Accompanying paper: SAE 2022-01-0540

REVIEW OF VEHICLE ENGINE EFFICIENCY AND EMISSION CONTROL REGULATIONS AND TECHNOLOGIES

April 5th, 2022

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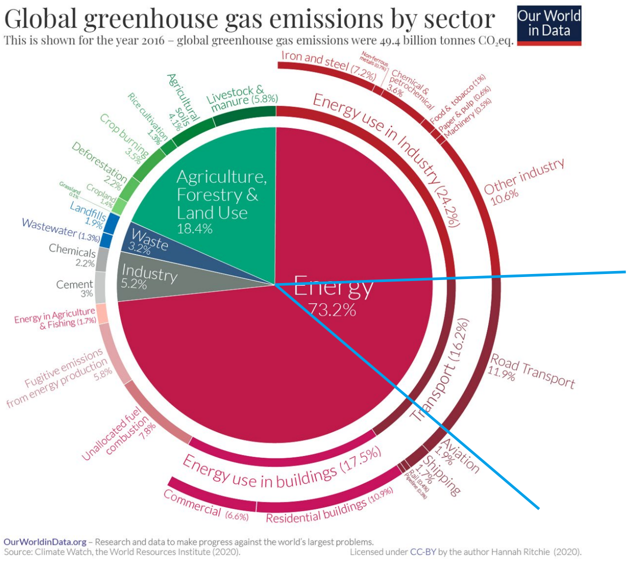
SAE INTERNATIONAL

CORNING

What are the problems we are trying to solve in the transportation sector?

Greenhouse Gas (GHG) emissions

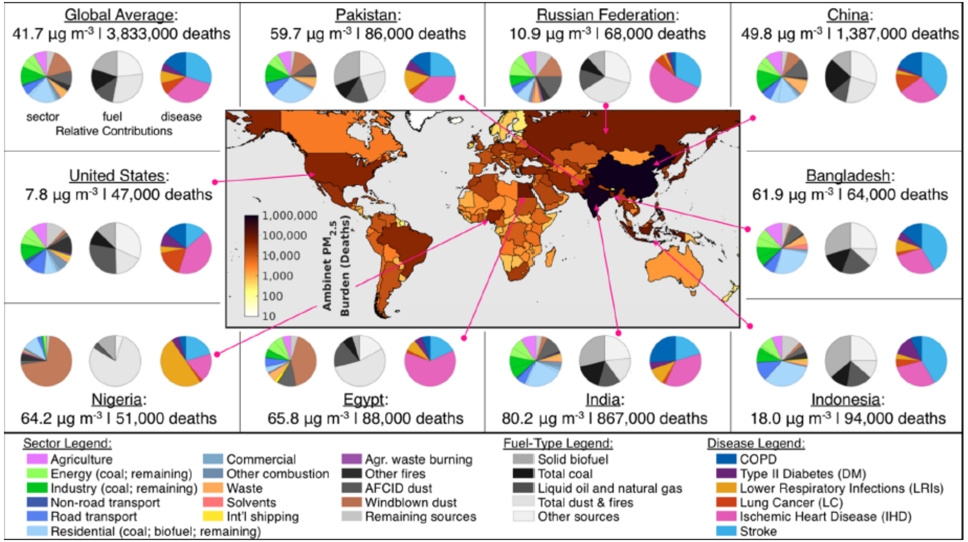
Road transport accounts for ~ 1/5th of GHG emissions associated with energy use



Source: Visual Capitalist

Criteria Pollutants

~ 4 million deaths annually attributed to fine particulate ($PM_{2.5}$) emissions



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

$PM_{2.5}$ = Fine particles with diameter < 2.5 µm

Topics covered today

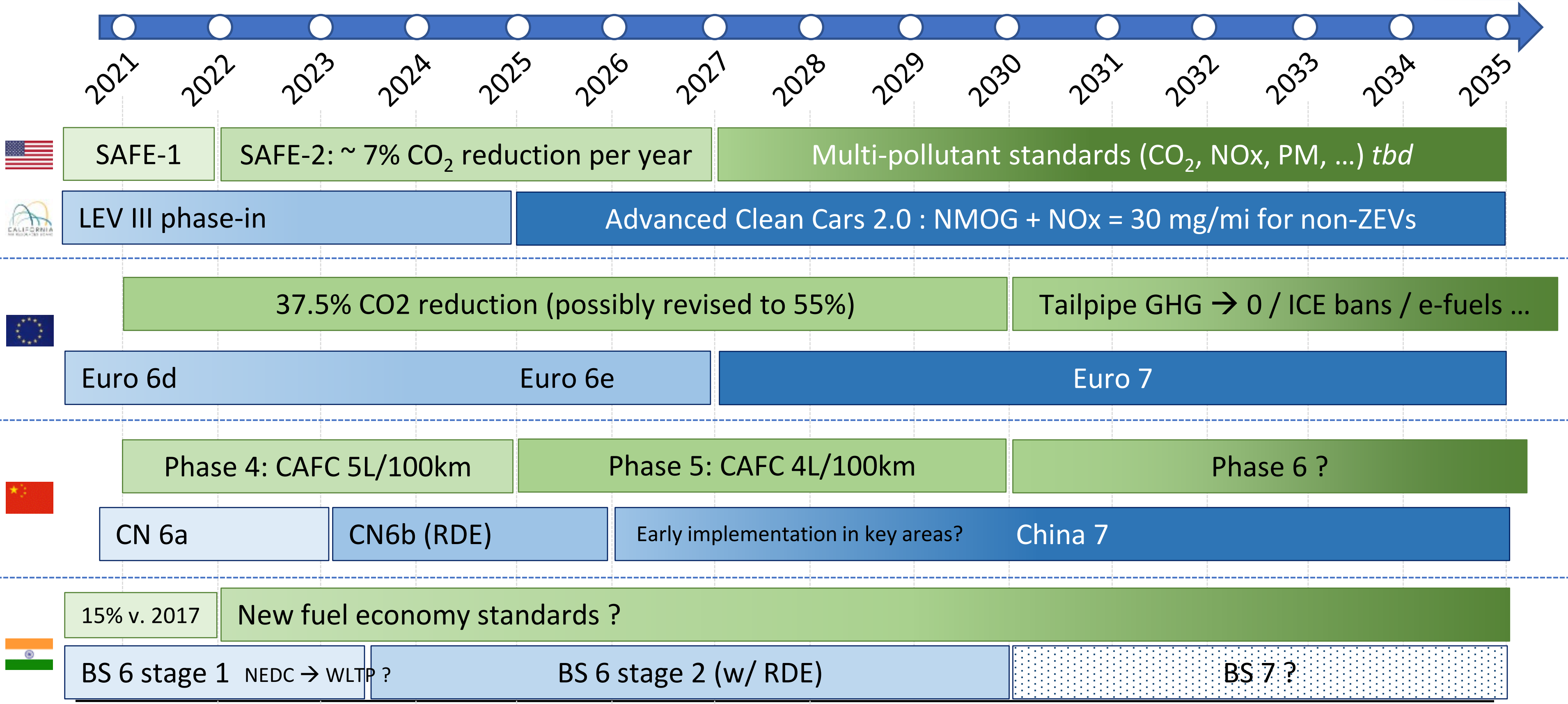
Light-Duty

- Regulations : Fuel economy and criteria pollutants
- Gasoline emissions control – Gas species
- Gasoline emissions control – particulates
- Diesel emissions control

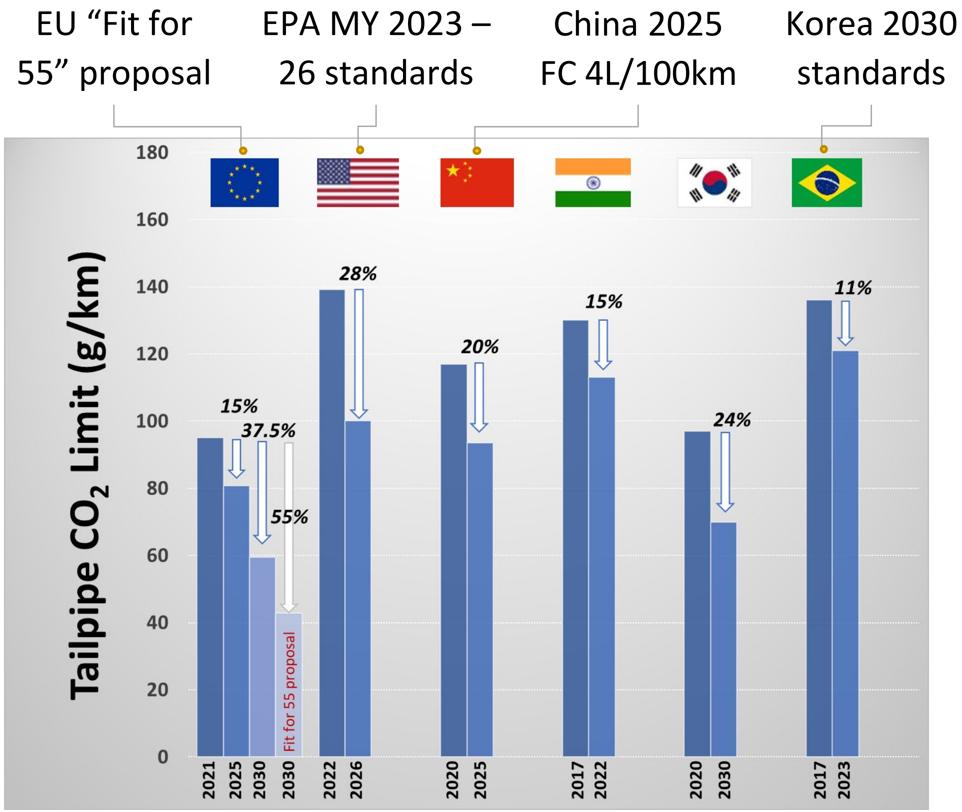
Heavy-Duty

- Ultra-Low NOx regulations (CARB, Euro VII) and technology pathways
- Greenhouse gas regulations and technology pathways
  - Diesel, alternative fuels, electrification

We are approaching the last major regulations on criteria pollutants (in major markets)

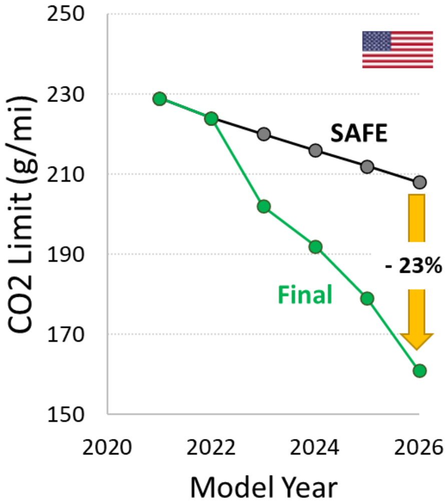


Tailpipe CO_2 standards continue to tighten across the world
Europe enforcing electrification, US making up for lost time



US EPA MY 2023 – 26 standards revised

- ~ 7% CO_2 reduction per year
- Multiplier incentives : MY 2023 – 24 only
  - EV = 1.5, PHEV = 1.3, 10 g/mi cap
- Full-size pickup credits for hybridization through MYs 2023 – 2024



+ 10mpg vs 2021 (NHTSA)

Path to 55% reduction in tank-to-wheel CO_2 emissions shown > 43% BTE DHE + hybridization + full electrification

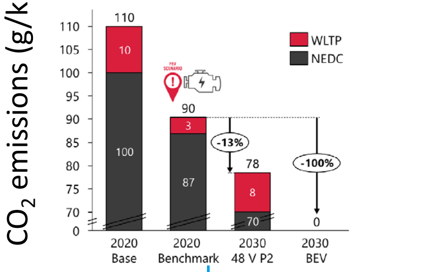
FEV, 42nd Intl. Vienna Motor Symposium, 2021

WLTP
NEDC

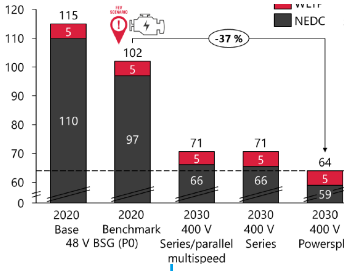
A/B : 48V HEV   C : HEV   D/E : PHEV

MY 2020 → MY2030
- 10% lower RR
- Lower drag
- 43% BTE dedicated hybrid engine
- CR ~ 14 – 15, Str./Bore ~ 1.3
- Miller VVT, LP c-EGR

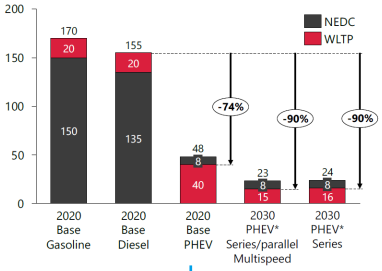
13% CO_2 ↓ vs 2020 benchmark gasoline



37% CO_2 ↓ vs 2020 benchmark 48V



90%* CO_2 ↓ vs 2020 diesel

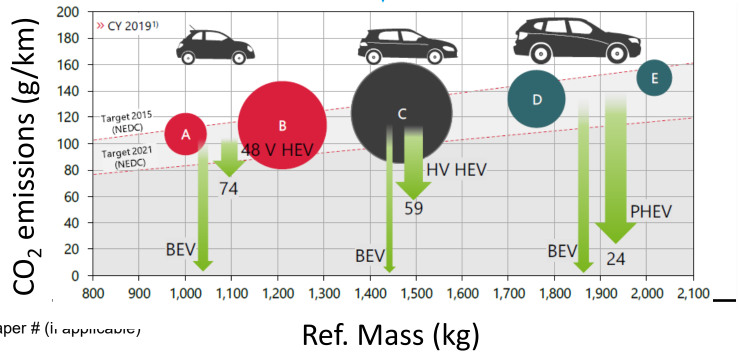


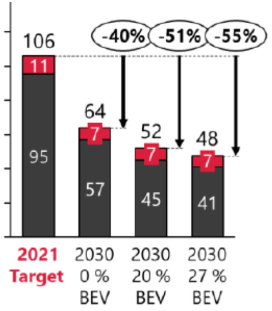
*28% CO_2 ↓ in CS mode

2030 fleet averaged CO_2

40% reduction possible via hybridization alone

55% reduction (2030 target) requires BEV share at 27%





Fleet averaged

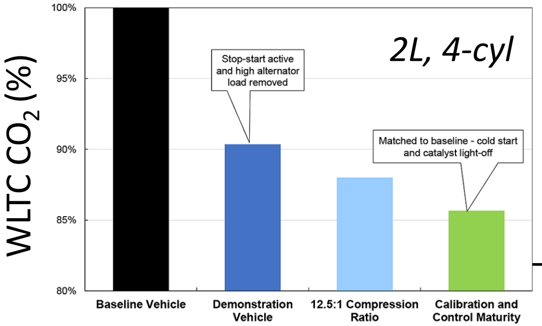
Engines are approaching > 45% peak BTE
Approach - Dedicated hybrid, lean-burn, pre-chamber, high CR + Atkinson

42% peak BTE
Lean Homogenous

Ricardo, JLR, U. Brighton, Garrett, JM
SAE 2021-01-0637

Increased charge motion & tumble
High-energy ignition system
350 bar injection
VNT + 48V e-compressor
CR 11 → can be increased

After-treatment:
EHC//TWLNT + c-GPF + SCR



43% peak BTE 1.5L NA DHE

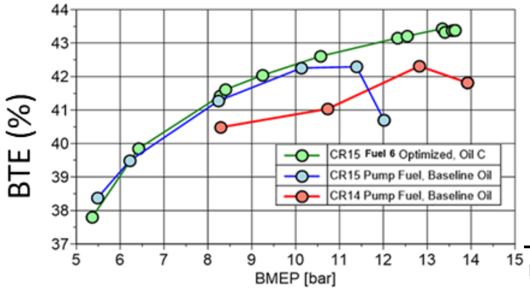
BYD, SAE 2021-01-1241

FC ↓ 25%, 3.8L/100km, CS mode

- CR 15.5 + Atkinson cycle
- Stroke / bore = 1.25 – 1.3
- Tumble ratio > 2X
- Friction ↓ 10%

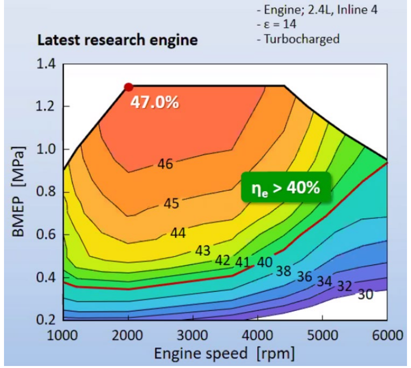
43.6% peak BTE

Ultra-lean + Jet Ignition
+ High CR + opt. fuel/lube
MAHLE, ExxonMobil SAE 2021-01-0462



