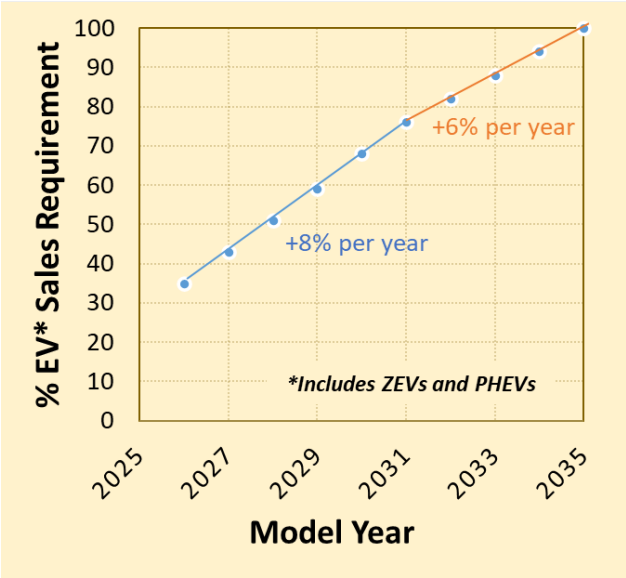
ZEVs phased out from fleet average

Fleet NMOG + NOx = 30 mg/mi



EV* sales mandate

100% sales of cars to be ZEVs and PHEVs by 2035



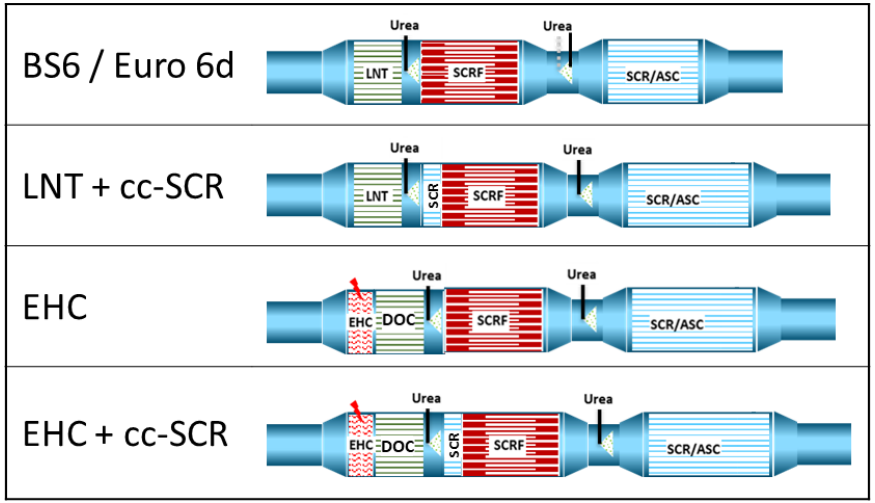
EVs include BEVs and PHEVs
Cap on PHEV fraction

Improved in-use NOx emissions

- Intermediate soaks
- PHEV high powered cold start emissions
- Quick drive-away emissions

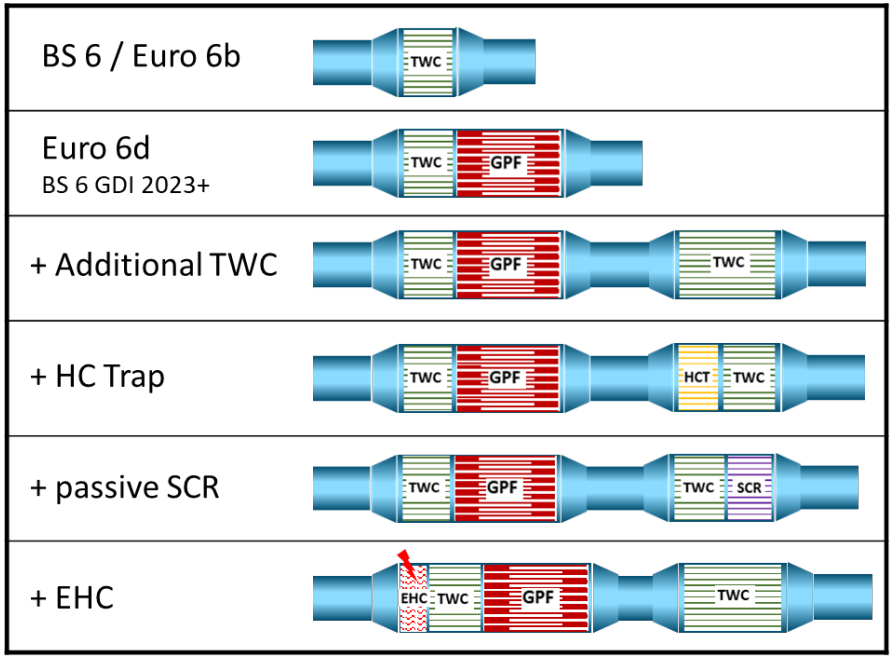
Next generation emission controls are ready for ~ Euro 7 standards

DIESEL



LNT = Lean NOx Trap
DOC = Diesel oxidation catalyst
SCR = Selective catalytic reduction (of NOx)
SCRF = SCR on filter
ASC = Ammonia slip catalyst
EHC = Electrically heated catalyst

