SAE INTERNATIONAL Mobility, Advanced™

Year in Review: Emissions, Fuels & Propulsion

SAE INTERNATIONAL Mobility, Advanced

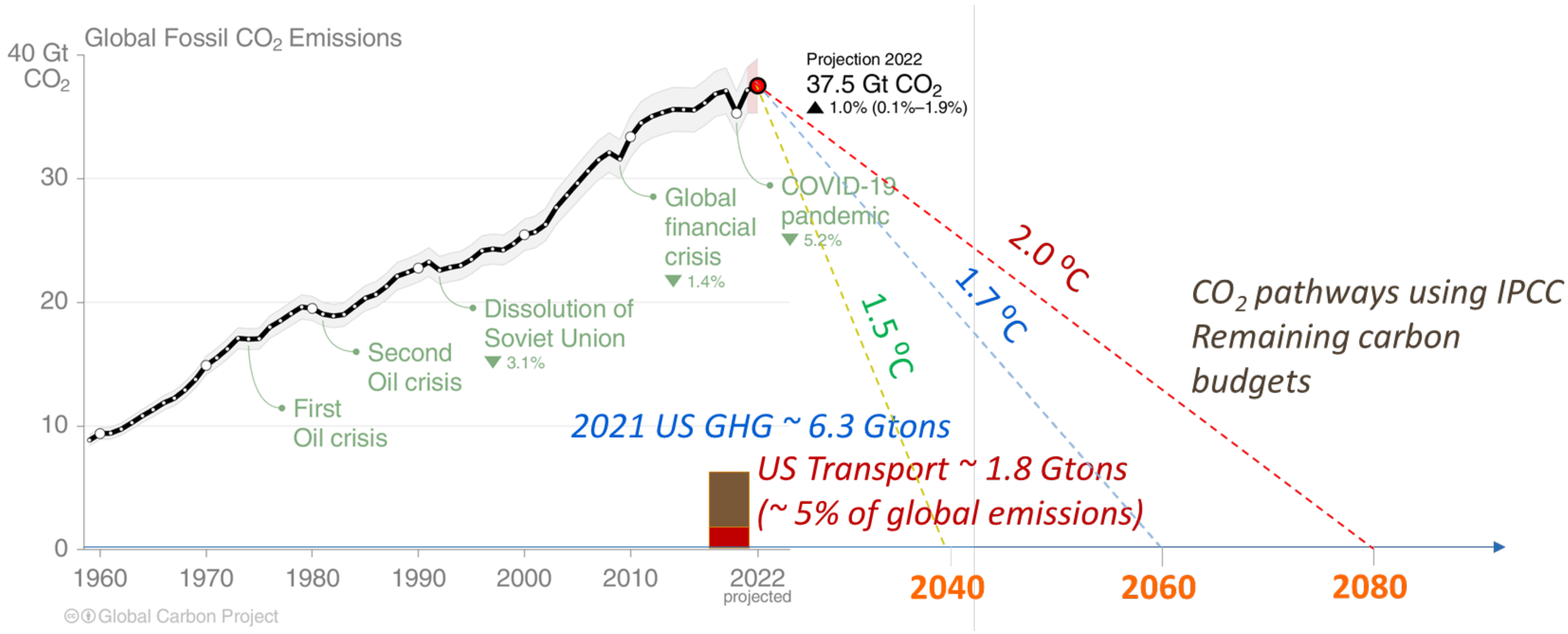
Year in Review Panel

Regulatory Overview

Dr. Ameya Joshi   ameya.joshi@clearflame.com

ClearFlame Engine Technologies

We are trying to reduce CO_2 in the atmosphere, not at the tailpipe – we will need all solutions to address the problem