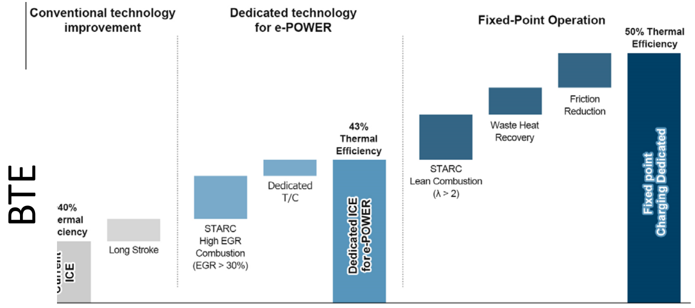
Research engine 47% peak BTE

Toyota, PF&L 2021



Nissan 50% BTE

"STARC" comb. - Fixed point dedicated charging



*Strong Tumble & Appropriately stretched Robust ignition Channel

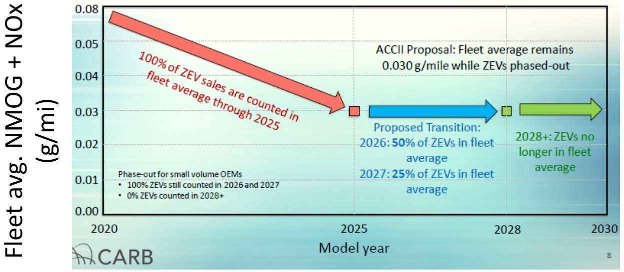
California Advanced Clean Cars II proposal

Broadly phasing in over 2026 – 2028

LEV 4

Fleet average NMOG + NOx

- 30 mg/mi & ZEV phase out



- Cert. bin : ~~LEV160 & ULEV125~~
  New bins down to SULEV15

- Separate FTP, US06 & SCO3 cert.
  US06 standard identical as FTP

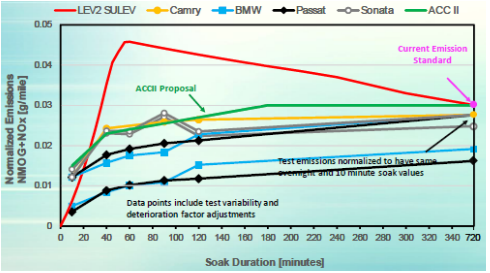
Particulates

PM limit 6 → 3 mg/mi on US06

Phase-in: 2027 – 2030 (25% each year)

Intermediate soaks

Limits:10min=0.5x, 40min=0.767x, 180+min=1.0xFTP



Quick drive-away (FTP)

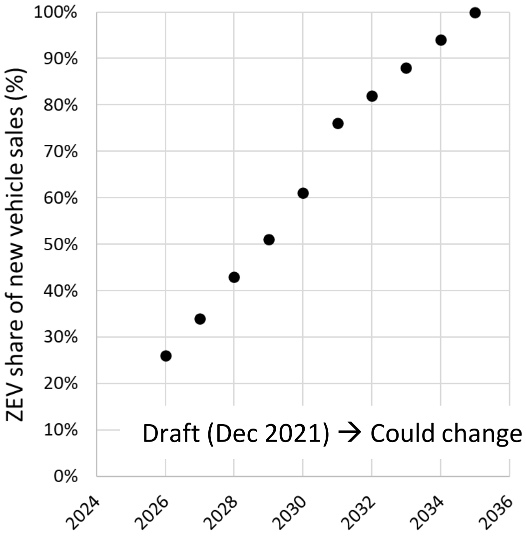
Current 20 sec idle + new 8 sec idle

PHEV high powered cold-starts

Cold-start US06 limits per cert bin (e.g. 100 mg/mi NMOG+NOx for SULEV30)

US06 capable PHEVs exempt

ZEV mandates



Target 100% ZEVs & PHEVs by 2035

- PHEVs must have >50 mi AER (and > 40 mi on US06)
- EJ credits for 25% discount off MSRP to qualified low-income household

Euro 7 Light-duty

Not a formal proposal yet - based on AGVES meetings (EU Commission)

Units: Gas mg/km, PN #/km	NOx	PN	PM	CO	HC	NH_3	HCHO	N_2O [b]	CH_4 [b]
Euro 6d – Gasoline	60	$PN_{23} = 6x10^{11}$ GDI only	4.5	1000	THC = 100 NMHC = 68	-	-	-	-
Euro 6d – Diesel	80	$PN_{23} = 6x10^{11}$	4.5	500	HC + NOx = 170	-	-	-	-
Euro 7 Fuel & technology neutral	20 – 30	$PN_{10} = 1x10^{11}$	2	400[a]	NMOG 25 – 45	10	5	10 – 20	10 – 20

No conformity factors

[a] CO included in RDE [b] Or $N_2O + CH_4$ < sum of individual limits

In-service conformity On-road PEMS testing	Main changes in Euro 7
Trip	Testing under “all” normal driving conditions
Boundary conditions	Normal : - 7 to + 35 °C, Alt. 1,600 m Extended (Limit 3x): - 10 to + 45 °C, Alt. 2,200 m
Cold start	Budget for total emissions in mg or total PN for < 16 km. Power restrictions in first 1 – 2 km tbd.
Other	No conformity factors (RDE limits = WLTP) Regen emissions included – averaging of 2 tests, one with and one without regen

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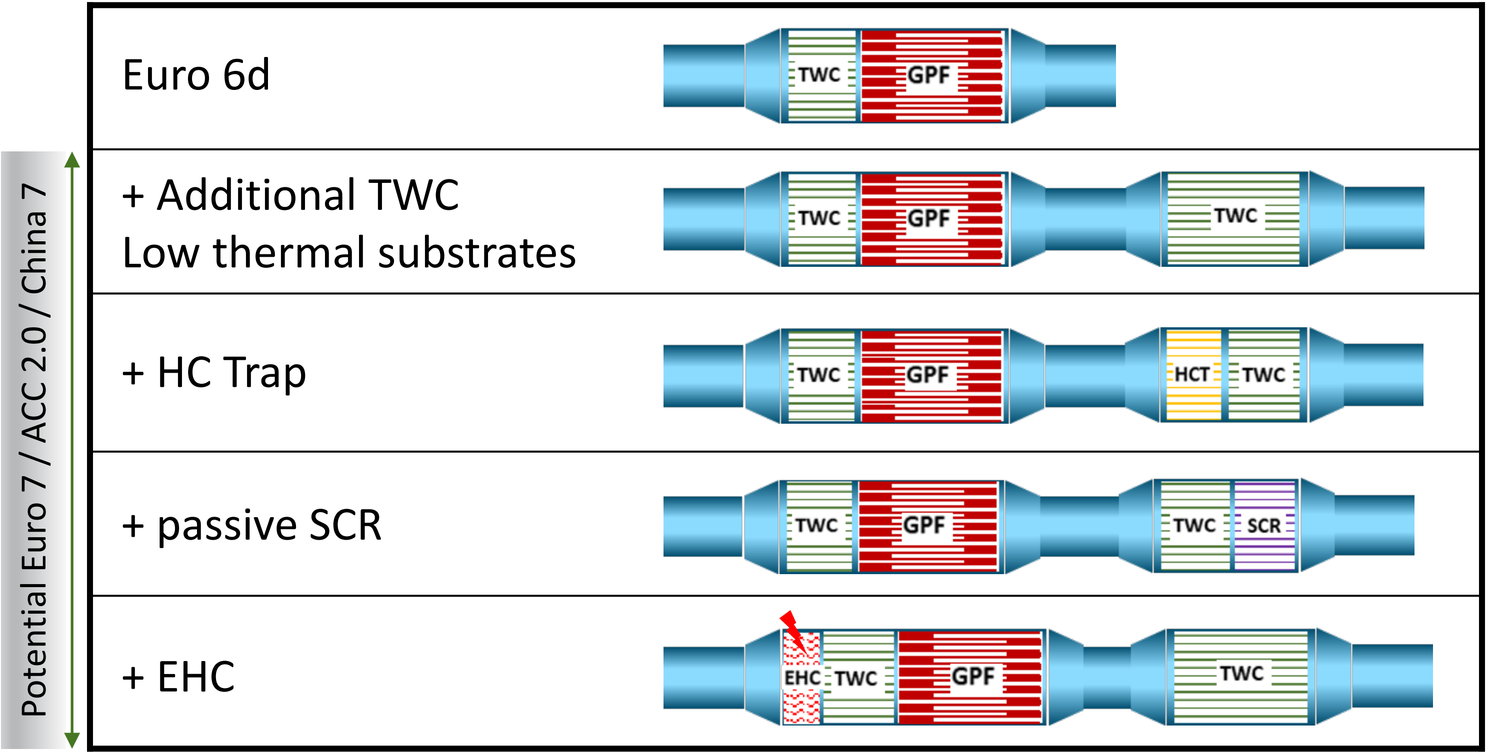
Gasoline after-treatment systems for ~ Euro 7 / ACC 2.0 / China 7



Low thermal mass substrates can help meet upcoming standards with good margin and/or reduced PGM

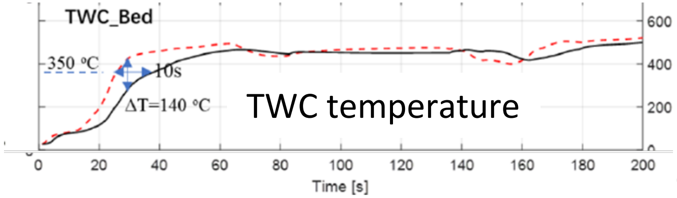
Corning, Sino-Pt Metals Cat., SGMW, SAE 2021-01-0581 doi:10.4271/2021-01-0581

Engine: 1.5L MPI, China 6b without RDE

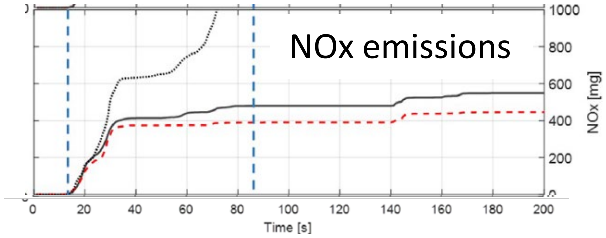
Formulation	Substrate	PGM loading
Group A	750/2 STD (OEM system)	100%,
	800/3.0 Low Mass	100%
Group B*	750/2 STD	100%
	800/3.0 Low Mass	75%

*New PGM baseline with optimized washcoat technology at same washcoat loading.

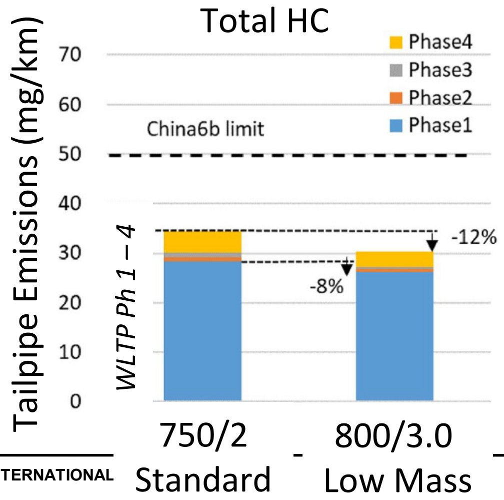
Low mass heats up faster

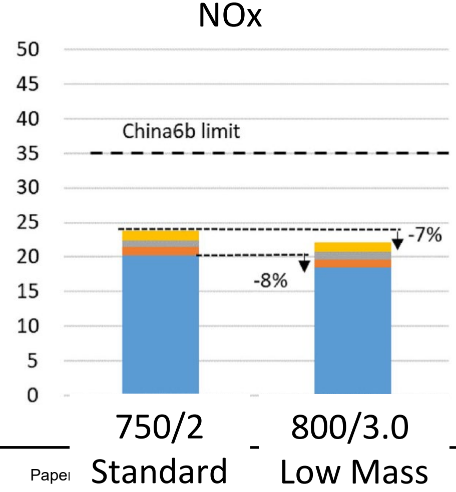


Resulting in lower cumulative emissions

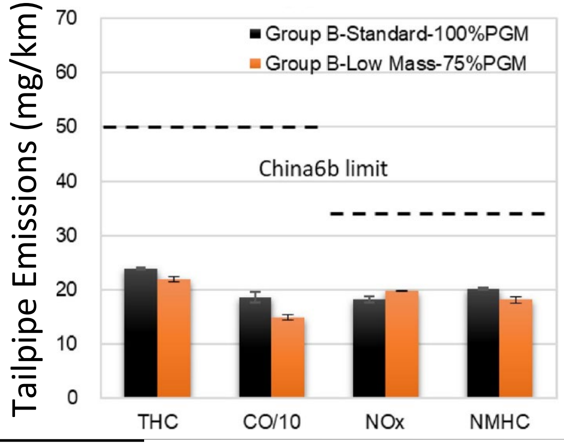


Same WCL & PGM content





25% less PGM for low TM substrate

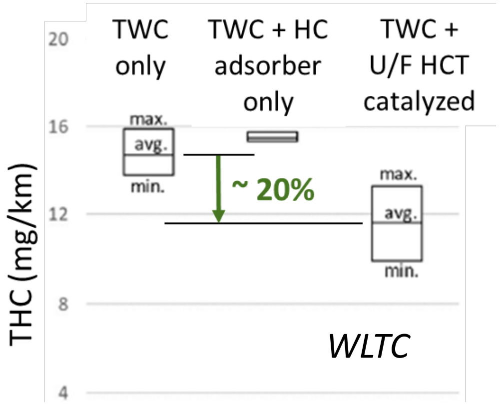


Note : Different coating technology

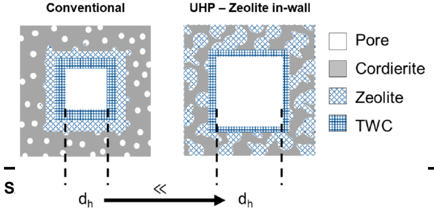
HC traps could help reduce cold start emissions – various innovative substrate and coating technologies being demonstrated

Corning 30th Aachen Colloquium 2021

Vehicle D-segment SUV, 2L TGDI

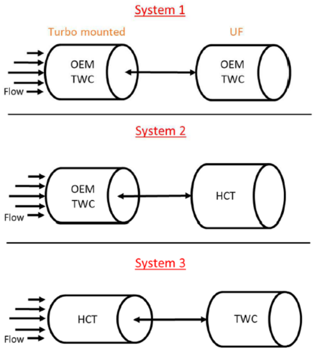


Ultra-high porosity substrates for in-wall zeolite coating

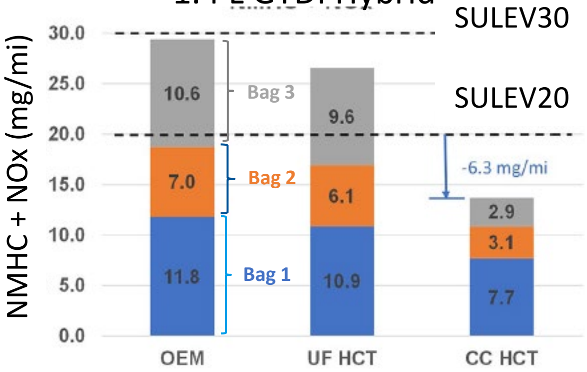


Umicore SAE 2021-01-0574

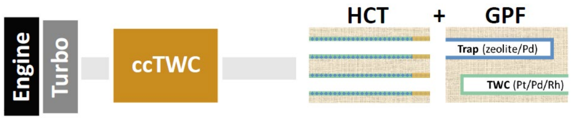
HC Trap in *cc-position ?* Works for T/C hybrids with exh. T < 800 C



Vehicle PZEV 2014 VW Jetta 1.4 L GTDI Hybrid

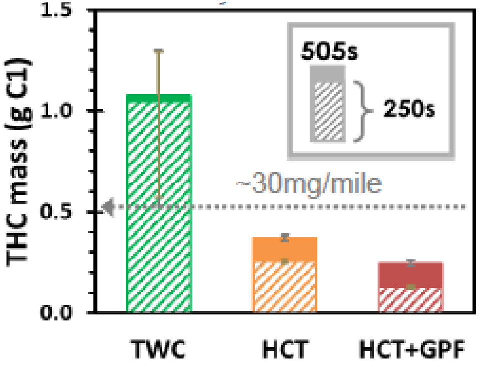


ORNL, DOE Annual Merit Review, 2021



HCT reduces THC by 65 – 77% over 1st bag of FTP cycle

Vehicle MY2018 GDI pick-up trucks, 2.7L turbo V6 and 5.3L NA V8



THC reduction	TWC → HCT	TWC → HCT+GPF
Cold-start (250s)	76%	88%
Cold-Start (505s)	65%	77%

Ammonia slip catalysts can help meet Euro 7 NH_3 proposed limit

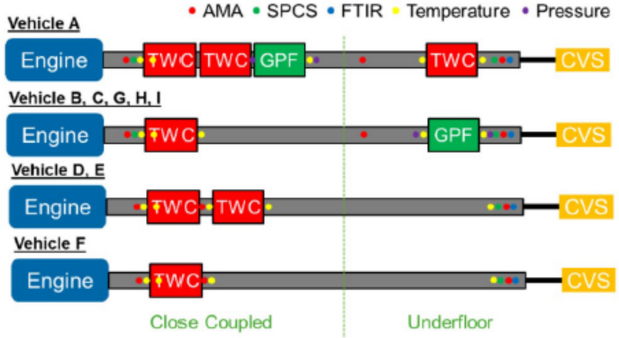
Umicore, SAE 2021-01-0580 doi:10.4271/2021-01-0580