GASOLINE / PETROL



TWC = Three-way catalyst
GPF = Gasoline particulate filter
HCT = Hydrocarbon trap

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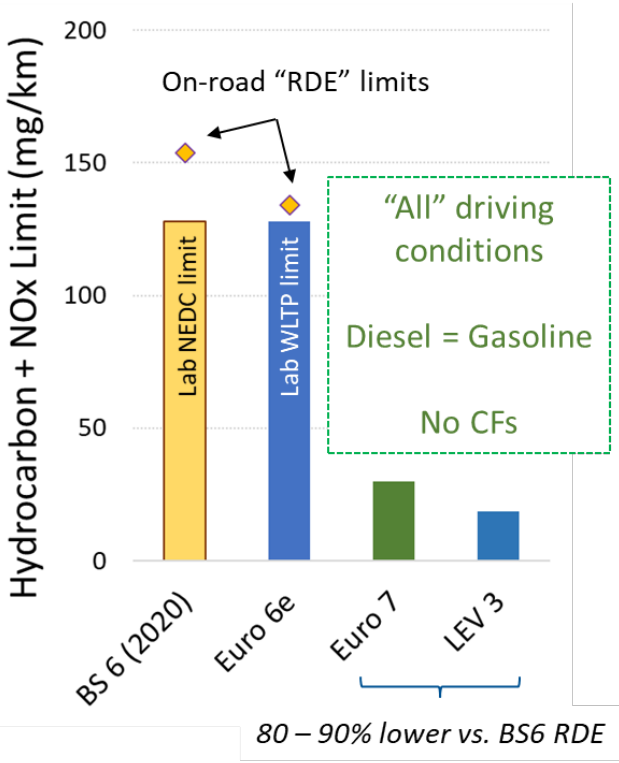
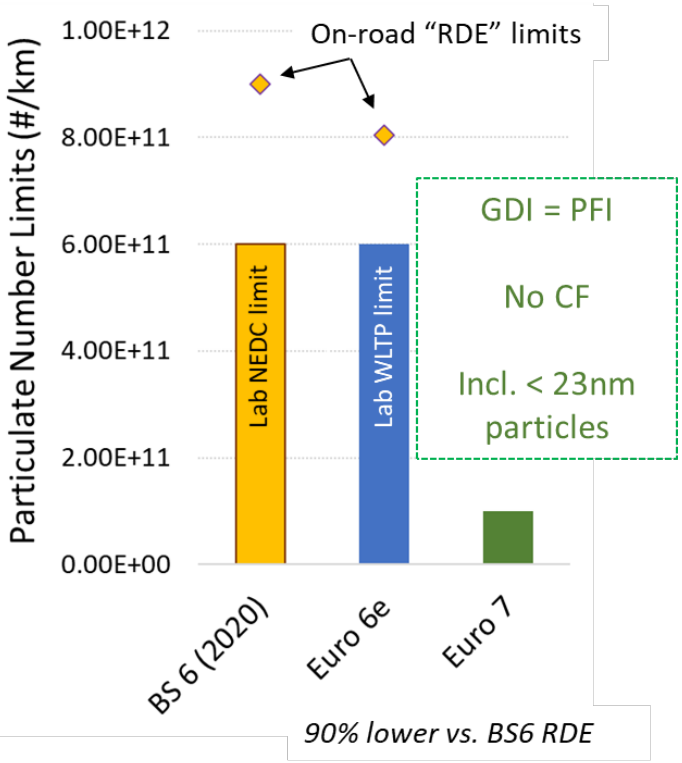
BS6 can be further strengthened to improve real-world emissions