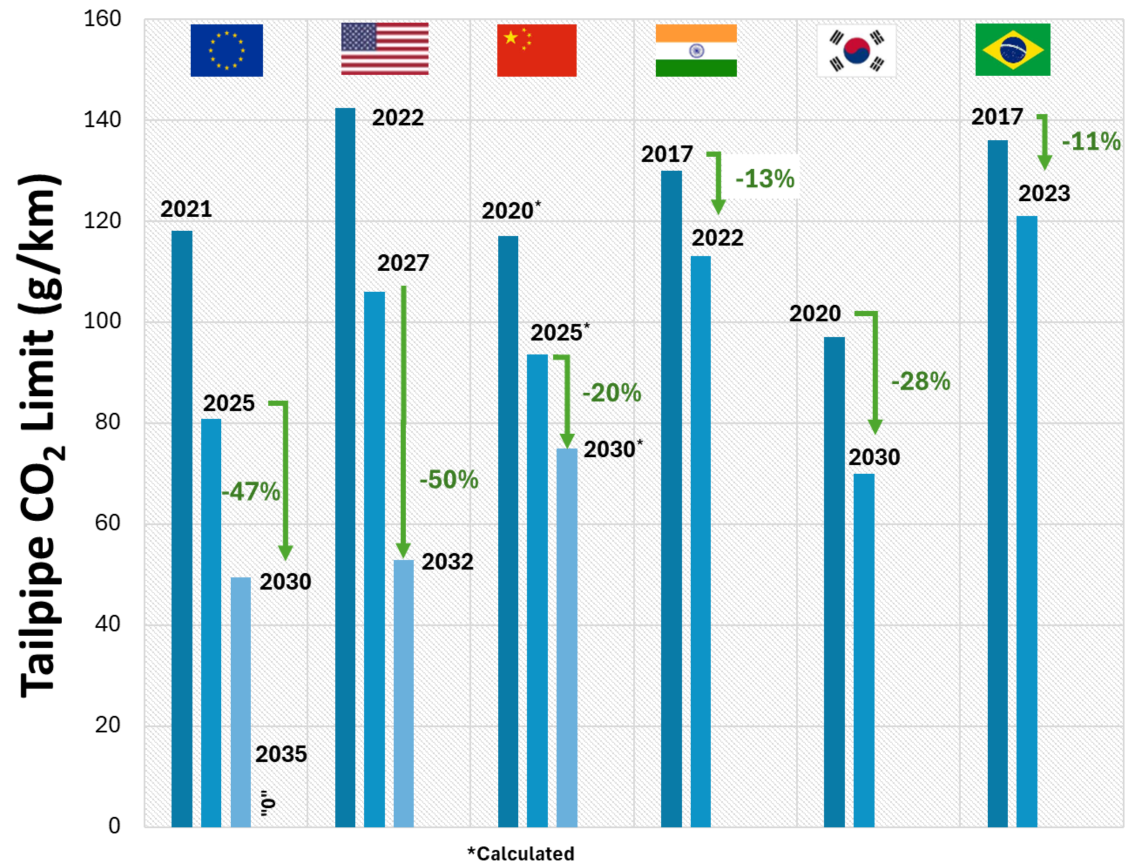
Global Carbon Project 2022

Emission Standards for Light- and Heavy-Duty Vehicles in 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)				
India	BS 6 Stage 1		BS 6 Stage 2 (w/ RDE)						BS 7 (~ Euro 7)			
Brazil	L6	PROCONVE L7			PROCONVE L8							

Heavy-Duty	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
US - CARB	US 2010			Low NOx MY 2024			Low NOx MY 2027 (~ aligned with EPA)					
US - EPA	US 2010, GHG Phase 2						Clean Trucks Plan, GHG Phase 3					
Europe	Euro VI-E							Euro VII *New All vehicles*				
China	China VIa		China VIb (w/ RDE)					China VII (~ Euro VII + EPA Low NOx)				
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)									

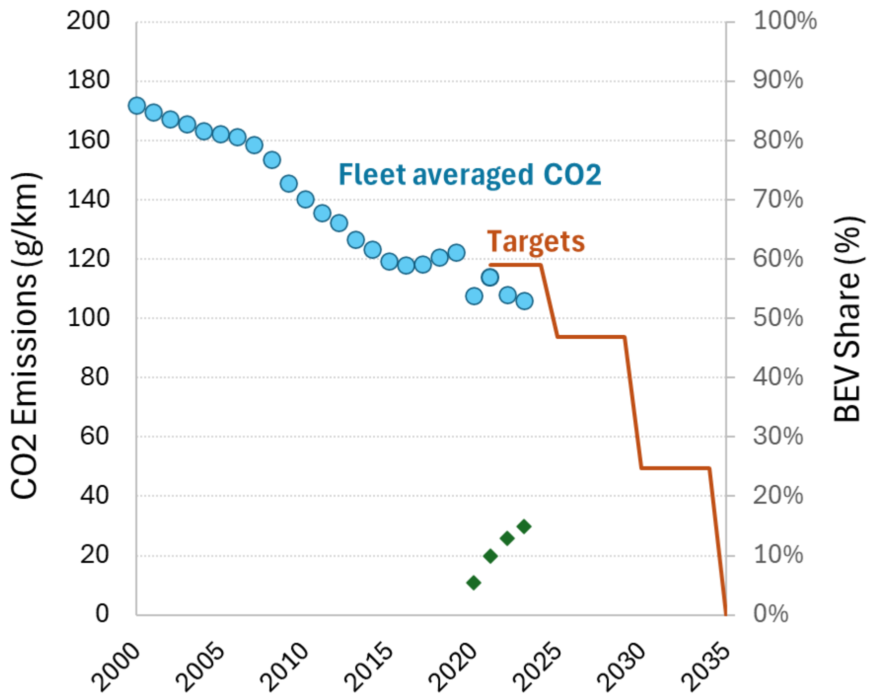
US & Europe: ~ 10% annual reduction in fuel consumption in next few years