9 China 6b compliant vehicles tested on WLTC / RTS-95

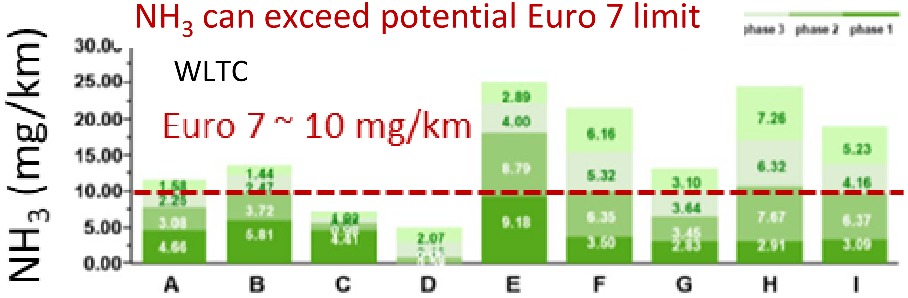
Vehicle	A	B	C	D	E	F	G	H	I
Engine Type	TD L4	TD L4	TD L3	MPI L4	TD L4	TD L4	TD L3	TD L4	TD L3
Vehicle Type	ICEV	ICEV	ICEV	HEV	ICEV	ICEV	ICEV	ICEV	ICEV
Displacement (L)	1.6	2.0	1.5	2.0	1.5	1.4	1.5	1.6	1.0
Catalyst Status	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Aged	Aged

Turbocharged direct injection (TD), Multipoint injection (MPI), In line four or three cylinders (L4 or L3)

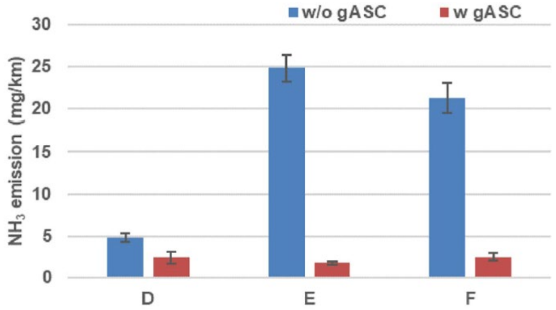
Production after-treatment – TWC, GPFs



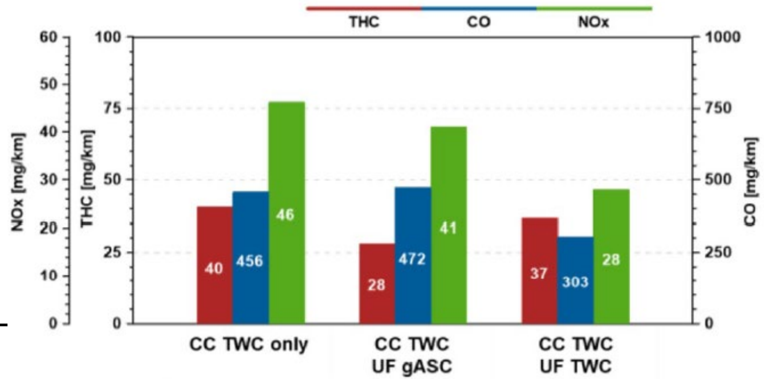
NH_3 can exceed potential Euro 7 limit



With add-on ASC, NH_3 emissions <10 mg/km



uF TWC not as effective at NH_3 control but can address other criteria pollutants better

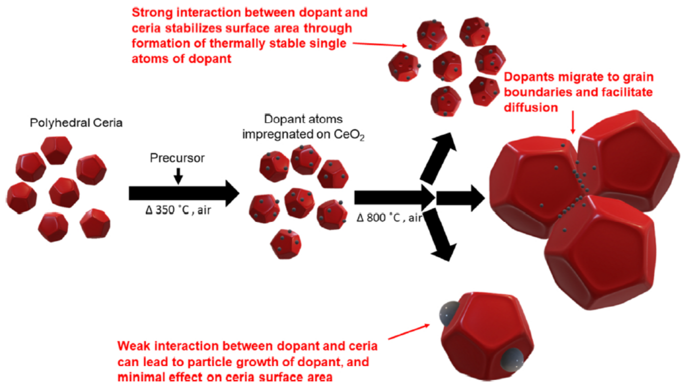


Highly dispersed catalysts synthesized via “atom-trapping” method promise very high reactivity

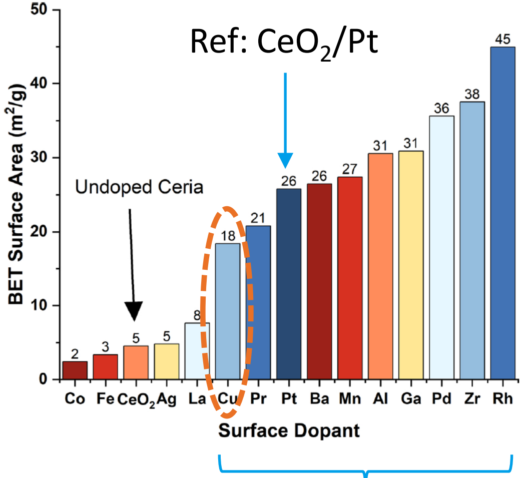
U. New Mexico, WSU, et al. Applied Catalysis B: Environmental 284 (2021) 119722

PNNL, DOE Annual Merit Review 2021

Atom-trapping method

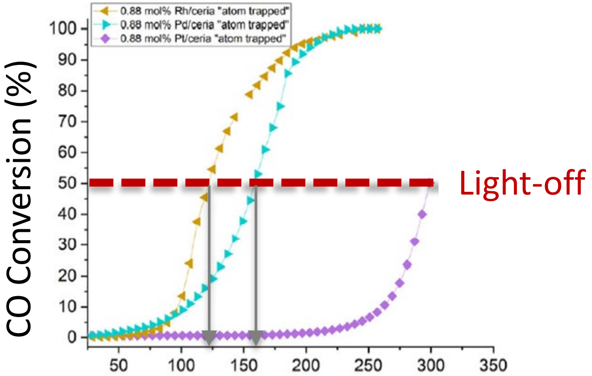


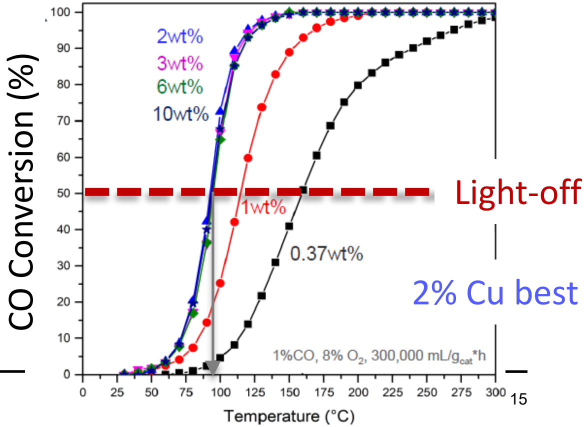
BET surface area after heating to 800 ° C in air for 5 hours



Promising dopant candidates

CO oxidation used as probe reaction
Light-off T < 150 ° C demonstrated





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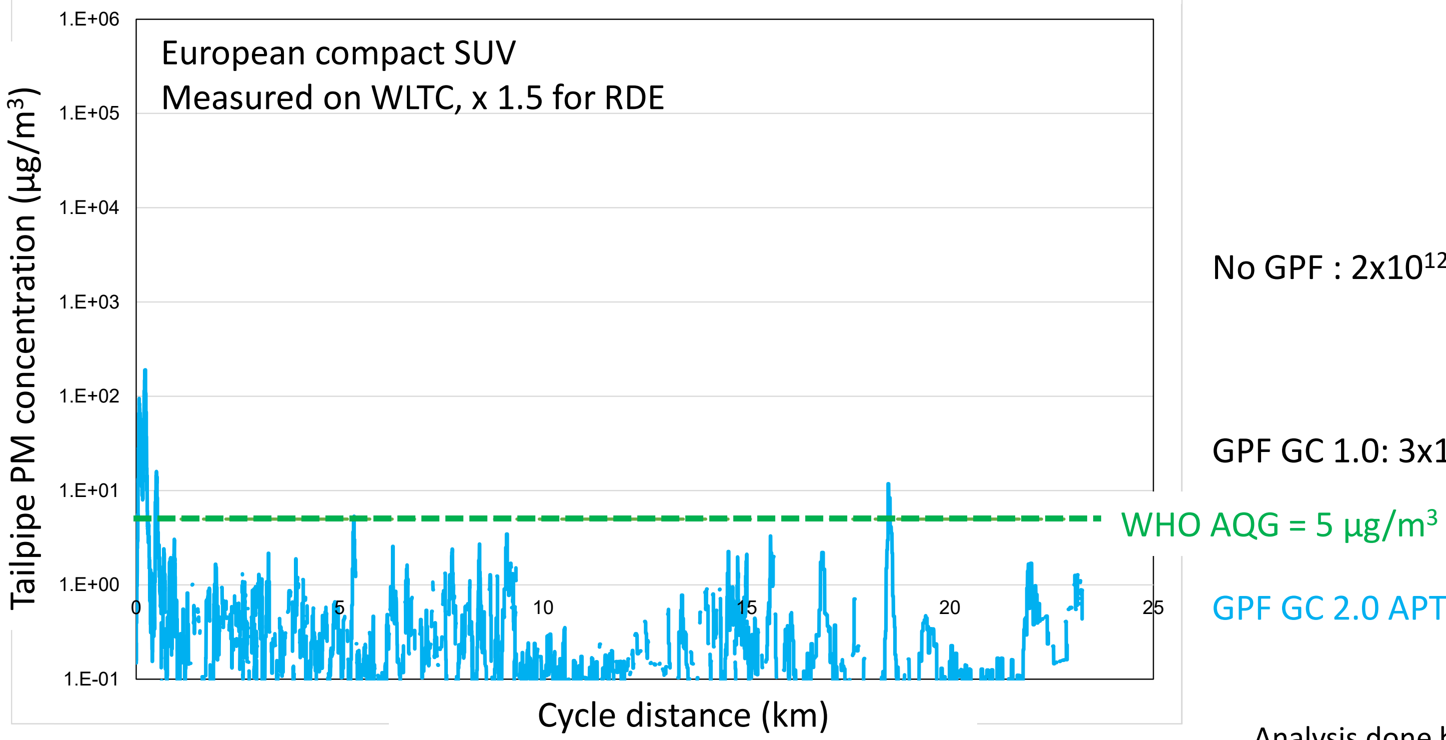
Advanced GPFs enable gasoline vehicles to be "negative" emitting



No GPF : $2x10^{12}$ #/km

GPF GC 1.0: $3x10^{11}$ #/km

GPF GC 2.0 APT: $1.3x10^{10}$ #/km

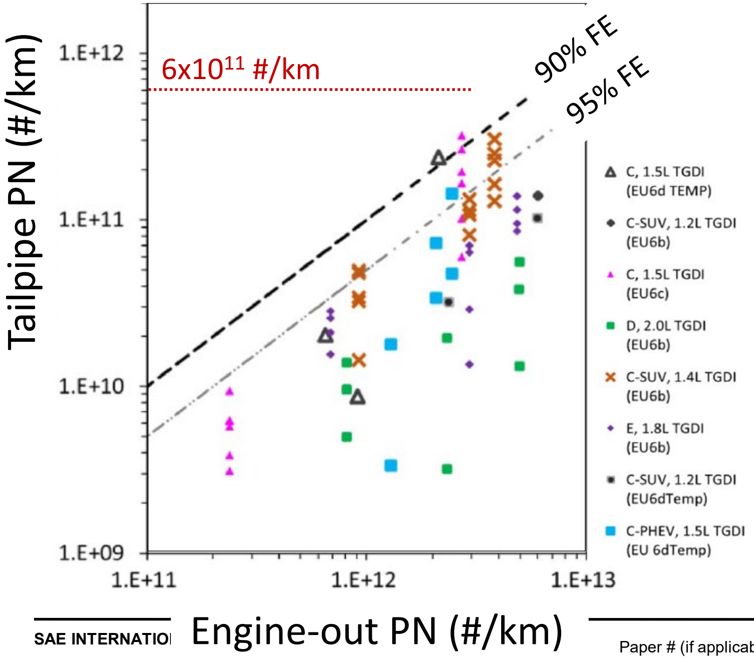
Analysis done by D. Lavric, Corning

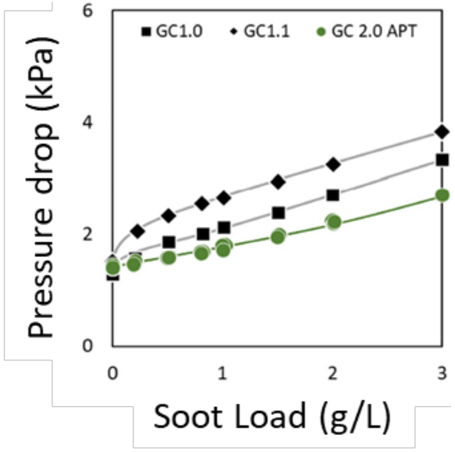
Corning SAE 2021-01-0584 doi:10.4271/2021-01-0584
12th VERT Forum, 2022 (online)

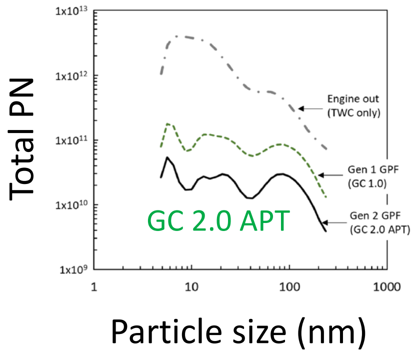
GPFs being developed for Euro 7

Very high “out-of-the-box” filtration (incl. < 23nm particles) at lower pressure drop

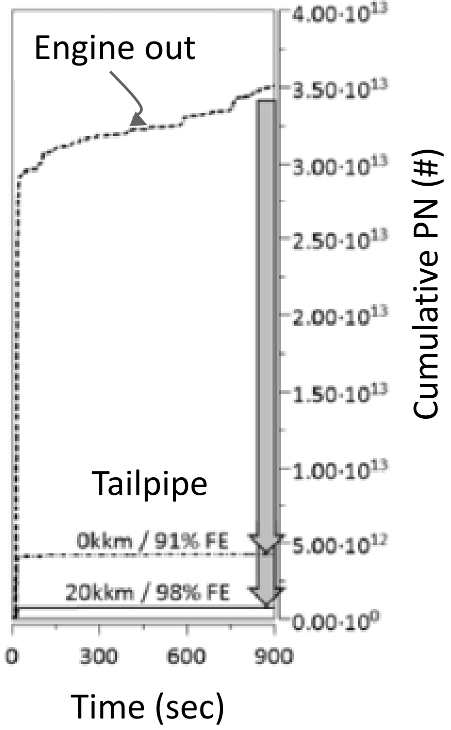
Filter Technology	GC 1.0	GC 1.1	GC 2.0 APT
Generation	1	1	2
Cell Design	200/8	200/8	200/8
Porosity	~55%	~55%	~55%
Pore Size	Base	Base – 3.5µm	Hierarchical







Filtration improves with mileage
Results using GC 2.0 APT



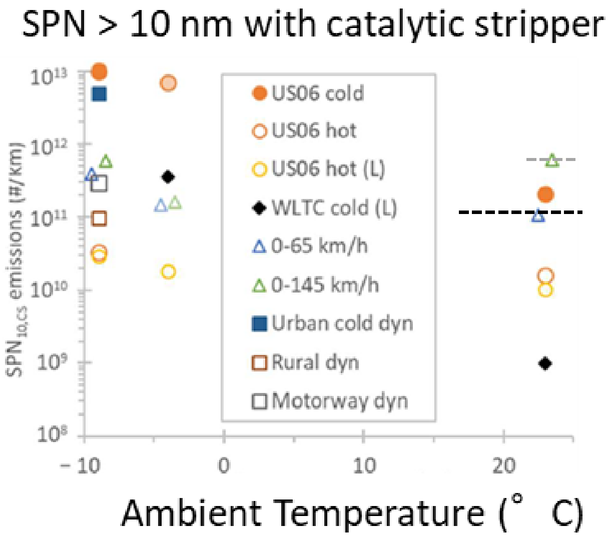
Particulate emissions evaluated under Euro 7-like conditions with advanced GPF

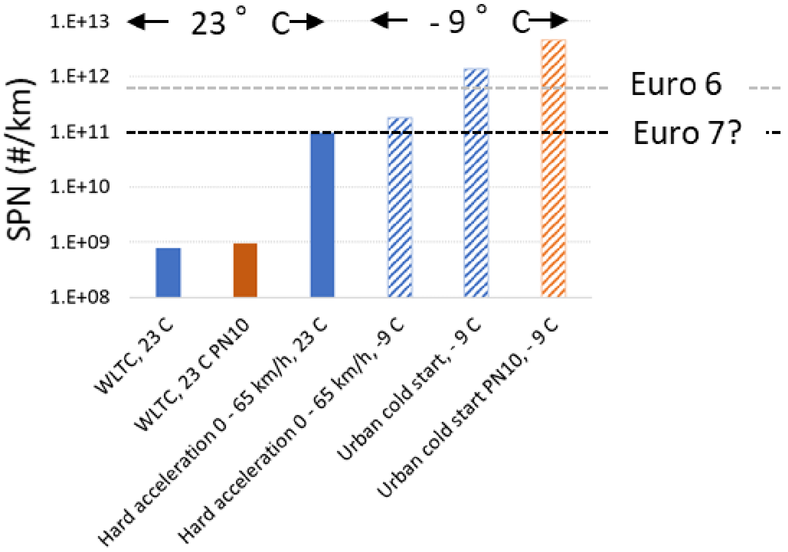
EU Commission, JRC Catalysts 2022, 12, 70.