GDI = Gasoline Direct Injected PFI = Port Fuel Injected

Key Recommendations for post BS-6 standards

Fuel & Technology neutral standards
Diesel = GDI = PFI = CNG

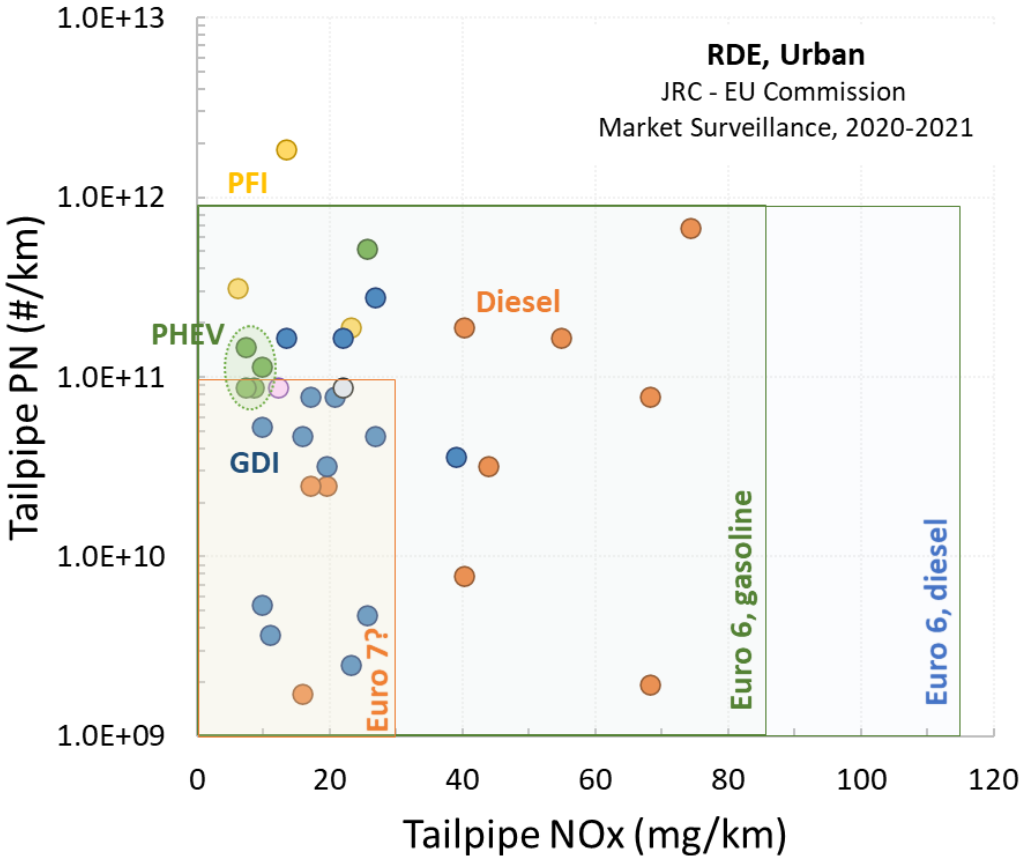
Testing under all driving conditions (no "RDE")

Elimination of conformity factors (real-world limits = lab limits)

Include sub-23nm particles (down to 10nm)