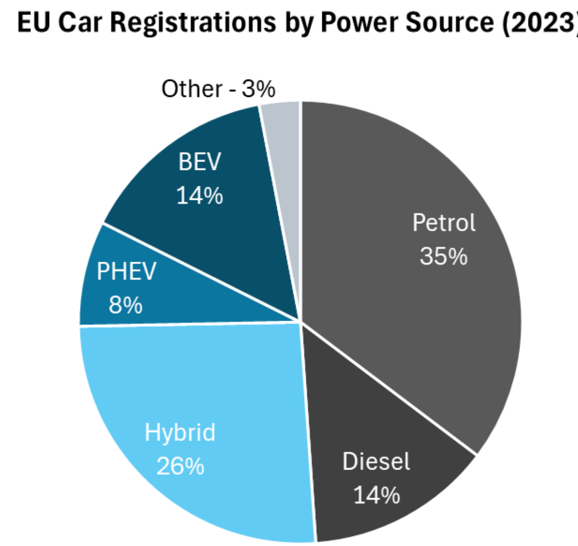
Europe is on track to meet 2025 CO_2 Targets
All forms of electrified powertrains are increasing market share

Europe is on-track to meet 2025 CO_2 targets

Most reductions in last few years are due to zero-tailpipe EVs



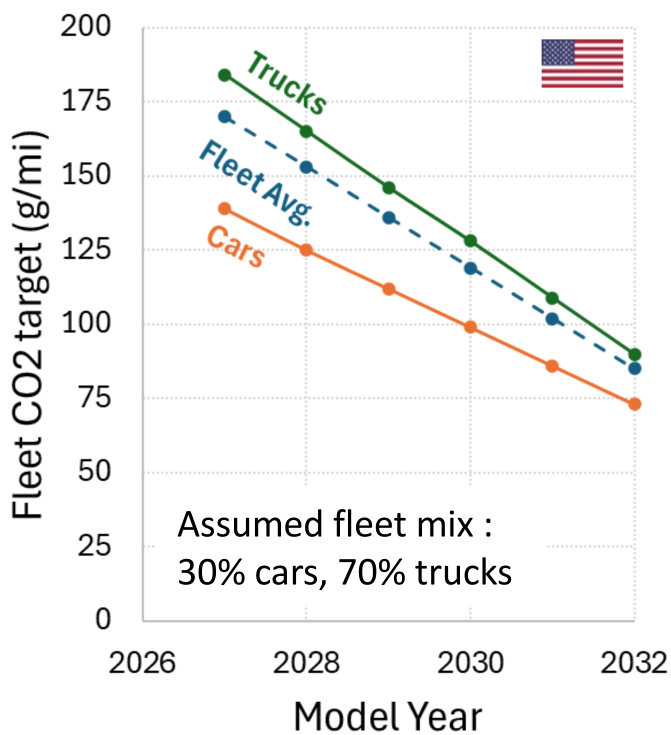
1/3rd new cars registered in 2023 were hybrids



Source: ACEA

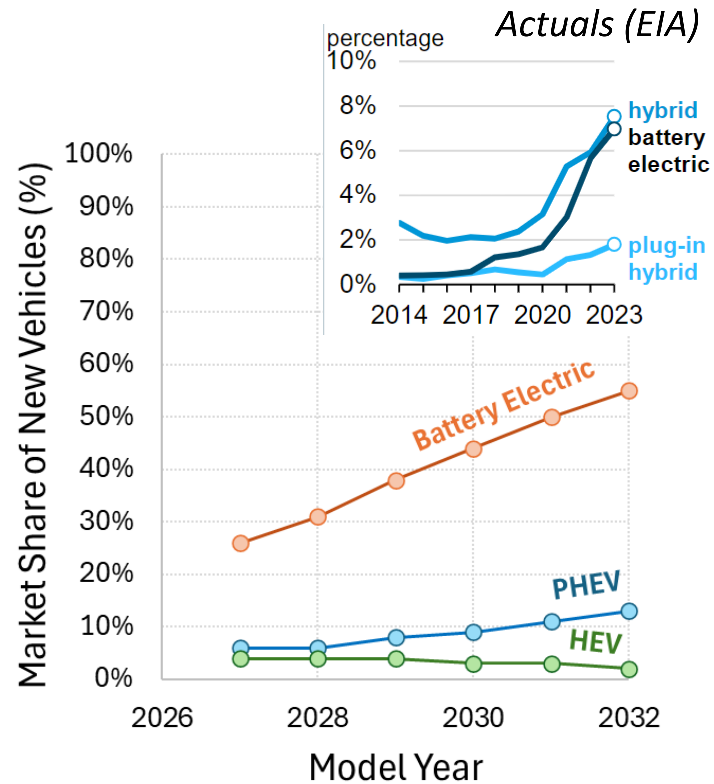
U.S. EPA Multi-pollutant Rule for MY 2027+ LD & MD Vehicles Greenhouse Gas Emissions

Fleet averaged
50% CO_2 ↓ from 2027 to 2032



- Technology neutral standards
- Actual CO2 targets for each OEM based on sales-weighted, footprint-based curves
- Various off-cycle and A/C refrigerant-based credits phased out (worth ~ 11 g/mi for 2030 for cars)
- Tier 3 fuel with 10% ethanol to be used for tests
- Utility factors for PHEVs adjusted (see previous slide)