Vehicle:
2019 Euro 6d-Temp, 1.2L GDI with TWC + bare cc-GPF
Fuel: E5 with PMI 2.2 (“bad quality” market fuel)
GPF: Bare 200/8 with 55% porosity, hierarchical pore structure

Tests: WLTC and RDE with challenging conditions (~Euro 7):

Clean GPF, dist. < 16 km, low T with auxiliaries, hard accelerations, dynamic driving on slope, 90% payload, etc.



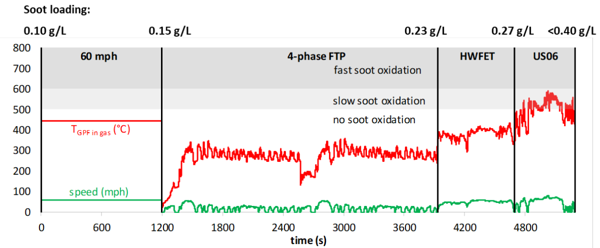


GPFs are very effective at reducing toxicity of PAHs associated with engine soot

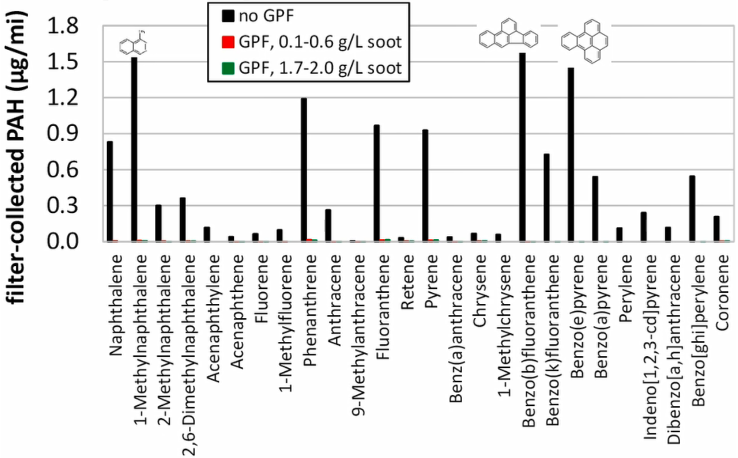
U.S. EPA, CSS, 32nd CRC Real World Emissions Workshop, 2022

Vehicle: 2011 Ford F150, 3.5L Ecoboost, wall-guided GDI

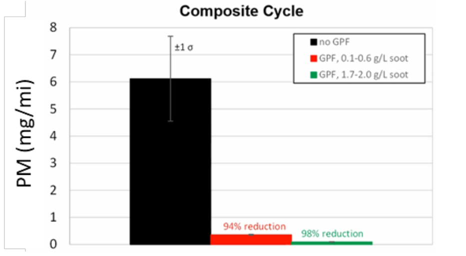
Commercial cGPF in uF position Ø5.66" x 4", 300/12, coated

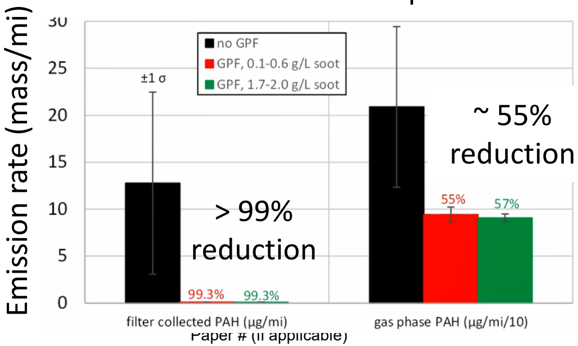


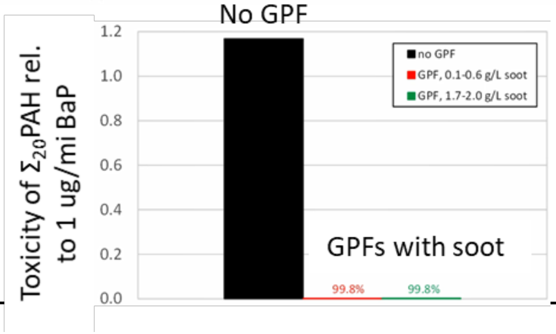
GPF reduced the toxicity of filter-collected PAHs by 99.8%



- PM reduced by > 94% and well below CA limit of 1mg/mi
- PAHs reduced by >99% (filter-collected) and 55% (gas-phase)

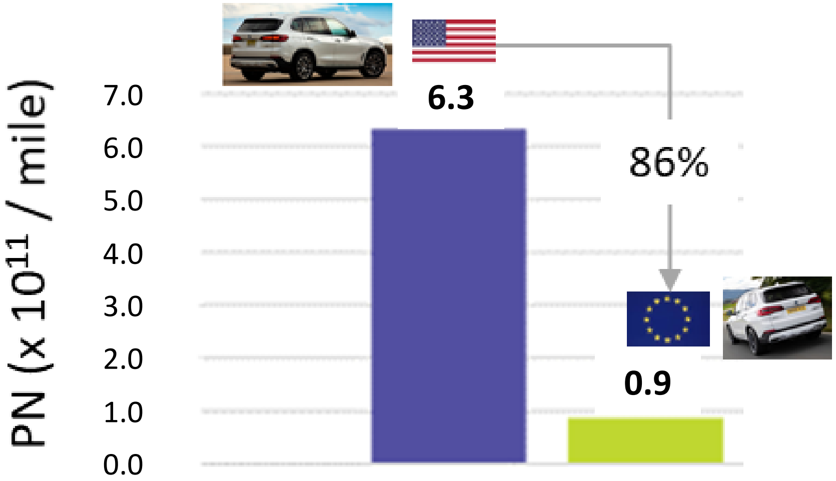






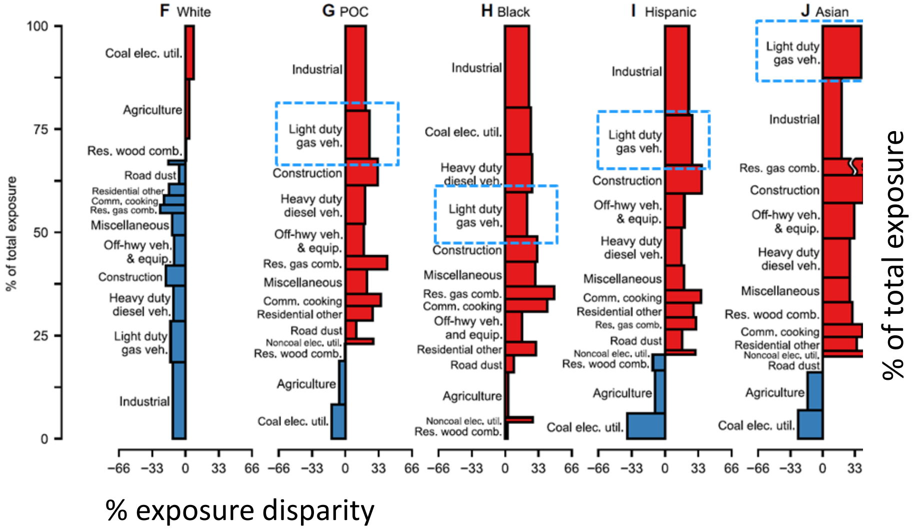
US needs to enforce GPFs: Particulate emissions are higher from US cars vs. EU – and they affect disadvantaged communities disproportionately

Same models in US are emitting much higher particulates than those sold in Europe



EmissionsAnalytics, on-road measurements

Gasoline particle emissions is a leading contributor to environmental injustice



Sci. Adv. 7, eabf4491 (2021) U. Illinois at Urbana-Champaign, U. Washington, UT Austin, UC Berkeley, U. Minnesota

Topics covered today

Light-Duty

- Regulations : Fuel economy and criteria pollutants
- Gasoline emissions control – Gas species
- Gasoline emissions control – particulates
- **Diesel emissions control**

Heavy-Duty

- Ultra-Low NOx regulations (CARB, Euro VII) and technology pathways
- Greenhouse gas regulations and technology pathways
  – Diesel, alternative fuels, electrification

Light-commercial vehicles – Technology packages used to meet Euro 6d final regulations described

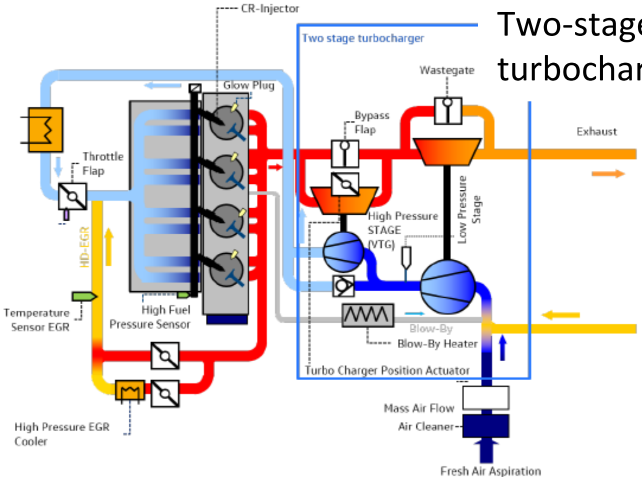
Volkswagen, 42nd Intl. Vienna Motor Symposium, 2021

EA288 light commercial vehicle 2.0L engine

Engine

Injection system : 2200 → 2500 bar

Solenoid valve technology → up to 9 injections

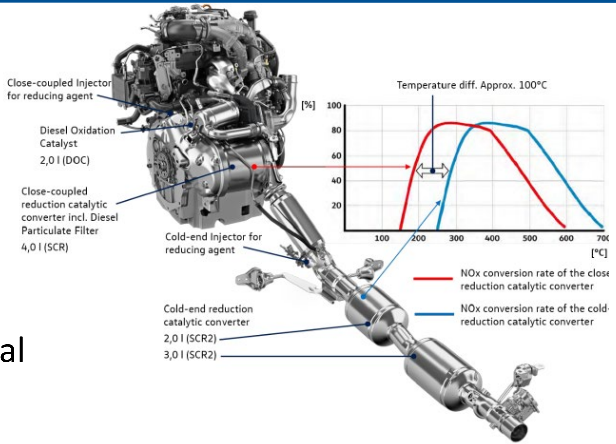


Two-stage serial turbocharging

High-P EGR (cooled or uncooled)

Low-P cooled EGR

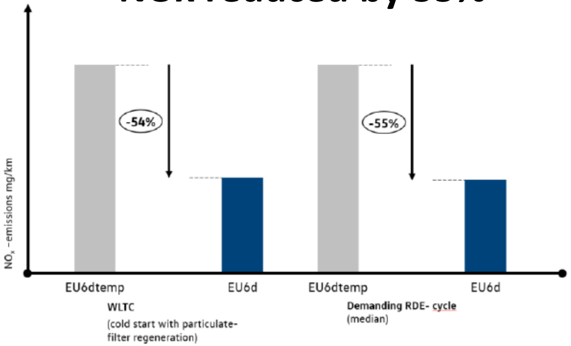
Paper # (i



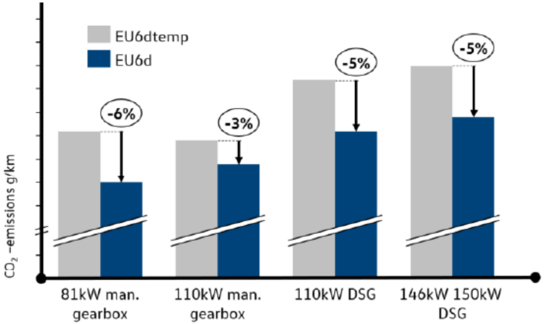
After-treatment

- DOC + DPF//SCR + 2xSCR
- Close-coupled DOC & DPF with SCR coating – 1st for commercial vehicle
- Downstream SCRs with independent urea injection (twin dosing) and ammonia ox. cat.

NOx reduced by 55%



CO_2 reduced by 3 – 6%

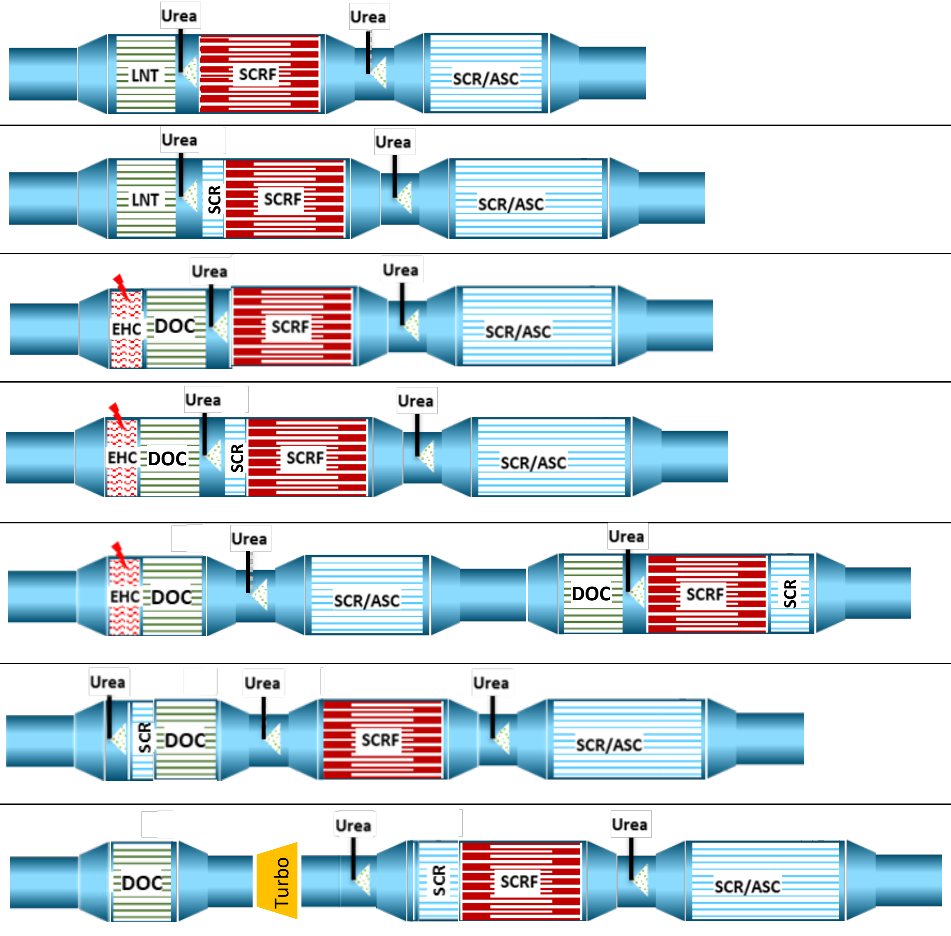


Fuel : Engine capable of running on renewable diesel (HVO)

Light-duty diesel after-treatment systems for ~ Euro 7

Potential Euro 7

(0)	Reference Euro 6d
(1)	LNT + cc-SCR
(2)	EHC
(3)	EHC + cc-SCR
(4)	EHC + 3 SCRs + 2 DOCs
(5)	cc-SCR + triple dosing
(6)	Pre-turbo DOC