Reduce limits for NOx & PN

Market Surveillance data from Europe

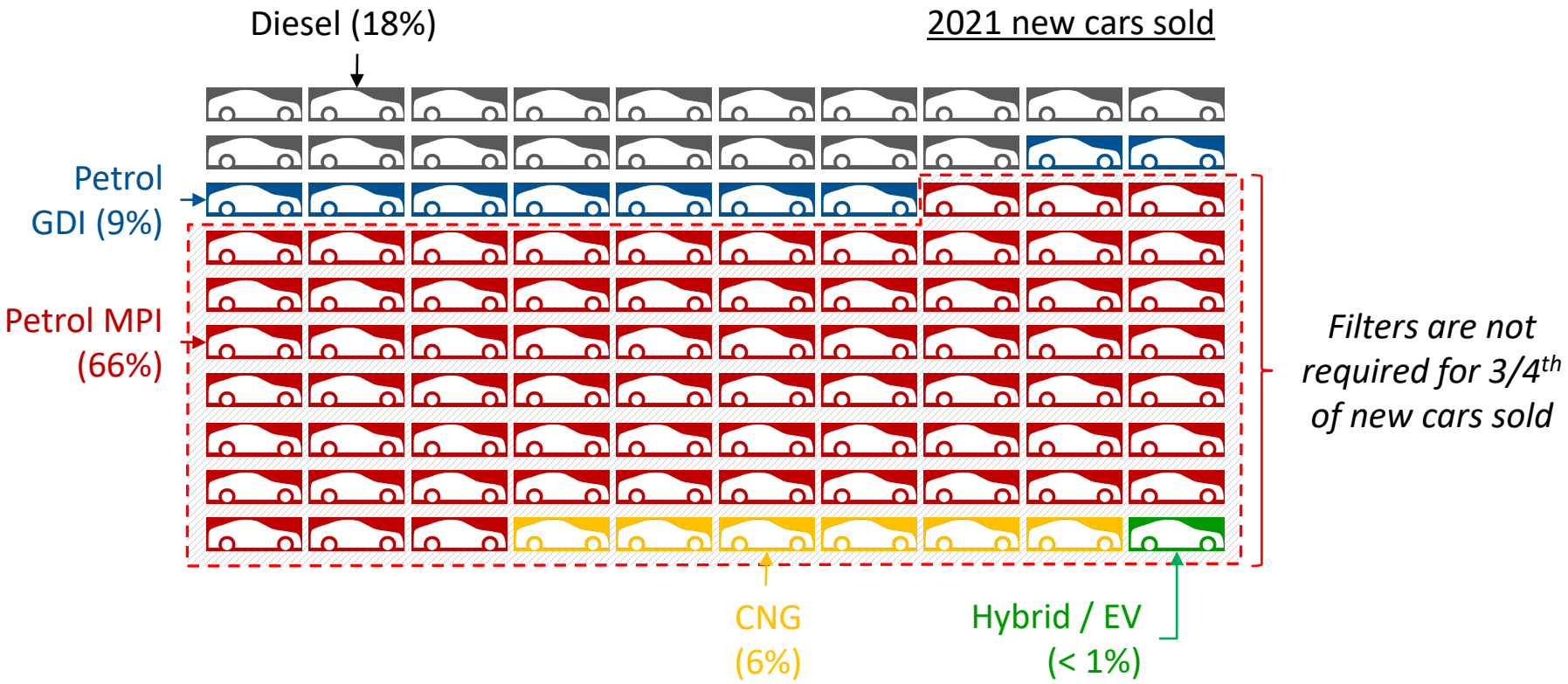


RDE testing has helped : vehicles are meeting limits on road

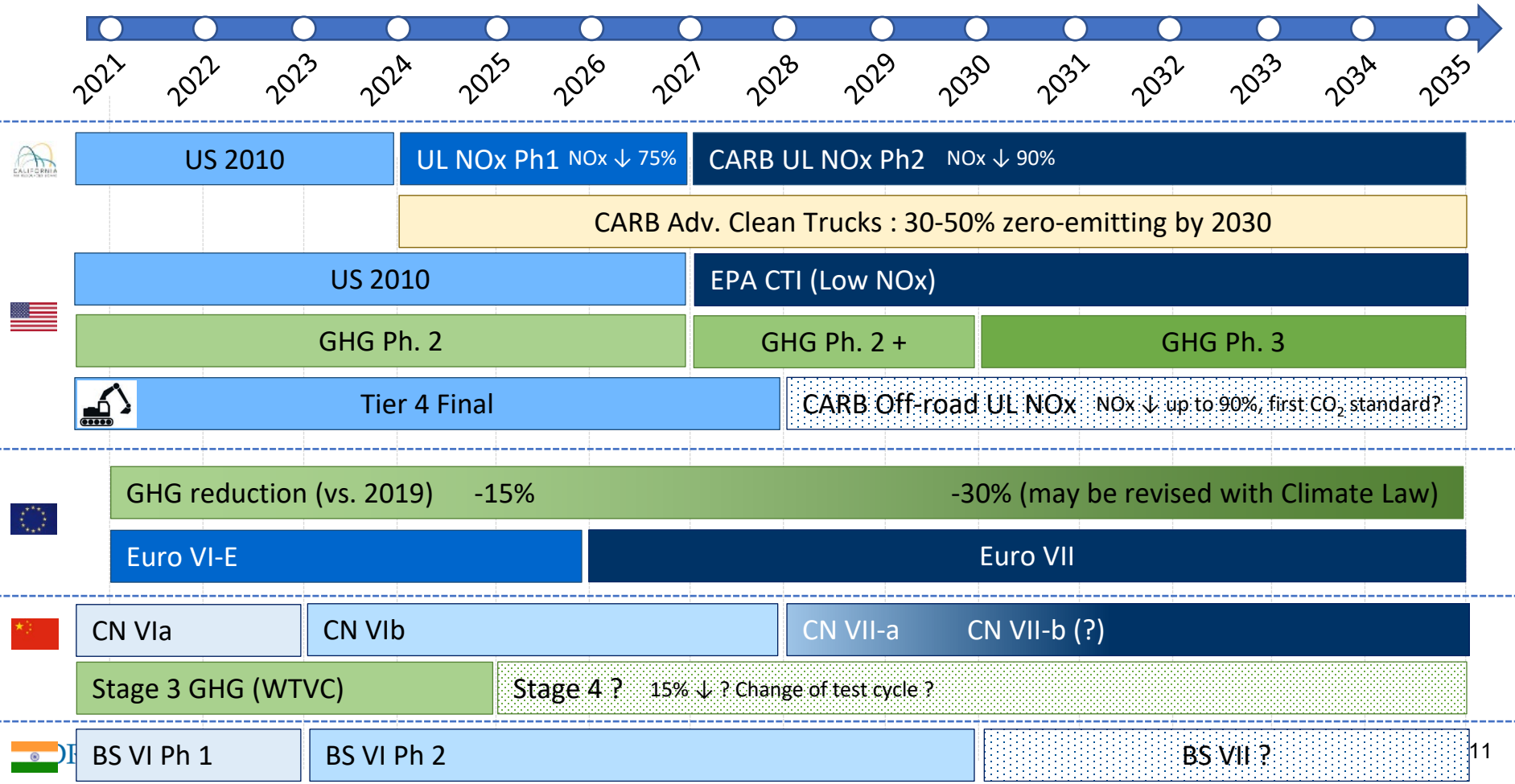
Diesels still lag gasoline for NOx emissions → need fuel neutral standards with reduced NOx limits

Petrol vehicles with PFI engines can be emitting over the PN limit and need to be regulated

BS6 particle number standards do NOT apply to majority of the vehicles in India → PN standards should apply to all vehicles