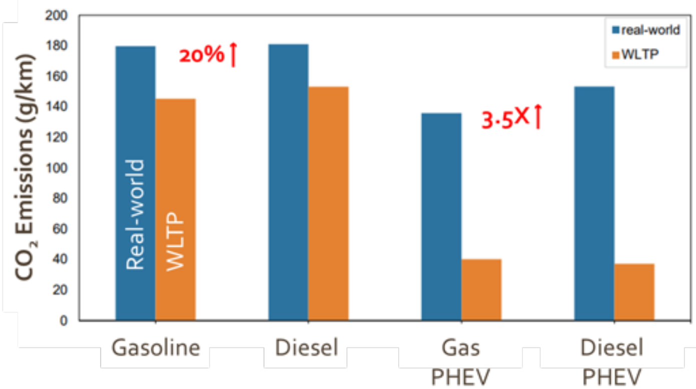
EPA estimated market share of electrified vehicles



Regulators are taking a harder look at real-world energy consumption CO_2 divergence seen for lab vs. on-road

CO_2 analysis of lab vs. on-road

EU Commission

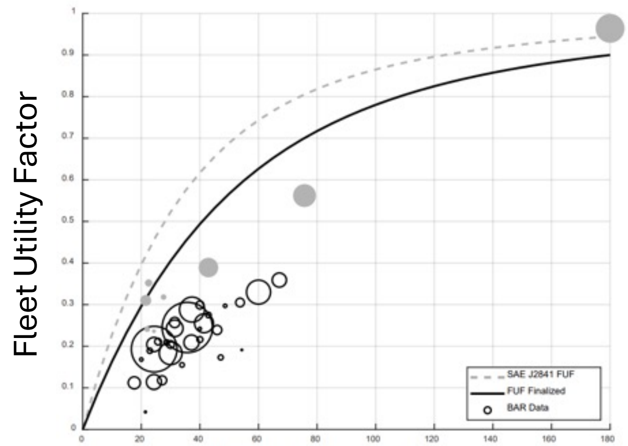


On-board fuel consumption monitoring (OBFCM) data from 617,194 cars

EU Comm. Real-world Fuel Cons. Rpt, March 2024

PHEV Utility Factors Revised

US EPA

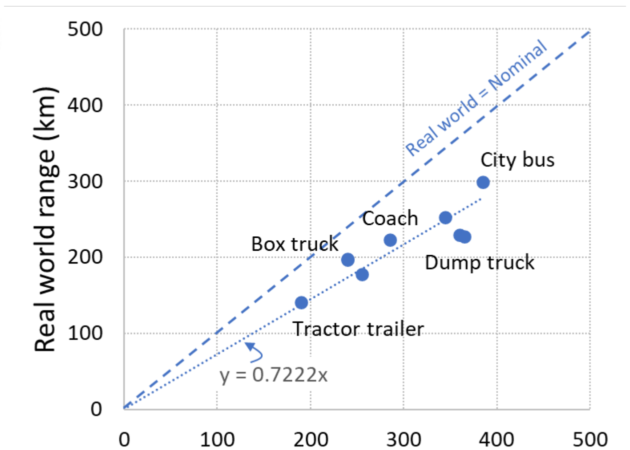


Charge Depleting Range (mi)

U.S. EPA Multi-Pollutant Emissions Standards for Model Years 2027 and Later LD and MDVs, March 2024