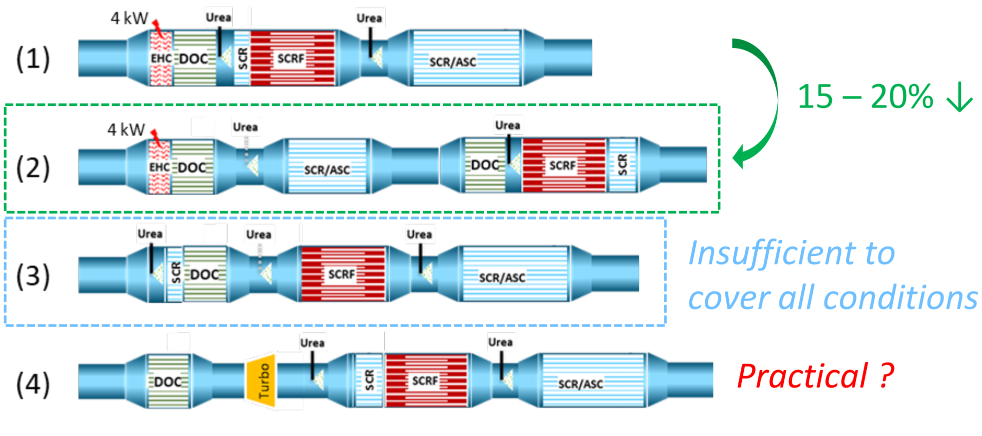


Light-commercial vehicles : Pathway to meet Euro 7 limits under a wide range of driving conditions

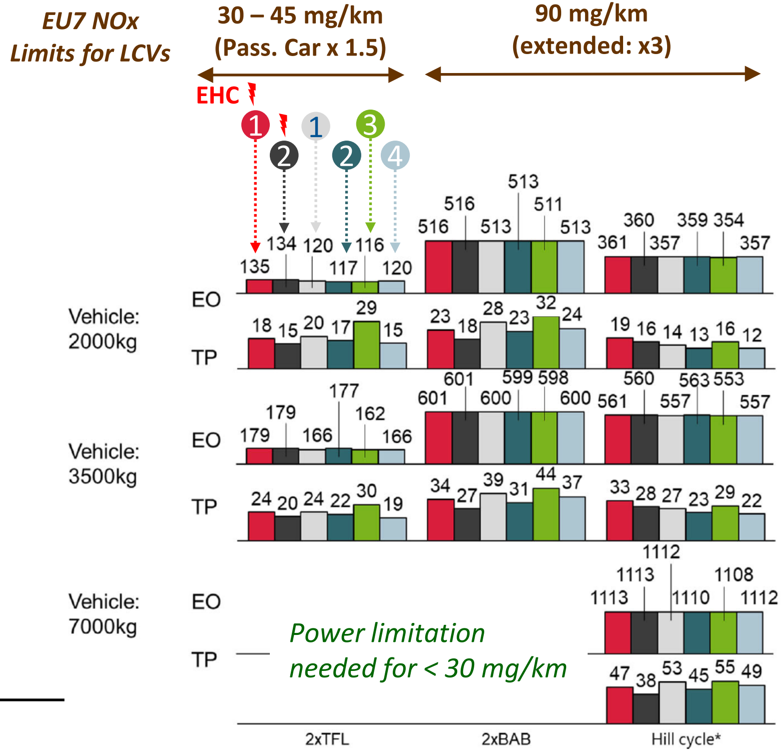
FEV, 30th Aachen Colloquium, 2021

Simulation conditions	Vehicle: Unloaded 2t, loaded 3.5t, with trailer 7t Engine: 2L, 140 kW	Temp = - 7 ° C, 16 km Empty + urban dynamic (TfL) | Fully loaded + aggressive dynamic (BAB) |Fully loaded + trailer + uphill driving

Euro 7 solutions evaluated



Engine measures when not using EHC
Miller cycle (VVT), HP-EGR w/ cooler bypass, post-injection



Low NOx and low wells-to-wheel CO_2 demonstrated through advanced after-treatment and renewable fuels

AECC, CONCAWE Sustainability 2021, 13, 12711

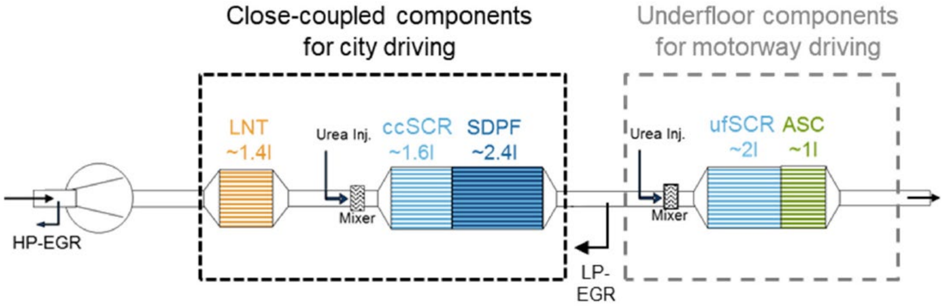
Vehicle

C-segment Euro 6b mild-hybrid diesel

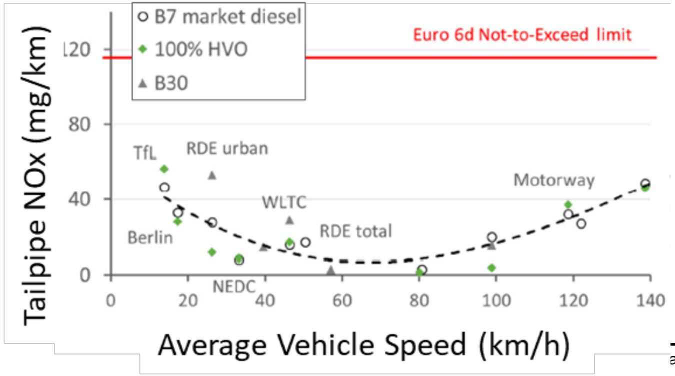
Fuels

1. B7 diesel
2. Diesel with 30% FAME blend (B30)
3. Hydrogenated vegetable oil (HVO)

Advanced After-treatment



NOx



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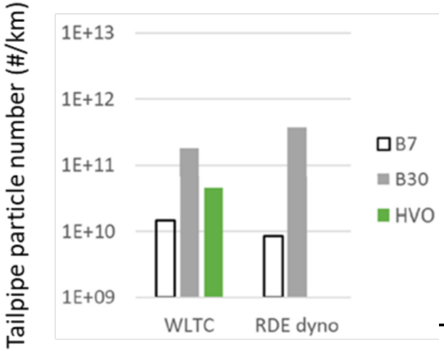
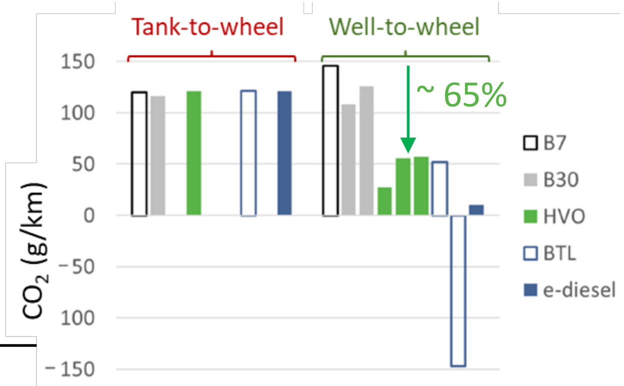
Particle number



CO_2



Topics covered today

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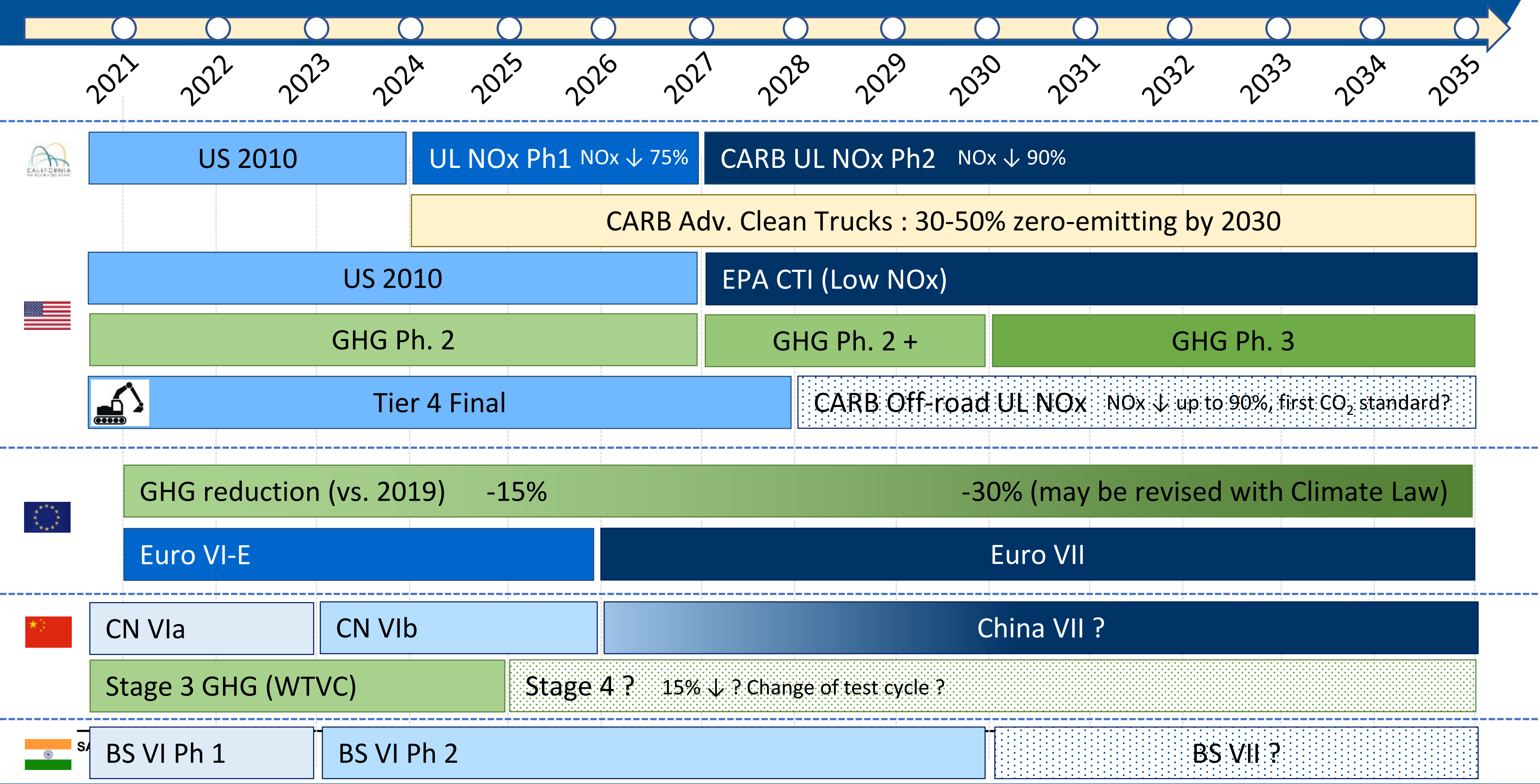
- Gasoline emissions control – particulates
- Diesel emissions control

Heavy-Duty

- **Ultra-Low NOx regulations (CARB, Euro VII) and technology pathways**
- Greenhouse gas regulations and technology pathways
  - Diesel, alternative fuels, electrification

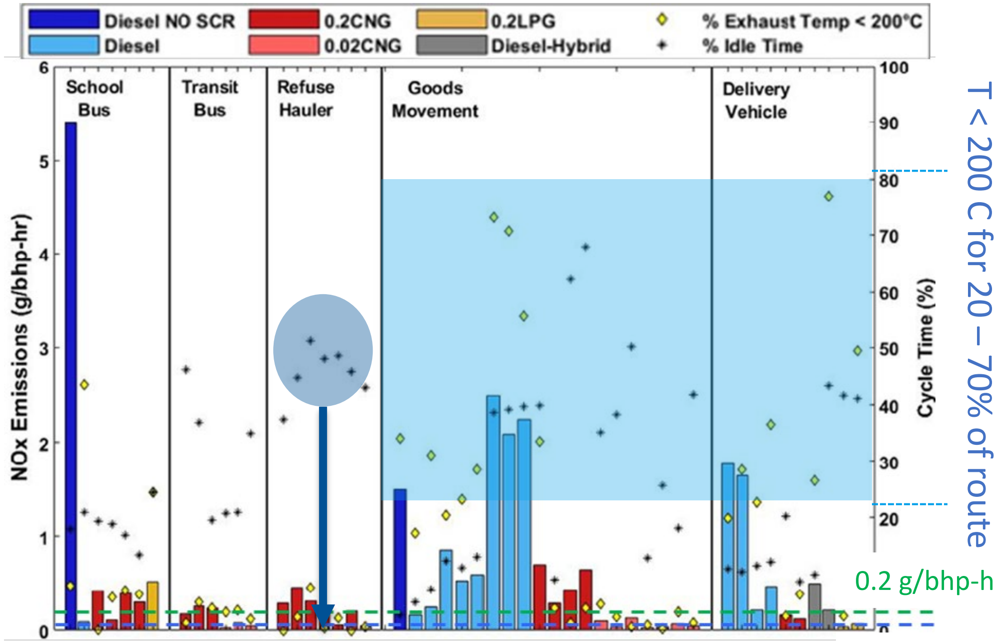
Heavy-duty regulatory roadmap in major markets



In-use PEMS testing shows high NOx emissions at low loads / idling

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

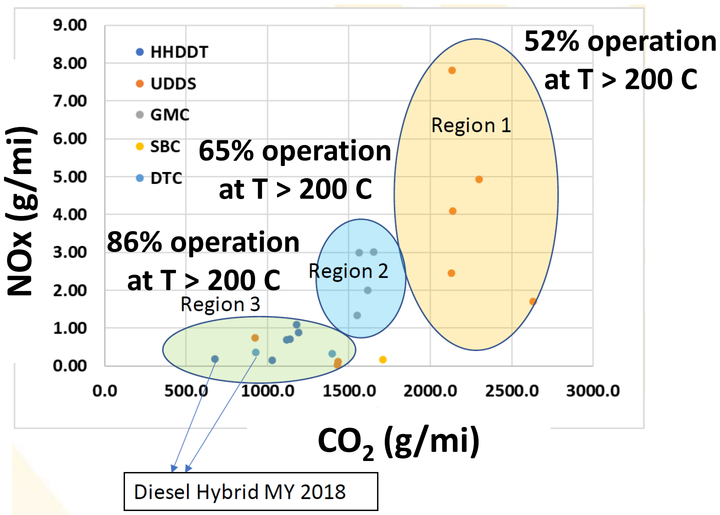
Fleet:
2 diesels without SCR, 14 with SCR, 2 diesel hybrids, 29 CNG, 3 LPG
Vehicles within useful life (< 435,000 miles)



Significant fraction spent in idling
→ Almost 1/3rd of emissions during idling

Reduction in NOx compared to Diesel w/ SCR		
0.02 CNG	LPG	Diesel hybrid
94%	79%	65%

Improved SCR activity also reduces CO_2



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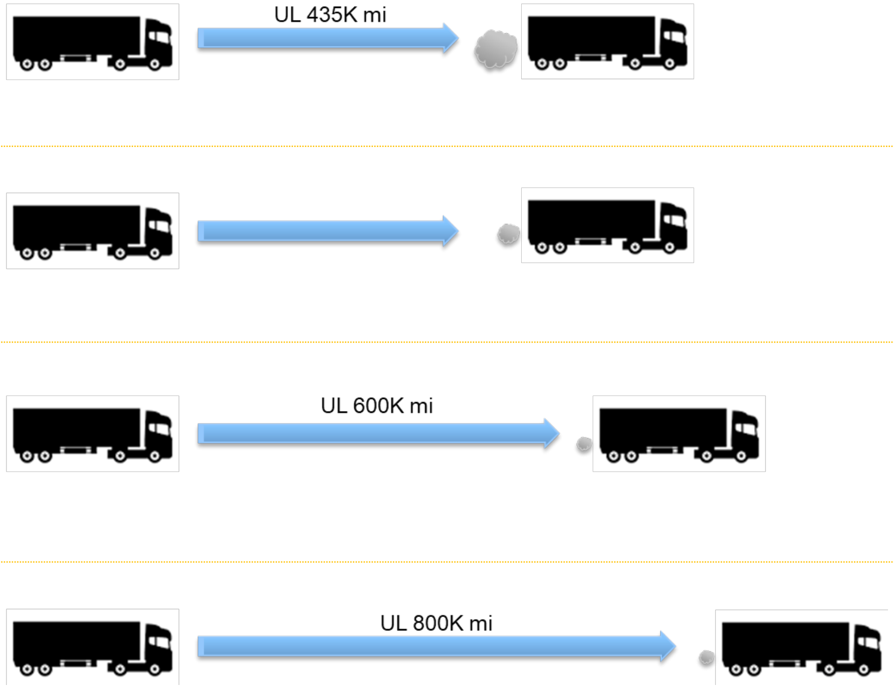
California Ultra-Low NOx Omnibus Rulemaking



	Regulatory Change
2020	*Reference US 2010* NOx 200 mg/bhp-h on FTP PM 10 mg/bhp-h on FTP IUC : NTE method
2024	NOx 75% ↓, PM 50% ↓ New: Low-load cycle IUC : MAW method OBD data transmission
2027	NOx 90% ↓ IUC : Cold-start included GHG Phase 2: CO_2 25% ↓
2031	All of above + adjusted deterioration

IUC = In-use compliance, NTE = Not-to-exceed, MAW = Moving avg. window, GHG = Greenhouse gas, UL = useful life