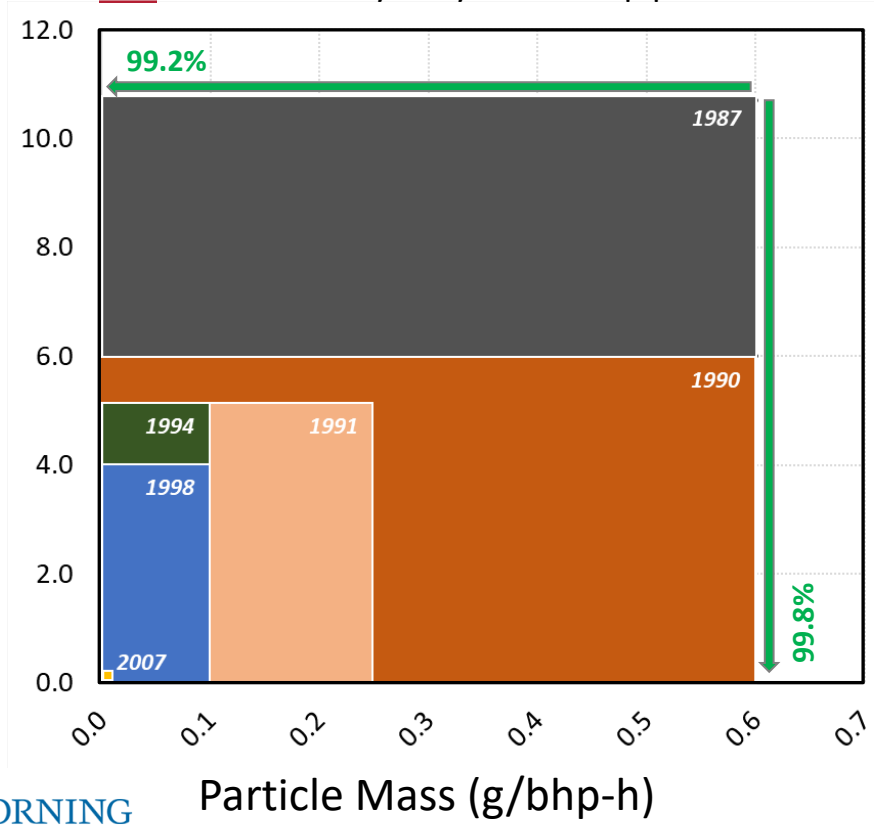


Heavy-duty regulatory roadmap in major markets



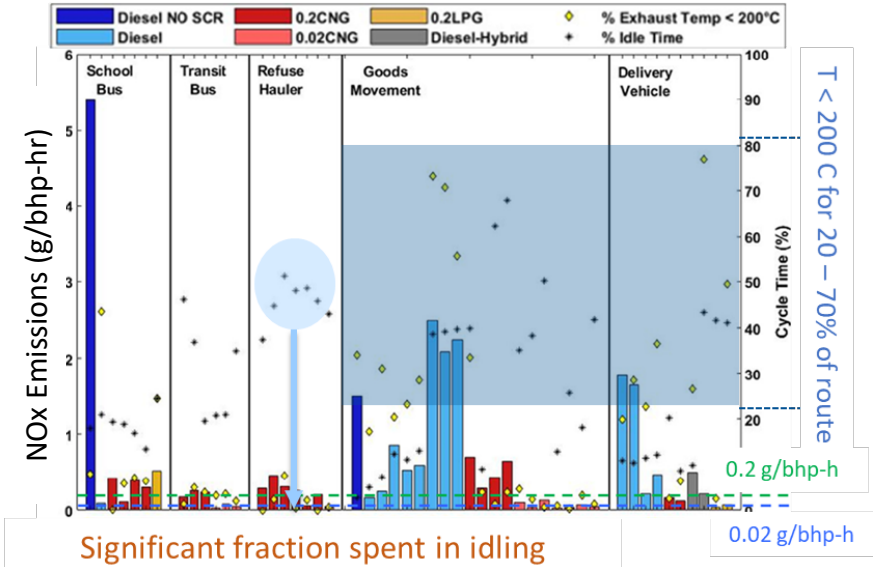
Tailpipe criteria pollutant limits have reduced by >99%
But we need to tackle real-world emission scenarios and high emitters

US EPA heavy-duty diesel tailpipe standards



Fleet emissions study of HD trucks and buses

2 diesels without SCR, 14 with SCR, 2 diesel hybrids, 29 CNG, 3 LPG
Vehicles within useful life (< 435,000 miles)



UC Riverside, SCAQMD https://doi.org/10.1016/j.scitotenv.2021.147224

Low NOx regulations will require advancing ICEs while also continuing to advance fuel efficiency & electrification

California Low NOx Omnibus Rule

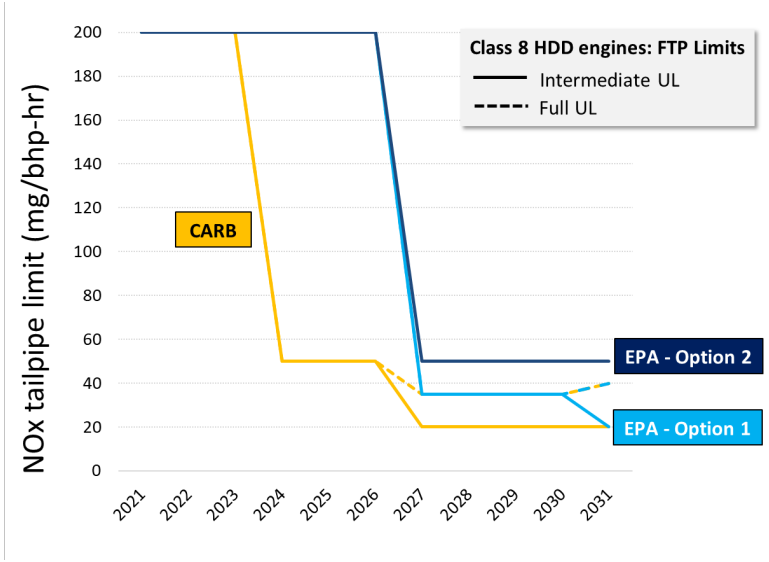
90% NOx emission reduction by MY2027

2020	UL 435K mi	Reference 2010
2024		NOx 75%↓, PM 50%↓ New: Low-load cycle
2027	UL 600K mi	NOx 90%↓ Useful life 600,000 mi
2031	UL 800K mi	UL 800,000 mi