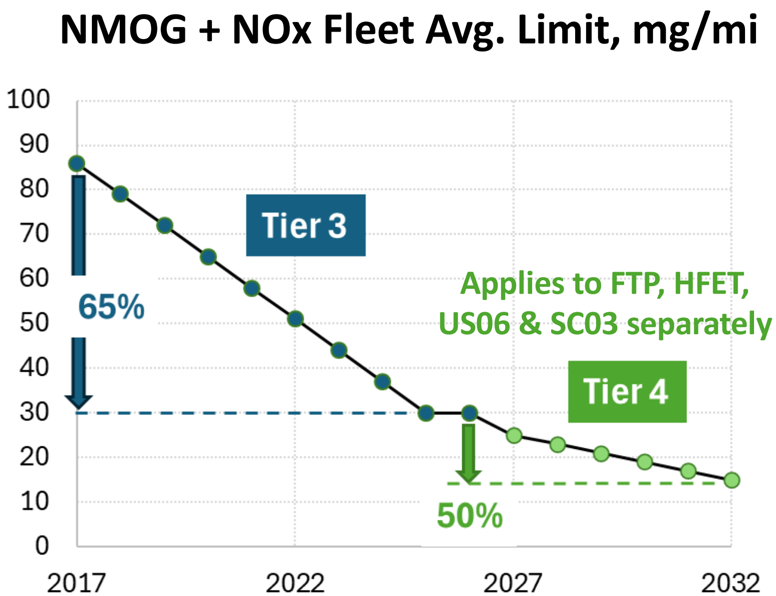
Real-world EV range of HDVs

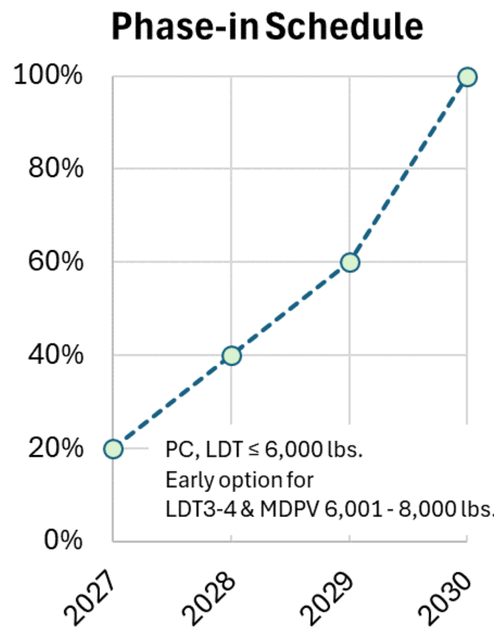
ICCT

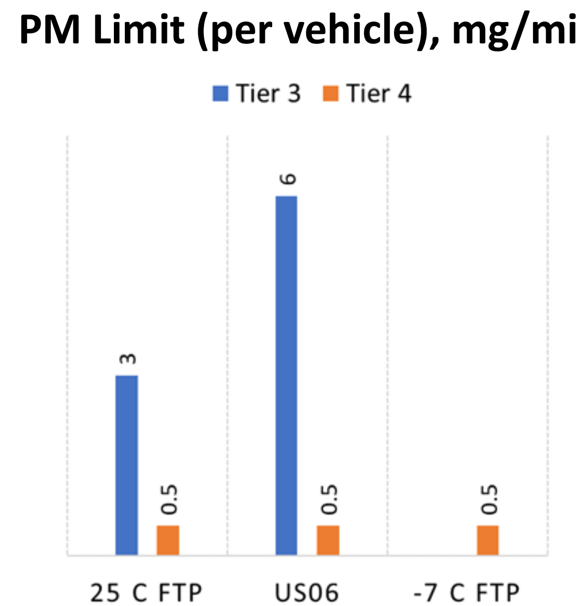


ICCT HDV China Real World Performance, April 2023

U.S. EPA Multi-pollutant Rule for MY 2027+ LD & MD Vehicles
Tier 4 Criteria Pollutant Standards







- Higher cert. bins removed, new lower ones introduced
- Default phase-in for 6,001 – 8,000 lb vehicles starts in 2030 (100%). OEMs can choose early phase-in and combine LDV, LDT1-2, LDT3-4, and MDPV as one fleet.
- Alignment with CARB ACC II provisions: early drive-off, PHEV high P cold start
- No standard for elimination of fuel enrichment in this rule

Euro 7: Light-Duty (M1, N1 vehicles)

M1, N1 Class I **Units - mg/km, #/km**	**Euro 6** PI / CI CF for RDE test	**Euro 7** PI / CI
NOx	60/80, CF = 1.1	60/80, CF = 1.1
PM	4.5	4.5
PN_{10} (#/km)	$PN_{23} = 6x10^{11}$ CF = 1.34	$PN_{10} = 6x10^{11}$ CF = 1.34
CO	1000 / 500	1000 / 500
THC	100 / -	100 / -
NMHC	68 / -	68 / -
THC + NOx	- / 170	- / 170
Evaporative g/test	-	1.5 (petrol only)
Brake PM (mg/km)	-	< Dec 2029: 3 for PEV, 7 for other powertrains > 2035 : 3 for all powertrains
Lifetime / Durability	160,000 km / 5 yrs.	160,000 km / 8 yrs. - Extended: 200,000 km / 10 yrs, Limits x 1.2 for gas emissions Batteries: Energy capacity should be > 80% at 5 yrs / 100,000 km, 72% at 8 yrs / 160,000 km

Timing

30 months after final regulation for new types, 42 months for all vehicles

Tailpipe Standards

Same WLTP limits in Euro 7 as in Euro 6

Conformity factors for RDE tests

PN limits for all vehicles (not DI only)

PN cut-off lowered to 10 nm

Durability

Extended for emission compliance

New durability requirements for batteries

Non-tailpipe emission standards

Tire abrasion test procedures and limits being developed at UNECE

ClearFlame ethanol-powered engines at work

Euro 7: Heavy-Duty (M2, M3, N2, N3 vehicles)

mg/kWh, #/kWh	Euro VI WHSC (CI) WHTC (CI & PI)	Euro VI RDE	Euro 7 WHSC (CI) WHTC (CI & PI)	Euro 7 RDE
NOx	400 / 460	690	200	260
PM	10	-	8	-
PN (#/km)	$PN_{23} = 8x10^{11}$ $PN_{23} = 6x10^{11}$	$PN_{23} = 9.8x10^{11}$	$PN_{10} = 6x10^{11}$	$PN_{10} = 9x10^{11}$
CO	1500 / 4000	6000	1500	1950
NMOG	- / 160*	240	80	105
THC	130 / 160**	-	-	-
NH_3	-	-	60	85 *New*
CH_4	- / 500*	750	500	650
N_2O	-	-	200	260 *New*
Brake PM	-		None till 2029, > 2030 TBD, test TBD	
Lifetime / Durability	M2: 100,000 km / 5 yrs. N2, N3<16 t, M3<7.5 t: 300,000 km / 6 yrs. N3>16 t, M3>7.5 t : 700,000 km / 7 yrs.		160,000 km / 8 yrs. Ext: 200,000 km / 10 yrs. 300,000 km / 8 yrs. Ext: 375,000 km / 10 yrs. 700,000 km / 12 yrs. Ext.: 875,000 km / 15 yrs	