US EPA Cleaner Trucks Plan proposed (March 2022)

Final rule after 45 day comment period

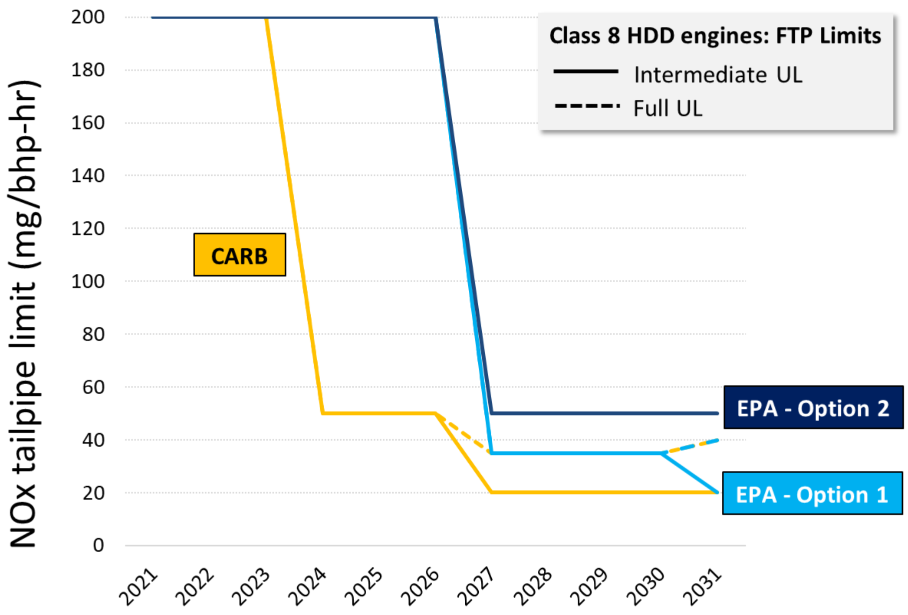
Option 1 (~ CARB after MY 2031):
NOx limit: 20 mg/bhp-hr after MY 2031
FUL : Increases to 600K mi in 2027 and 800K mi in 2031

Option 2:
NOx limit: Fixed at 50 mg/bhp-hr after MY2027
FUL: Fixed at 650K mi

Test changes

- New low-load cycle (LLC) test similar to CARB
- Off-cycle testing : Similar to California's 3-Bin MAW method
- HD SI engines will require testing on SET lab cycle (previously only for CI engines)

Multi-pollutant rule: Targeted revision of GHG Phase 2 MY2027 – 2029 standards for applications with significant electrification: School buses, transit buses, commercial delivery trucks, and short-haul tractors



- Credit multipliers for early compliance, and credits for HEVs/BEVs/FCEVs
- No emission credit multipliers for HEVs/BEVs/FCEVs

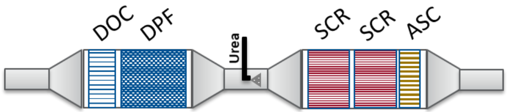
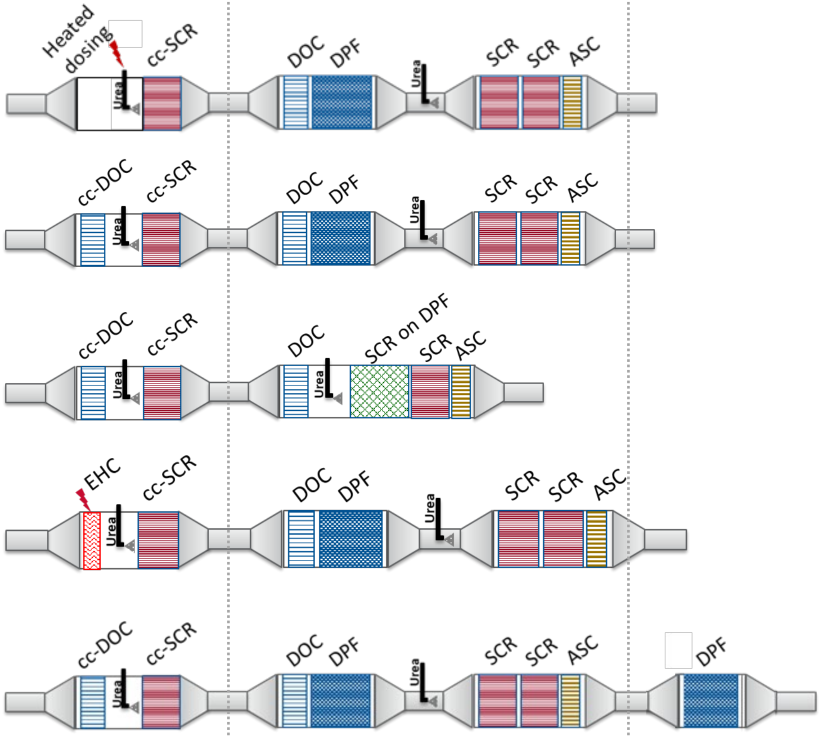
Euro VII (HD) Proposal Based on AGVES Meetings (EU Commission)

Euro VII CLOVE proposal Units: Gas mg/kWh, PN #/kWh	NOx	PN_{10}	PM	CO	NMOG	NH_3	N_2O	CH_4
100 percentile	175 – 350	$5x10^{11}$	12	1500 – 3500	75 – 200	65	160	85 – 100
90 percentile	90	$1x10^{11}$	8	200	50	65	60	50
Budget ≤ 3xWHTC work	100 – 150	$2x10^{11}$	10	600 – 1250	50 – 75	65	140	30

Lower limit assumes cc-SCR, higher limit assumes active heating. Limits up to 700K km for N3 > 16t and 300K km for others.

In-service conformity On-road PEMS testing	Euro VI-D (2019)	Euro VI-E (2021)	Euro VII (2025+)
Trip	30% Urban, 25% Rural, 45 Motorway%		Testing under "all" normal driving conditions
Power threshold	> 10% P_{max}		No P threshold : Inclusion of low load emissions
Payload	10 – 100%		No payload restrictions
Boundary conditions	- 7 to + 38 ° C, Alt. 1,600 m		Normal : - 7 to + 35 ° C, Alt. 1,600 m Extended: - 10 to + 45 ° C, Alt. 2,200 m (Limit 2x)
Cold start	Excluded	Included, $T_{coolant}$ > 30 ° C	Included, all emissions from engine start
Evaluation method	90th percentile < limit for compliance		3 compliance methods / limits (see below)
Durability	N2,N3, M3 < 16t: 300,000 km / 6 yrs N3 > 16t: 700,000 km / 7 yrs		N2,N3, M3 < 16t: 700,000 km N3 > 16t: 1,200,000 km

Potential low NOx systems

Euro VI / US 2010	Ref.	
Euro VII / CA2027 (example configurations)	1 2 3 4 5	
		"Close-coupled" catalysts · Conventional system · 2nd filter

	Technology for low NOx	Impact on NOx	Impact on CO_2
Engine	Engine calibration	Lower engine out NOx	Little / none
	Cylinder deactivation	Increased EO temp. → higher NOx conversion	Lower CO_2
	EGR pump	Better EGR authority	Improved pumping loop efficiency
	SuperTurbo	Turbine bypass allows for early SCR warm-up	Engine heating can be offset
	Opposed piston	Elevated temp. for early LO	Lower heat loss → lower CO_2
	Hybridization	Lower fuel consumption and emissions	Lower CO_2, can offset EHC penalty
+ Added SCR	Increase SCR volume and catalyst loadings	Improved deNOx at high flow rates	Increased backpressure
	Added cc-SCR w/ twin dosing	Early light-off and urea dosing possible	Increased backpressure
	+ cc-DOC for NO_2	Increased fast SCR, slower light-off of cc-SCR	Increased backpressure, N_2O
	SCR on filter	Early light off of main (uF) SCR	Passive regen is complicated
	Model based A/T controls, NH_3 storage	DeNOx sensitive to level of pre-stored NH_3	Lower urea consumption
+ Heat	Late & multiple injections	Early light-off	Fuel penalty, increased HC/CO
	Heated urea dosing	Early urea dosing, lower deposition risk	Some fuel penalty for heating
	Catalyzed DEF solution	Low nitrate deposits, earlier dosing possible	Can eliminate heated dosing
	Electrical heater / EHC	Early light-off	Need to manage fuel penalty
Fuel	Diesel → CNG / LPG / Gasoline / H2-ICE / …	Lower engine out NOx and/or simpler A/T	Watch for CH_4
	Low S, low impurity fuels	Extended durability	Lower CO_2 → reduced desulfation

Dynamic cylinder deactivation increases exhaust temperature and delivers significant NOx and CO_2 reductions

Tula SAE COMVEC 2021

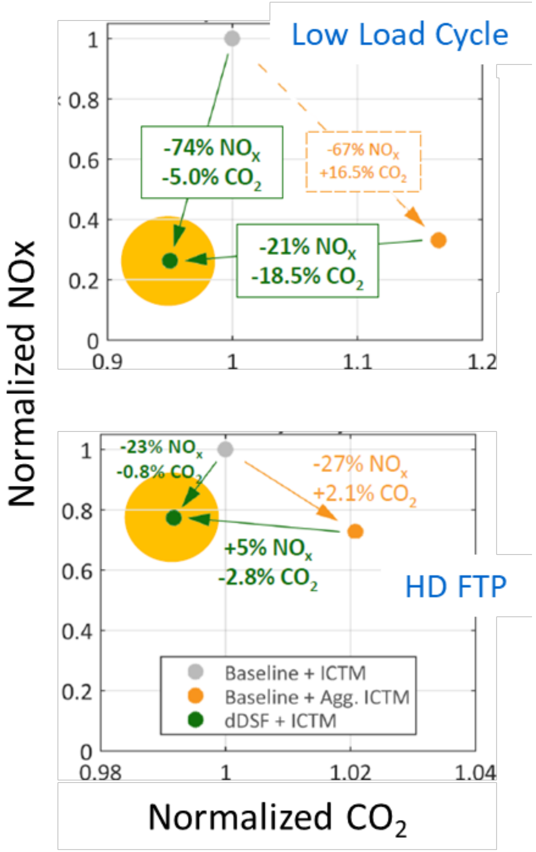
Baseline Engine Specifications:

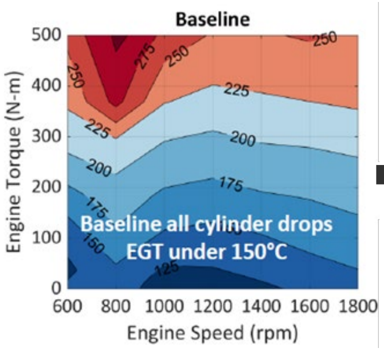
ENG	
	➢ Cummins X15 Efficiency Series ➢ 15L I-6 HHD Diesel ➢ 373 kW (500 hp) Max Power ➢ 2508 Nm (1850 lb-ft) Peak Torque ➢ HP-EGR ➢ XPI High Pressure Common Rail Fuel System ➢ Single Stage Variable Geometry Turbocharger

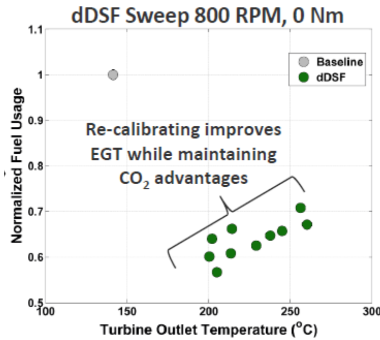
Baseline Aftertreatment Specifications:

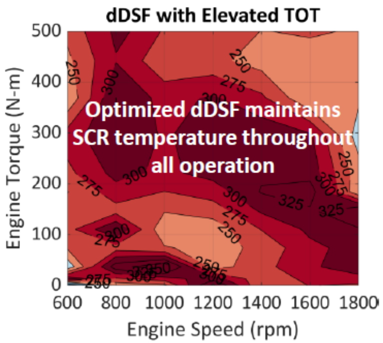
AT	
	➢ DOC/DPF ➢ DEF Injection System ➢ Cu-Ze SCR/ASC

- With dynamic skip fire, engine out temperature increased by 50 – 90 ° C, and > 225 ° C over map
- HD-FTP : 74% reduction in NOx with 5% CO_2 reduction
- LLC: 23% reduction in NOx with 0.8% CO_2 reduction
- Implemented on Freightliner Cascadia









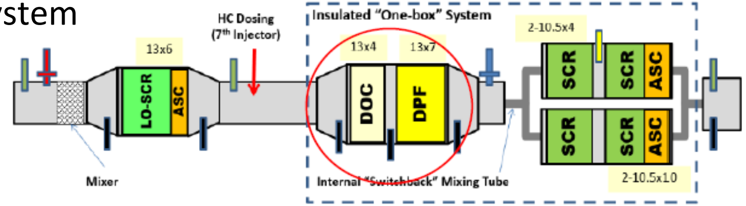
Paper # (if applicable)

SWRI/CARB Low NOx study: Latest results with system aged to 800K

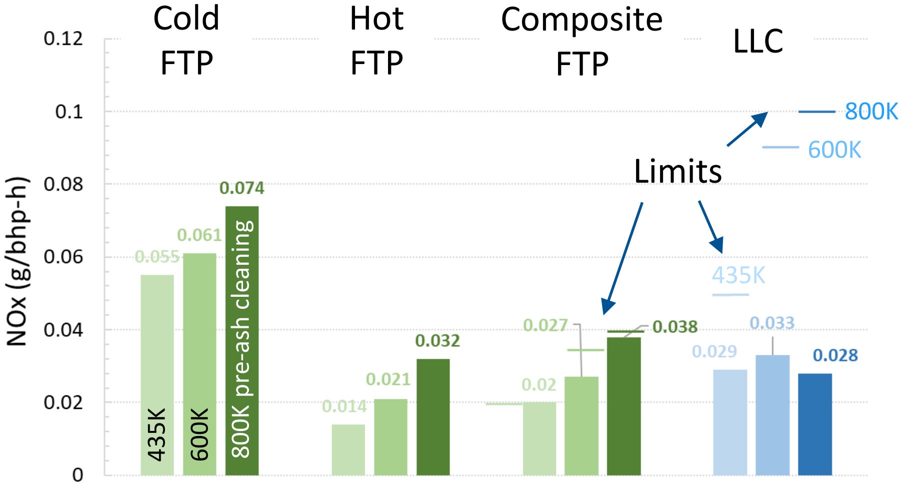
SWRI, CRC Real World Emissions Workshop, 2022

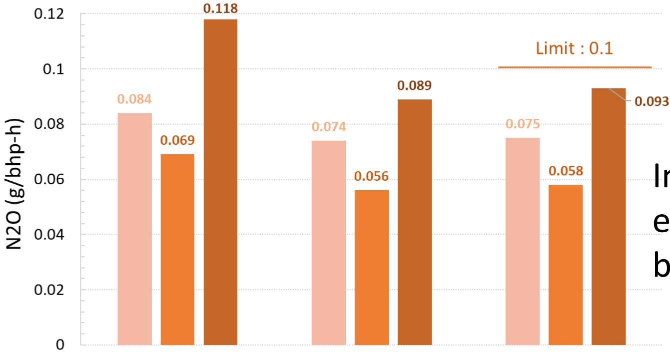
<u>Engine</u>:
Cummins 2017 X15 6-cyl.
+ modified calibration
+ added advanced technologies
EGR cooler bypass, Cyl. deactivation

<u>After-treatment</u>: Stage 3 Rework system



+ Improved mixing



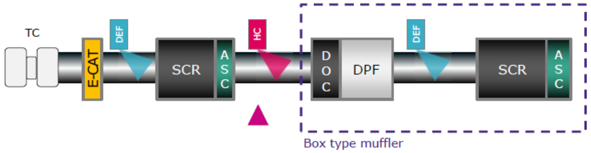


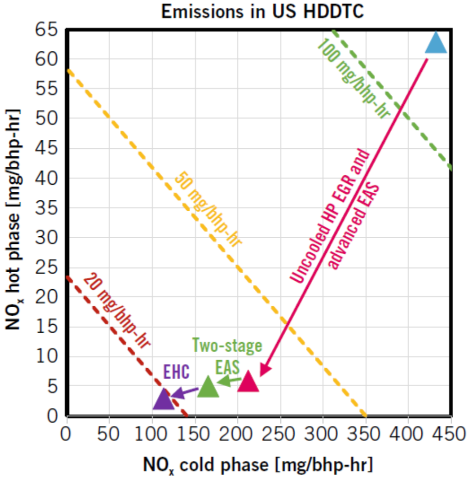
Increased emissions at 800K but still < 0.1

Note:
- Almost no change in CO_2 (not shown)
- Infrequent regen. Upward adjustment factor not included, adds 0.002 to FTP-RMC, 0.005 to LLC

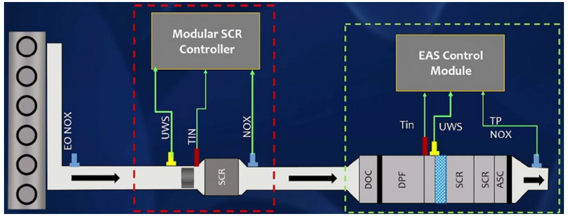
Electrically heated catalysts for HD Low NOx ?