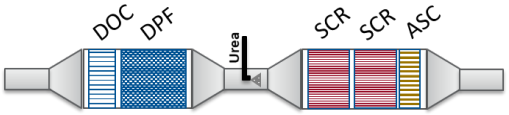
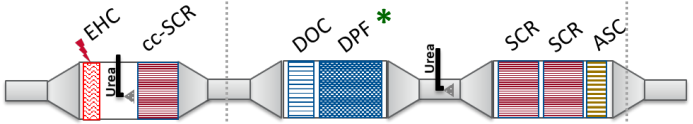
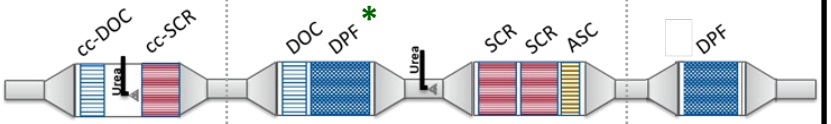
+ GHG Phase 2: CO_2 25% ↓

EPA Cleaner Trucks Plan

Two options proposed
Most likely application starting MY 2027



Included: Low NOx limit, Low load cycle, MAW, increased UL
Targeted GHG Phase 2 revisions to some vocational segments

US 2010 / Euro VI	**Ref.**			
CA2027 / Euro VII (example configurations)	1			
	2			
	3			
	4			
		“Close-coupled” catalysts	Conventional system	2nd filter

Advanced technologies

- Close-coupled SCR / DOC
- Dual NH_3 dosing
- Active thermal management – electric heater, heated dosing etc.
- SCR on filters
- Ultra-high porosity substrates

…

*High filtration DPFs

Non-road agricultural & construction machinery

California is targeting further tightening of NOx and PM standards

Tractor

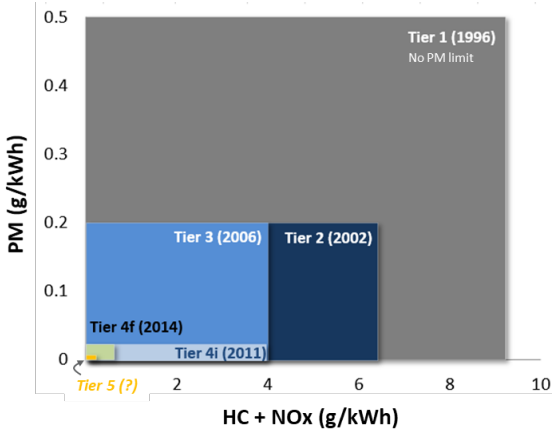
Excavator

Wheel Loader

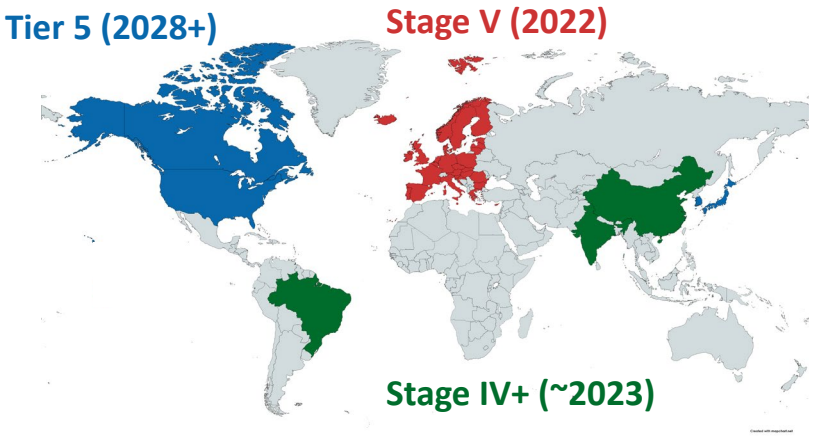
Dozer

Backhoe

PM & gas emissions have been reduced by 90% in last 2 decades



Tighter standards are being implemented across the world



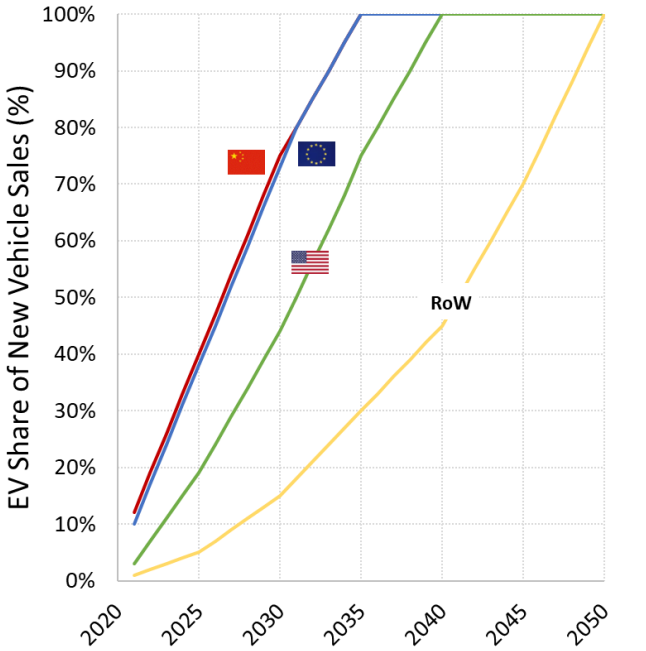
- India only other market to have adopted EU Stage V standards
- California is considering 75 – 90% reduction in NOx & PM
- China has introduced PN limit and telematics