Timing

48 months after final regulation for new types ,
> 60 months for all vehicles

Tailpipe Standards

WHSC = WHTC
No CF for RDE
PN cut-off reduced to 10 nm
THC replaced by NMOG & CH_4
Power threshold for MAW window cut-off changed from 10% to 6% (more low load operation included)

Durability: Extended
No battery requirements yet

Non-tailpipe standards

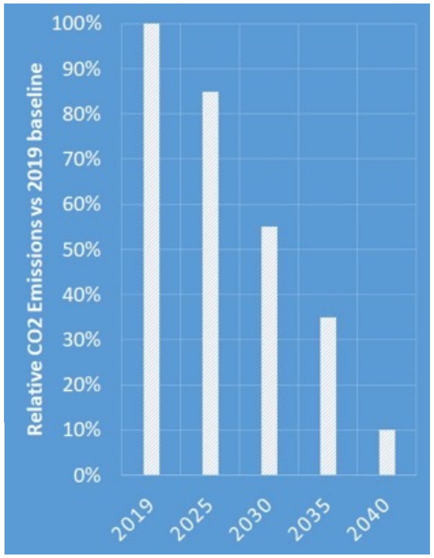
Brake PM limits tbd > 2030

*Gas engines only
** Diesel only

European revised CO_2 standards

Fleet averaged targets:

- 15% CO_2 reductions from 2025
- 45% from 2030
- 65% from 2035
- 90% from 2040

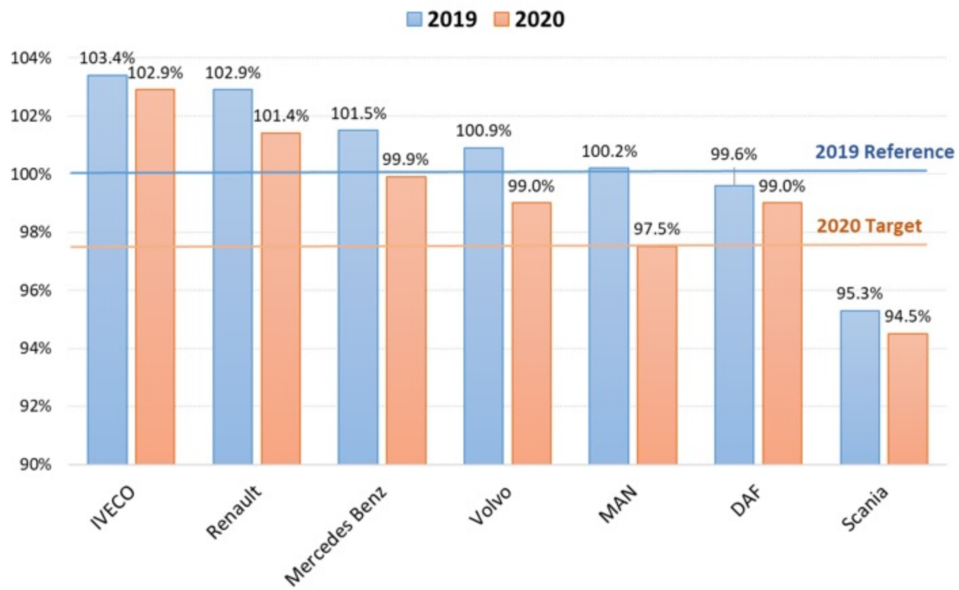


Penalty
€4,250 per vehicle per gCO_2/t.km exceeded

Zero-emitting vehicles
ZEV defined as a vehicle with "< 5 g/(t·km) of CO_2 emissions"

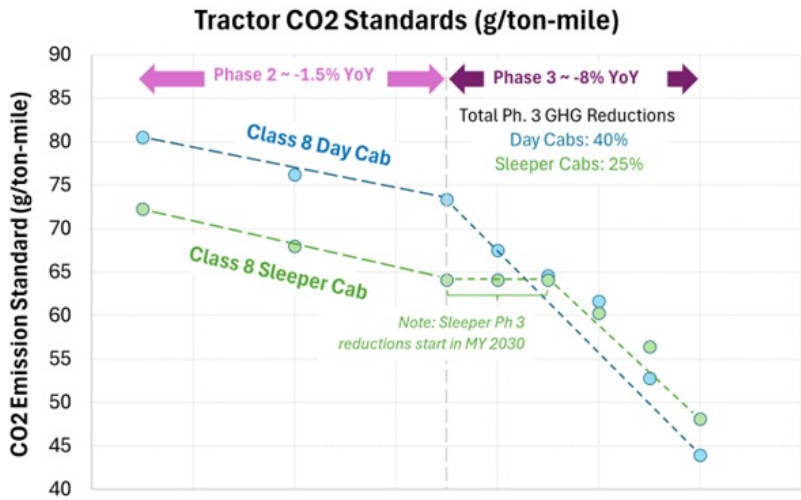
New city buses to be zero-emission by 2030