AVL CLEERS 2021 & MTZ 03/2021





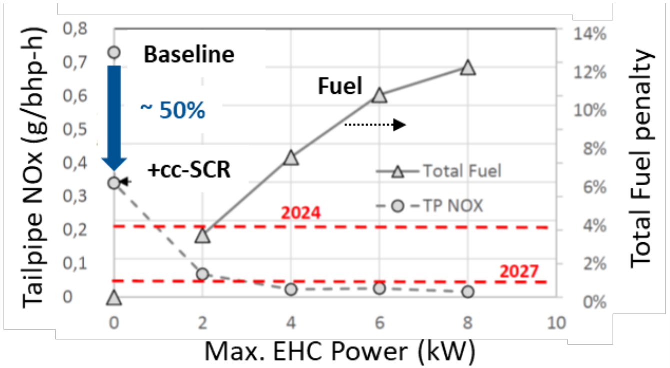
PACCAR, Vitesco Aachen Colloquium, 2021



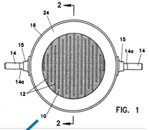
Engine: 2017 PACCAR MX-13, HE400

After-treatment:

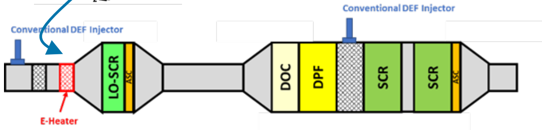
+ 48V EHC + cc-SCR (dual dosing)

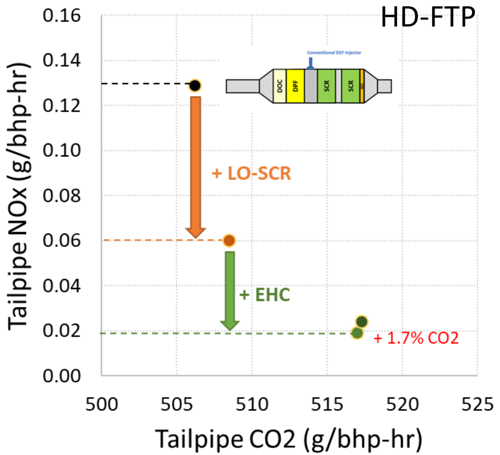


Eaton, SWRI, Corning, to be published



Engine: Cummins 2017 X15 6-cyl.





Opposed piston engine : Real-world on-vehicle data

AchatesPower, CRC Real World Emissions Workshop, 2022

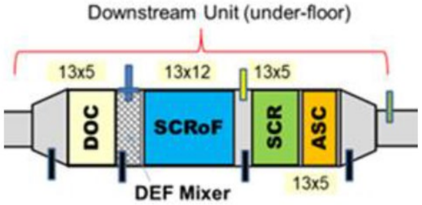
1st Gen : Peak BTE 47.1%

2019 Peterbilt 579 sleeper 10.6L 400 hp engine

<u>Walmart fleet in-use data</u>

10+% fuel economy advantage vs reference 2021 DD15 engine

Dev. aged



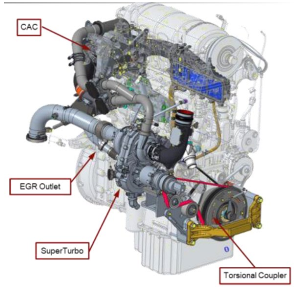
6.7 – 10.8 mpg vs 5.7 – 7.7 on ref. truck

FTP NOx : 0.016 g/bhp-hr

> 30% margin on in-use 3-bin MAW 2031 limits

	Achates_ D1	Achates_ D2	Achates_ D3	Average	EPA Low 2031+ IUL	Margin to EPA	CARB 2030+	Margin to CARB
BIN 1	0.25	0.05	0.15	0.15	11	99%	7.5	98%
BIN 2	0.048	0.039	0.039	0.042	0.105	60%	0.075	44%
BIN 3	0.024	0.015	0.022	0.020	0.042	52%	0.030	32%

2nd Gen : Peak BTE 49.2%



<u>Added hardware</u>

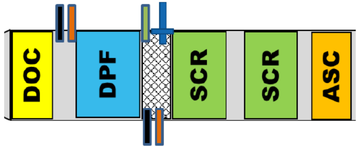
SuperTurbo, EGR pump

vs Gen 1:

5% lower CO_2 on SET, 8% on Hot FTP

30% higher exh. heat for cat. LO- mode

Underfloor SCR only



Modeled based on measured engine out

	Achates Power HD Second Generation Engine	2027 Regulatory Limits (CARB/EPA)	Improvement vs. 2027 Standards
SET Cycle	*0.014 g/hp-hr NO_x* **415 g/hp-hr CO_2**	0.020 g/hp-hr NO_x 432 g/hp-hr CO_2	30% 4%
FTP Cycle	*0.007 g/hp-hr NO_x* **465 g/hp-hr CO_2**	0.020 g/hp-hr NO_x 503 g/hp-hr CO_2	65% 8%
Low Load Cycle	*0.021 g/hp-hr NO_x*	0.050 g/hp-hr NO_x	58%
Clean Idle	*0.02 g/hr NOx*	5 g/hr NO_x	99.6%

Low NOx emissions demonstrated on a European truck

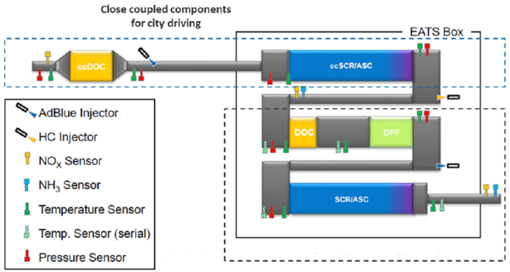
JRC (EU Commission), AECC, FEV, Horiba, AIP   Catalysts 2022, 12, 184

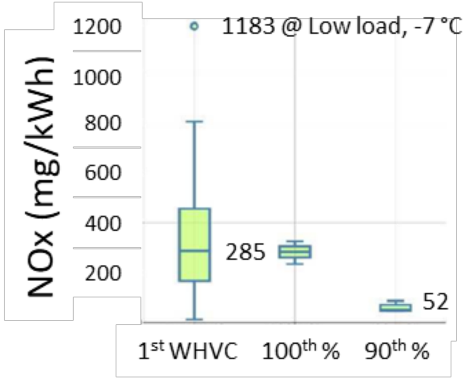
Vehicle

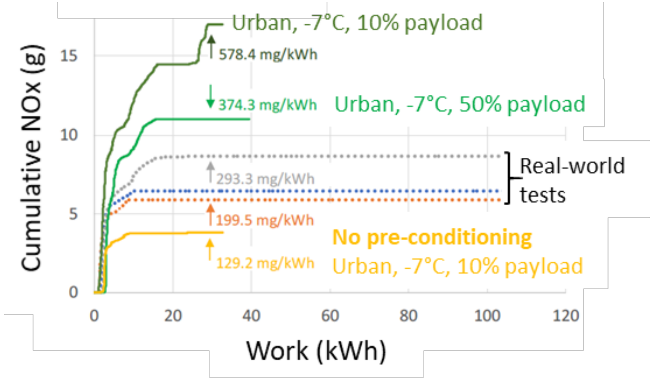
MB Actros 1845
LS 4x2
Euro VI C, 12.8 L,
6 cyl., HP EGR.

After-treatment system

Parts aged to 500K km target



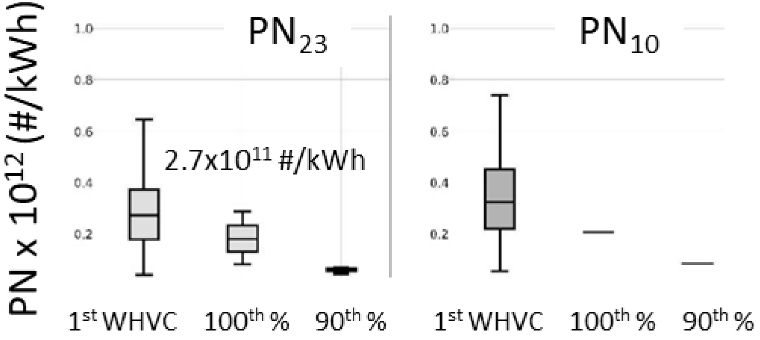




Pre-conditioning: 30 min driving at 70 km/h

Test conditions

Type	Starting Condition	Payload (%)	Ambient T (°C)	Conditioning Performed
WHVC	Cold, Hot	55	−7, 0, 23	yes, no
Real World Test	Cold	10	−7, 23, 35	yes
Urban delivery	Cold	10, 55	−7, 23	yes, no
JRC city	Cold	10	−7	yes
Brenner cycle	Cold	10	−7	no
Idling	Hot	-	23	no
DPF regeneration	Hot	-	23	no



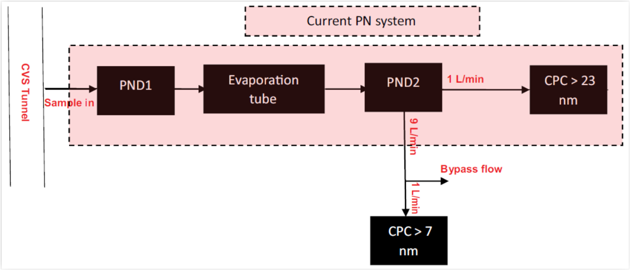
Test condition	NOx	PN
Ambient T. 23 °C → -7°C	↑	↑
Payload 50% → 10%	↑	↓
Dynamic, low speed driving	↑	↑
Pre-conditioning (urea depletion)	↑	-

$PN_{23} \rightarrow PN_{10}$: +15 – 30%

Sub-23 nm and urea derived particles could push tailpipe PN > Euro VII limit

Cummins, UC Riverside, W. Virginia Univ., Horiba, AVL, TSI SAE 2021-01-5024 doi:10.4271/2021-01-5024

1. Measurements using evaporation tube

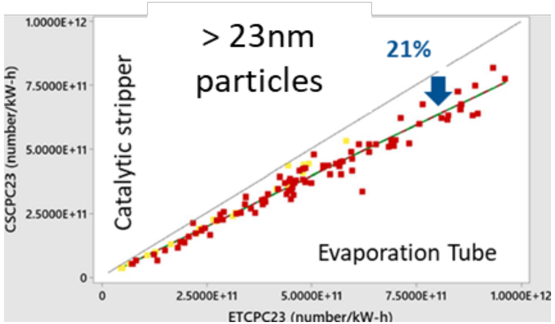


Engines : 2 diesels with DOC, DPF, SCR
1 diesel with DOC, SCR | 2 NG with TWC
166 test cycles: NRTC, WHTC, WHSC, RMC, …

Sub-23 nm particles increase PN count by
10% to 3.8X (280%)

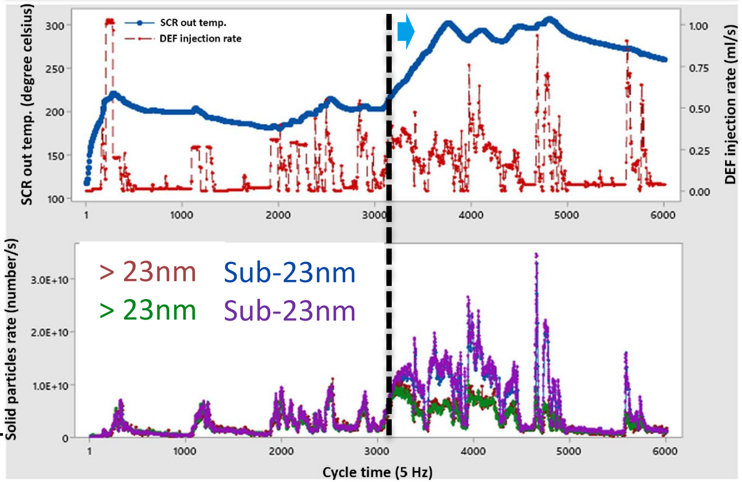
Engine	Fuel	Aftertreatment	Test runs	CPC7:CPC23 ratio (Min, Avg, Max)
AA	ULSD	DOC + SCR	7	1.30, 1.30, 1.40
AB	ULSD	DOC + DPF + SCR	21	1.40, 2.37, 3.80
AB	B20	DOC + DPF + SCR	12	2.10, 2.74, 3.40
AC	NG	3-way catalyst	35	1.50, 1.96, 3.40
AD	ULSD	DOC + DPF + SCR	64	1.10, 1.40, 3.10
AE	NG	3-way catalyst	27	1.25, 1.60, 3.20

2. Measurements using catalytic stripper (2 CNG engines)



Catalytic stripper important for > 23nm as well !
(at least for NG engines)

Majority of sub-23nm particles associated with hydrolysis & decomposition of DEF at T > 250 ° C



Paper # (if applicable)

Topics covered today

Light-Duty

- Regulations : Fuel economy and criteria pollutants
- Gasoline emissions control – Gas species
- Gasoline emissions control – particulates
- Diesel emissions control

Heavy-Duty

- Ultra-Low NOx regulations (CARB, Euro VII) and technology pathways
- **Greenhouse gas regulations and technology pathways**
  - **Diesel, alternative fuels, electrification**

All pathways for decarbonization being pursued – no silver bullet

Reducing greenhouse gas emissions from HD transportation

1. **Improving conventional powertrains**

   SuperTruck II - 55% BTE
   Vehicle scale – aerodynamics etc.

2. **Electrification**

   Hybridization
   Battery electric
   Fuel cell

3. **Low carbon fuels**

   H_2 ICE
   HVO
   e-Diesel
   …

Super-Truck II : 55% brake thermal efficiency demonstrated

Improved combustion

CLEMSON UNIVERSITY
SOLUTION SPRAY TECHNOLOGIES
OAK RIDGE National Laboratory

High CR + 0.3 – 0.8 BTE
Thermal barrier coatings - 1 % BSFC
Lower friction +0.5% BTE

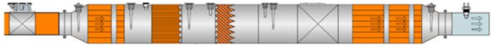
Improved air handling

Eaton

EGR pump (+0.9 BTE)
Miller cycle LIVC (up to +1.4% BTE)
Optimized turbochargers

ENGINE

Improved after-treatment



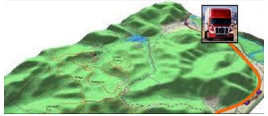
Navistar

Low ΔP design
cc-SCR, high cell density, thin wall

Waste heat recovery

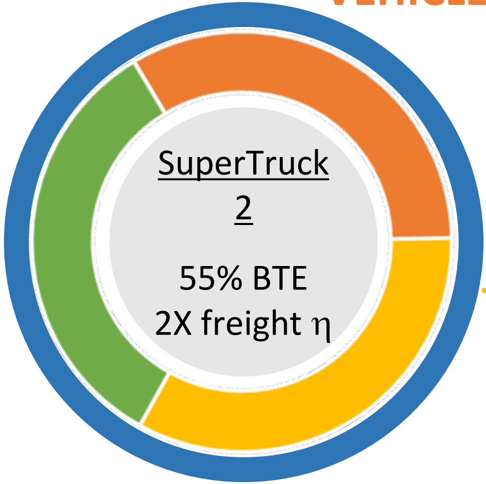
~ +3 – 4.5% BTE
ORC with cyclopentane
Dual entry turbine

Model-based control



MICHIGAN ENGINEERING

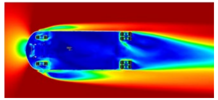
VEHICLE



Weight reduction

Cummins: Lightweight chassis & trailer - 4,700 lbs
Peterbilt: Lightweight chassis - 500 lbs

Aerodynamics & tires

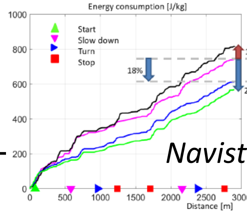


Kenworth: 60% aero drag ↓
Chassis height control
Low rolling R tires : Up to +5% fuel economy expected (Volvo)

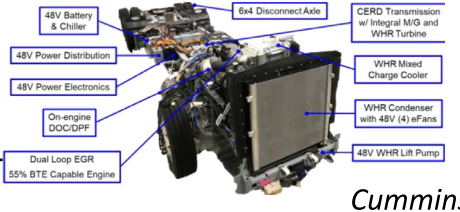
TRANSMISSION, ELECTRIFICATION

48V mild hybridization, 7 – 15 kWh Li-ion battery. Electrification: HVAC, P-steering, coolant pumps, CAC, e-hoteling, etc.