Region	Standard	Timing	Technology
N. America	Tier 5	2028+	DPF on all equipment
Europe	Stage V	2022	PN limit = DPF
China	Stage IV + PN	2023	SCR + DPF
India	Stage V	2024	SCR + DPF
Brazil	Stage 4	> 2025	SCR

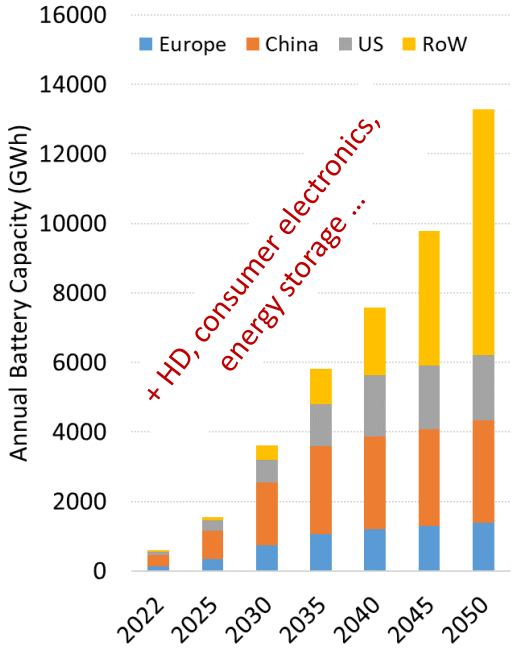
Why emission regulations – won't electric vehicles solve all problems ?

Battery raw materials could be a bottleneck for EVs in the next few years

EV share (light-duty)



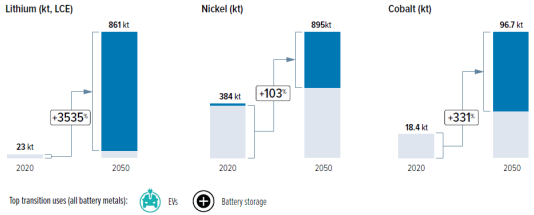
Battery demand for LD



Raw materials

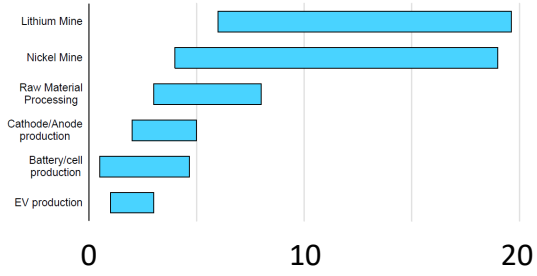
Future needs for EU alone

Li : 36X Ni : 2X Co : 4X



"Metals for Clean Energy: Pathways to solving Europe's raw materials challenge" Eurometaux, 2022

Mines cannot be built overnight



<u>Assumptions</u>

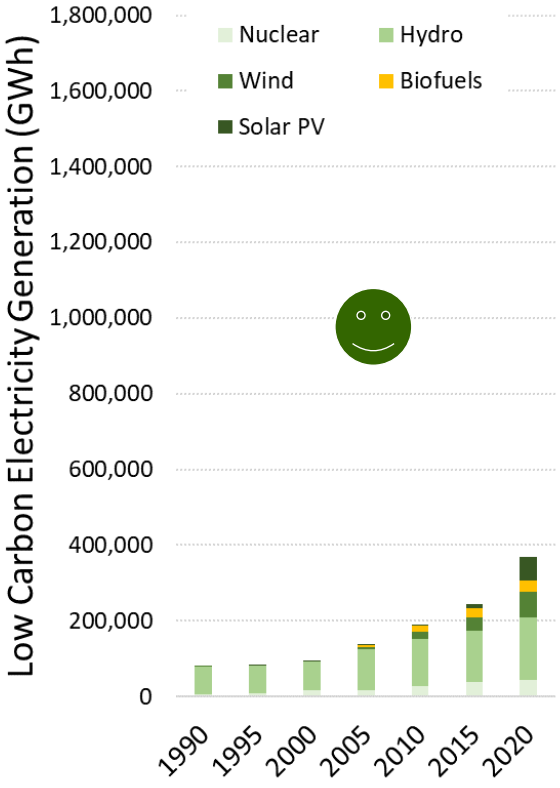
Avg. battery pack sizes – 50 kWh in China, 60 kWh in Europe, 75 kWh in US