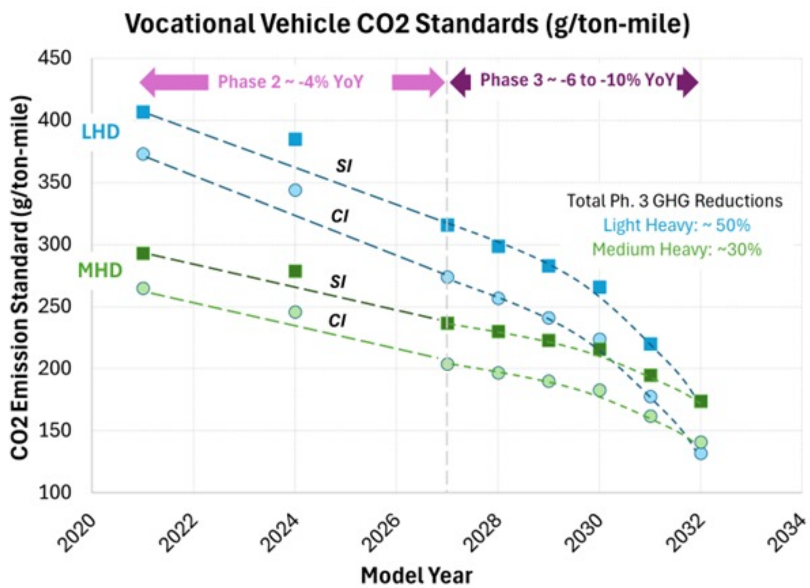
CO_2 emissions reduced by 1% from 2019 to 2020 vs. required 2.5% per year to meet 2025 target

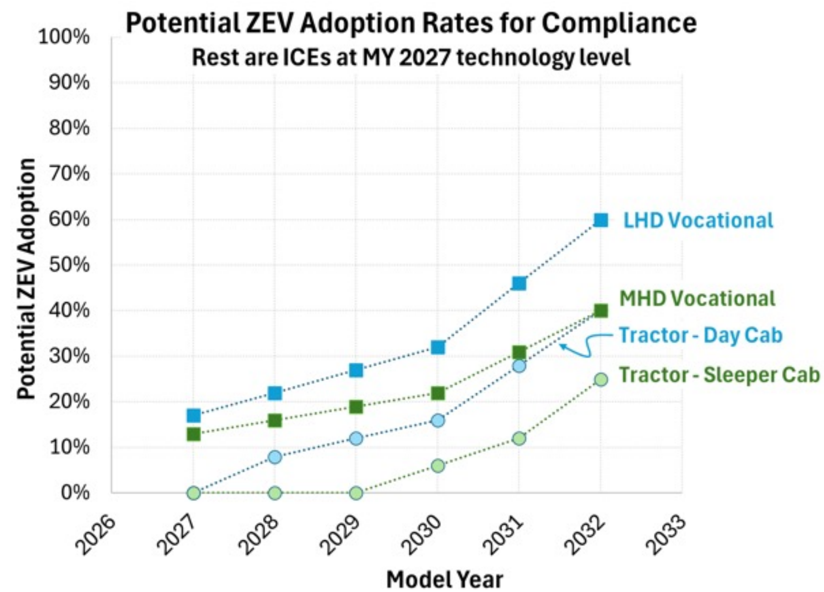


At rate of 1% reduction each year, OEMs will require:
~ €20K per truck in fines in 2025 !

U.S. EPA HD GHG Phase 3 Rule







- Technology neutral standards
- CO_2 reductions at accelerated pace compared to Ph 2
  - 8% YoY for tractors, 6-10% YoY for vocational
- Projected ZEV share by 2032:
  - 25 – 40% for tractors, 60% for LHD vocational
- H2-ICE default CO2 emission value = 3 g/hp-hr
- Vehicles with H2-ICE and neat H2, CO_2 = 0

U.S. EPA nationwide MY 2027+ HD Low NOx Standards
CARB is now aligned with EPA following deal with EMA

- Starting MY 2027, NOx reduction of 82.5% on FTP & RMC lab transient test cycles
- New low load cycle with tighter-than-CARB limits for full useful life

CI Standards Units: mg/hp-hr	NOx		HC		PM		CO	
	Current	MY2027+	Current	MY2027+	Current	MY2027	Current	MY2027+
SET & FTP*	200	35	140	60	10	5	15,500	6,000
LLC	-	50	-	140	-	5	-	6,000