Predictive cruise control



Navistar



Cummins

Paper # (if applicable)

Strategies from Super-Truck II participants for 55% BTE engines

	Daimler 	Volvo 	Cummins / Peterbilt 	Navistar 	PACCAR / Kenworth 
Combustion & Air Mgmt	• Thermal barrier coatings (TBC) • Miller cycle • 2 stage turbo & 2 stage c-EGR	• TBC • High CR 23:1, wave piston • EGR pump • Optimized turbocharger • Miller cycle	• Low heat transfer • Reduced friction • High efficiency turbocharger	• Cylinder deactivation • Fuel injector and cylinder bowl optimization	• Thermal barrier coatings (TBC) • 2-stage turbocharger
Waste heat recovery	Recovery from exhaust & EGR	48V e-WHR Dual-loop recovery from coolant & Exhaust	Dual HP & LP loop Recovery from coolant, EGR & exhaust	+3% BTE demonstrated	On track for +4% BTE Dual HP & LP loops, recovery from coolant + exhaust
After-treatment	cc-SCR w/ dual dosing	High cell, thin wall subs., low ΔP short DPF/SCR	Dual loop EGR On-engine DOC/DPF	cc-SCR/AMOX and also EHC after upstream SCR – durability & fuel penalty being evaluated	48 V e-heater + SCR in cc position, dual dosing. Targeting 2027 UL NOx.

HD ZEVs* : CARB mandates in place, OEMs have announced several models
Long-haul challenges – large battery pack (weight, price, charging time), infrastructure

California Advanced Clean Trucks Regulation

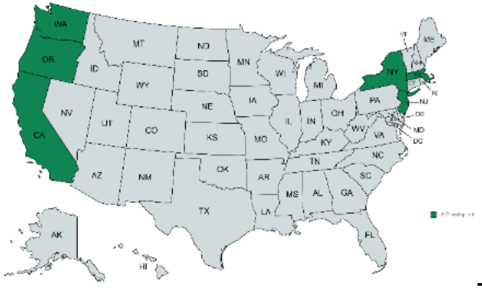
Also adopted by Washington state, Oregon, New York, New Jersey and Massachusetts

Manufacturer ZEV* requirements as a % of annual sales

Model Year (MY)	Class 2b-3	Class 4-8	Class 7-8 Tractors
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	40%
2034	50%	70%	40%
2035+	55%	75%	40%

Plug-in hybrids get partial credit based on all electric range

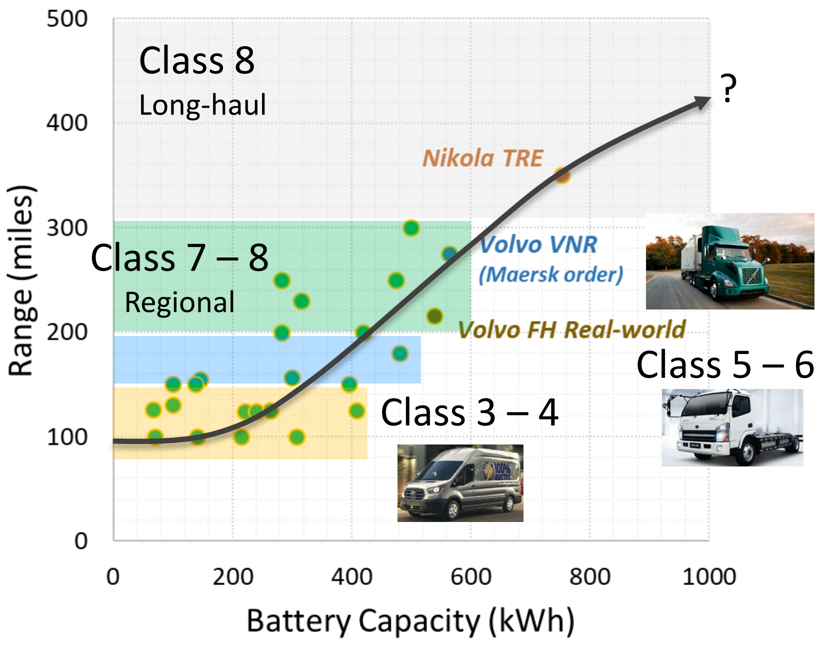
6 states have adopted ACT, including California



MOU signed by 15 states + DC
- Represent ~ 34% of HDV market

30% sales by 2030, 100% by 2050

> 1MWh battery pack needed for 500+ mile range



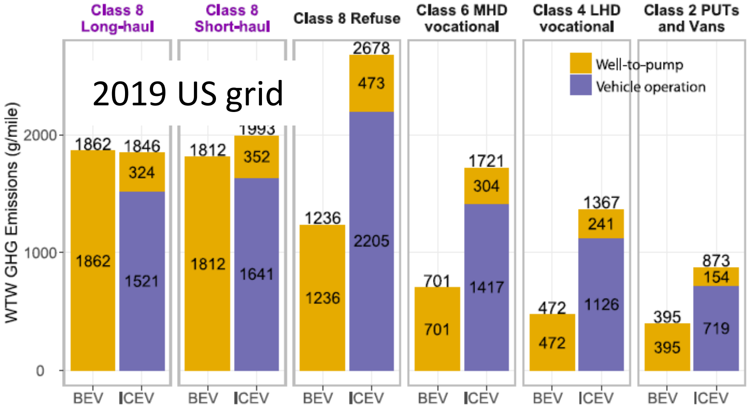
5 – 9% lower range at – 7 or +35° C (ICCT)
Range also varies with payload

* ZEVs defined as vehicles with zero tailpipe CO_2 (BEV, FCEV)

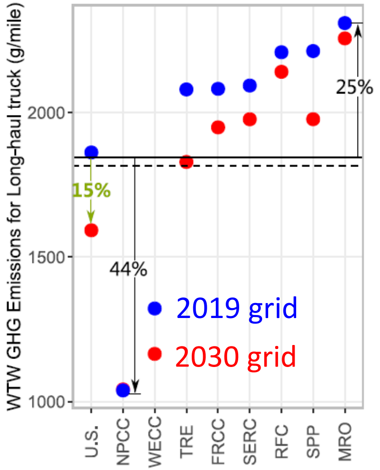
Wells-to-wheel analysis: Battery electric long-haul trucks could offer ~ 15% GHG reduction by 2030. But PM emissions could increase by 100%.

Argonne Natl. Lab Environ. Sci. Technol. 2021, 55, 1, 538–546

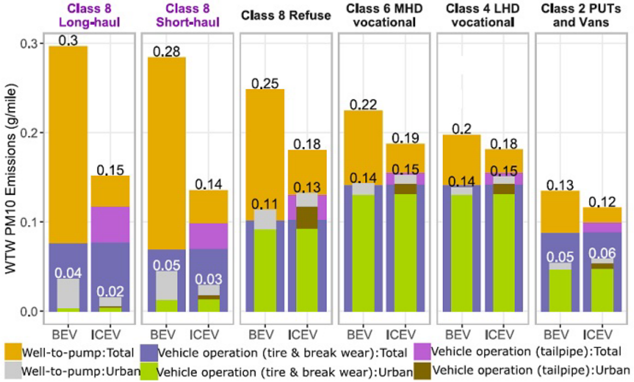
WtW GHG Emissions, 2019 US Grid



WtW GHG, Long-haul trucks US grid 2019 & 2030



PM emissions increase by 2X due to coal-based electricity



- Class 4 – 6 BEV trucks offer significant WtW CO_2 reduction
- Class 8 trucks offer little CO_2 reduction today, improve to 15% by 2030
- Emissions vary across regional grids → in some parts CO_2 *increases* up to 25%
- PM emissions predicted to increase due to coal-based emissions (need better controls)

Battery pack and fuel cell prices need to significantly reduce for total cost of ownership parity for BEV and FCEV long-haul trucks vs diesels

FASTSim tool used to model various powertrains and applications over representative drive cycles

NREL (2021) https://www.nrel.gov/docs/fy21osti/71796.pdf

<u>Some key assumptions in the study</u>

- Battery pack price:

$197 /kWh today → $100/kWh (2025) → $ 80 /kWh (2050)

Battery pack mass: 4.7 kg/kWh today → 2.5 kg/kWh (2050)

- H_2 price $10/kg today → $4 (2050)
- Fuel cell cost:

$197/kW today → $60/kW (2050)

- Diesel Class 8 efficiency : 47% today → 52% (2025) → 57% (2050)
- Diesel cost :

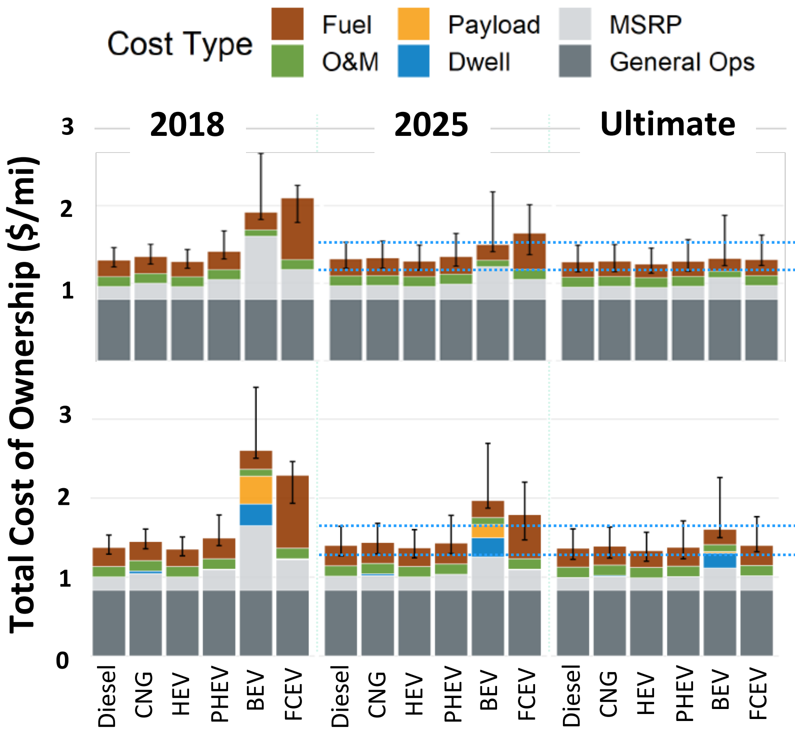
Advanced engine : +$1,500 in 2025, -$6,000 (2050)

WHR adds $10K in 2025, $5K (2050)

Single-Shift, Volume-Limited scenario
No dwell time costs
No lost payload capacity costs

Multi-Shift, Weight-Limited scenario
+ Dwell time costs
+ Lost payload capacity costs

Class 8 long-haul tractor (750-mile range)

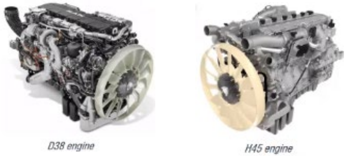


Total cost of ownership of H_2-ICE similar to diesels by 2030

80% carry-over parts from diesels

MAN, 42nd Intl. Vienna Motor Symposium, 2021

New TGX with H2 ICE powertrain



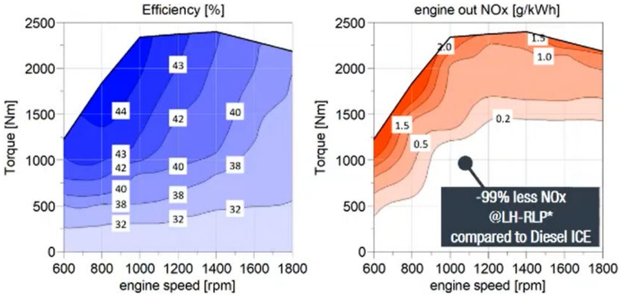
	D38	H45
Displacement	15,2 L	16,8 L
Cylinders	6 / Inline	6 / Inline
Torque	3000 Nm	up to 2600 Nm
Power	471kW/640hp	up to 375kW/510hp
Comp. ratio	1:19	1:11-13
Pmax	250 bar	170 bar

Engine specific parts

80% carry-over parts from diesels

- H2 and CH4 specific parts
  - Pistons/Liners
  - Single-stage turbo
  - Cylinder head
  - Ignition system
  - Gas handling (H2 and Air)
  - Control unit
  - Intake throttle

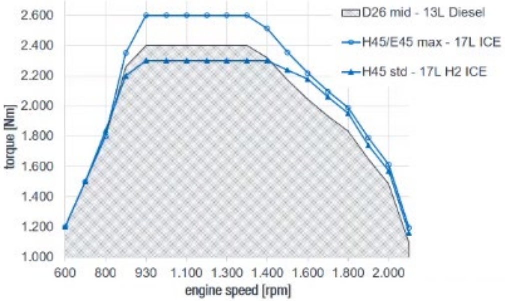
Peak BTE 45% (similar to diesel) – but with 99% lower NOx at road load point



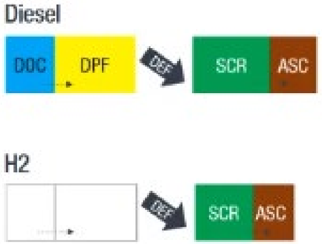
Engine maps w/o EGR

- Engine upsizing for transient response
- Direct injection for improved efficiency and low end torque
- Fuel tank : 700 bar system
- Single-stage turbo sufficient to reach λ = 2.7 and low engine out NOx

Engine can provide comparable torque as a 13L diesel



After-treatment : Only SCR

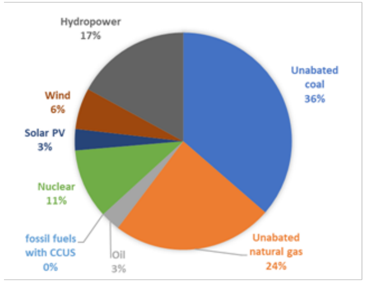


300 cpsi SCR/ASC
V_2O_5 extrudate combined with Ammonia oxidation catalyst

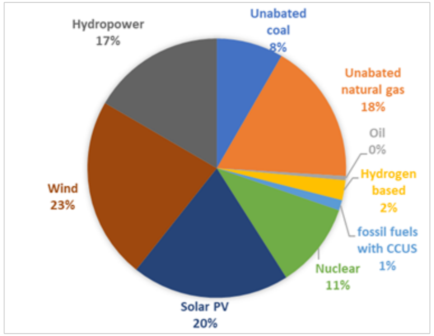
Decarbonization will require massive investment in renewable electricity and minerals

Annual solar PV capacity additions need to reach 630 GW by 2030 → ***equivalent to installing the world's current largest solar park roughly every day***

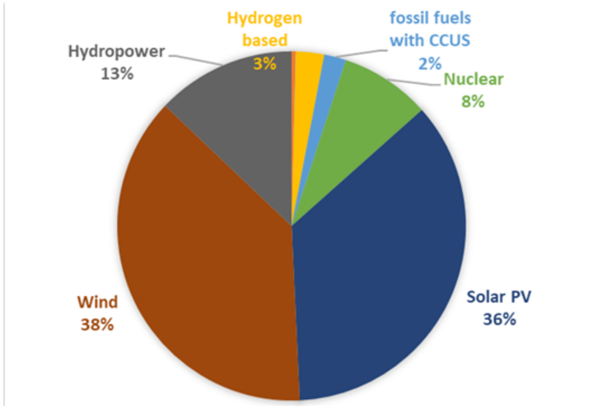
2020
~ 26,000 TWh

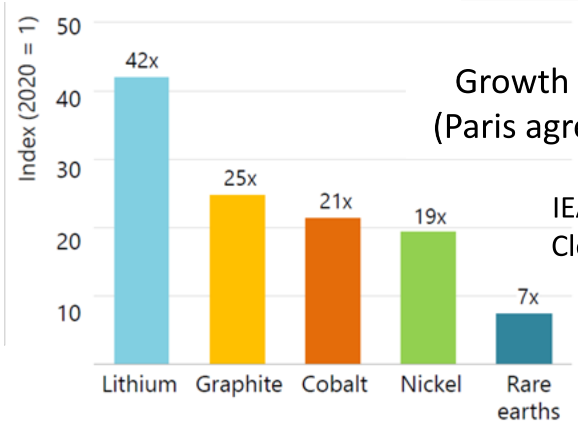


2030
~ 35,000 TWh



2050
~ 65,500 TWh





Growth relative to 2020
(Paris agreement scenario)

IEA, "The Role of Critical Minerals in Clean Energy Transitions", May 2021

<u>Batteries</u>:
160 GWh today to 6,600 GWh in 2030
→ ***equivalent of adding ~ 20 gigafactories each year for the next ten years***

SDS = Paris agreement (< 2 ° C), NZE = net-zero by 2050

Diverse technology solutions available to achieve clean air goals

R & D → TECH MATURITY & CONSUMER ACCEPTANCE → EXISTING INFRASTRUCTURE

Correct	Avoid	Shift	Improve
CO_2 capture	Telecommuting	Public transportation	Improved ICE efficiency
Synthetic or e-fuels	Geo-fencing	Rail & marine for goods	Hybridization
	Electrification	Ride-sharing	Improved aftertreatment systems
	Green H_2, NH_3, etc.	Renewable fuels	Light-weighting, aerodynamics etc.
	Recycling	Cycling	Predictive cruise control, platooning
			Waste heat recovery
			Particulates from tires

Thank you

Dr. Ameya Joshi
Corning Incorporated

For a copy of the slides:

joshia@corning.com https://www.linkedin.com/in/joshiav/