Vehicle sales flat in US and grow at 0.5% per year in all other regions

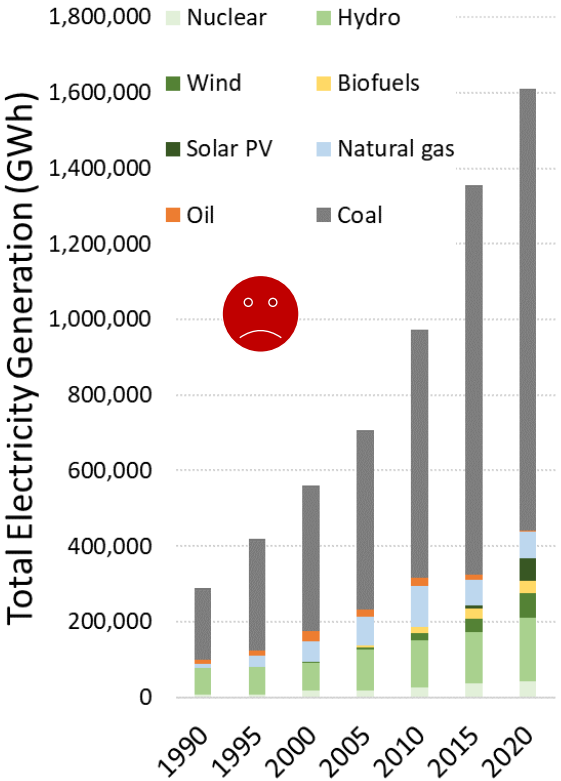
No separation of PHEV and BEV for simplicity

True benefit of electrification is tied to grid carbon intensity

Low carbon electricity has increased by ~ 2X in the past decade



But > 70% of the total electricity is still coal-based



We need to pursue all pathways for transport decarbonization

Detroit DD15, inline 6-cyl
2024 GHG compliant

Efficiency improvements
55% BTE, Opposed piston

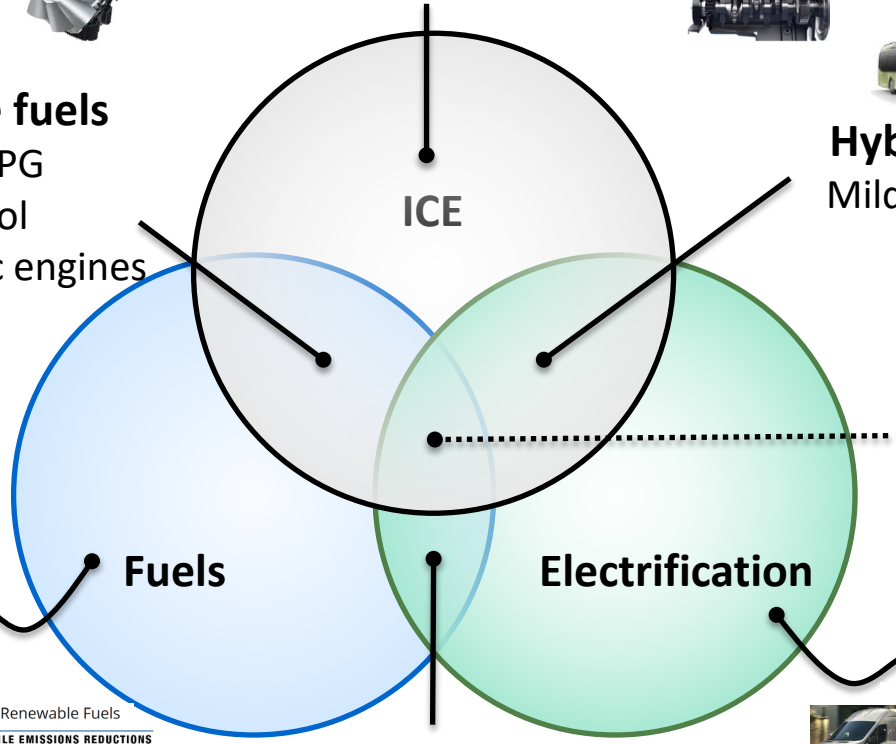
AchatesPower Opposed Piston engine

Volvo 7900 hybrid

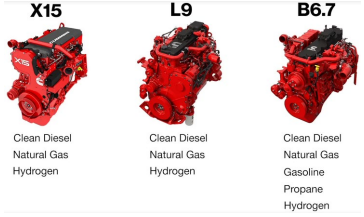
ClearFlame Engine
Runs on ethanol

Alternate fuels
CNG, LPG
Ethanol
Fuel agnostic engines

Hybridization
Mild, full hybrid



Cummins fuel agnostic engines



Hybrid + green fuel
H_2 ICE
Plug-in + Syn fuel

Cummins 15L H_2 ICE

Low carbon fuels
Renewable fuels

Phillips 66 Makes Final Investment Decision to Convert San Francisco Refinery to a Renewable Fuels Facility

May 11, 2022

It will be one of the world's largest facilities of its kind; expected to begin commercial operation

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Synthetic fuels
e-diesel

ZEVs
Battery electrics
Fuel cell vehicles

MOBILE EMISSIONS REDUCTIONS
8 million
metric tons per year of lifecycle carbon emissions reductions, the equivalent of taking 1.4 million cars off the road