*FTP 1/7 cold and 6/7 hot weighting factors kept unchanged

- PEMS-based off-cycle emissions analyzed using moving average window method

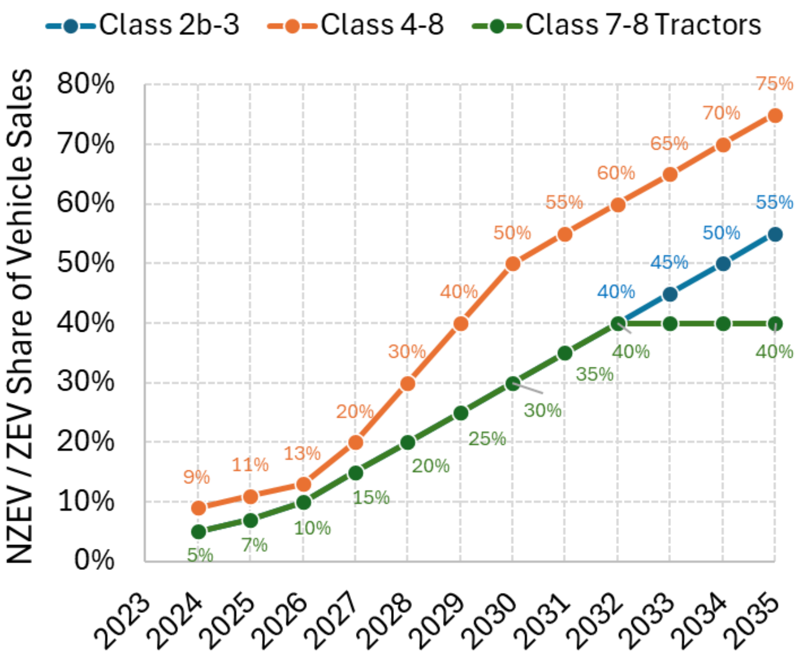
Off-cycle limits, 2-Bin MAW*	NOx	HC	PM	CO
Bin 1**: Idle, low load (g/hr)	10	-	-	-
Bin 2**: Higher power (mg/hp-hr)	58	120	7.5	9,000

*MAWs of 300 sec interval, continuous engine operation. No prescribed routes.
** Normalized average CO_2 : Bin 1: ≤ 6%, Bin 2 > 6%

- NOx compliance allowance of 15 mg/hp-hr for in-use testing for duty cycles and for off-cycle Bin 2
- No NOx or PM emission credits for zero-emitting vehicles (ZEVs)

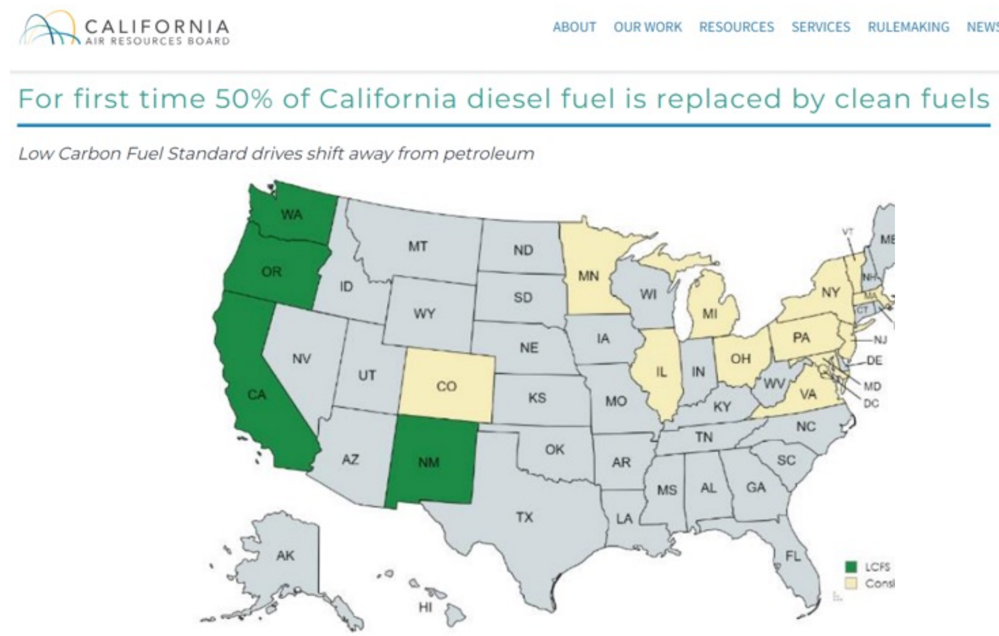
More states are adopting alternative fuel mandates

Advanced Clean Trucks



- 11 states have adopted ACT
- CA, CO, MA, MD, NJ, NM, NY, OR, RI, VT, WA
- Represent ~ 26.3% of all U.S. HD vehicle registrations

Low carbon fuel standards



- New Mexico became the fourth state to enact a Clean Transportation Fuels Standard
- Requires reduction of carbon intensity of transport fuels used in the state by 20% by 2030 & 30% by 2040

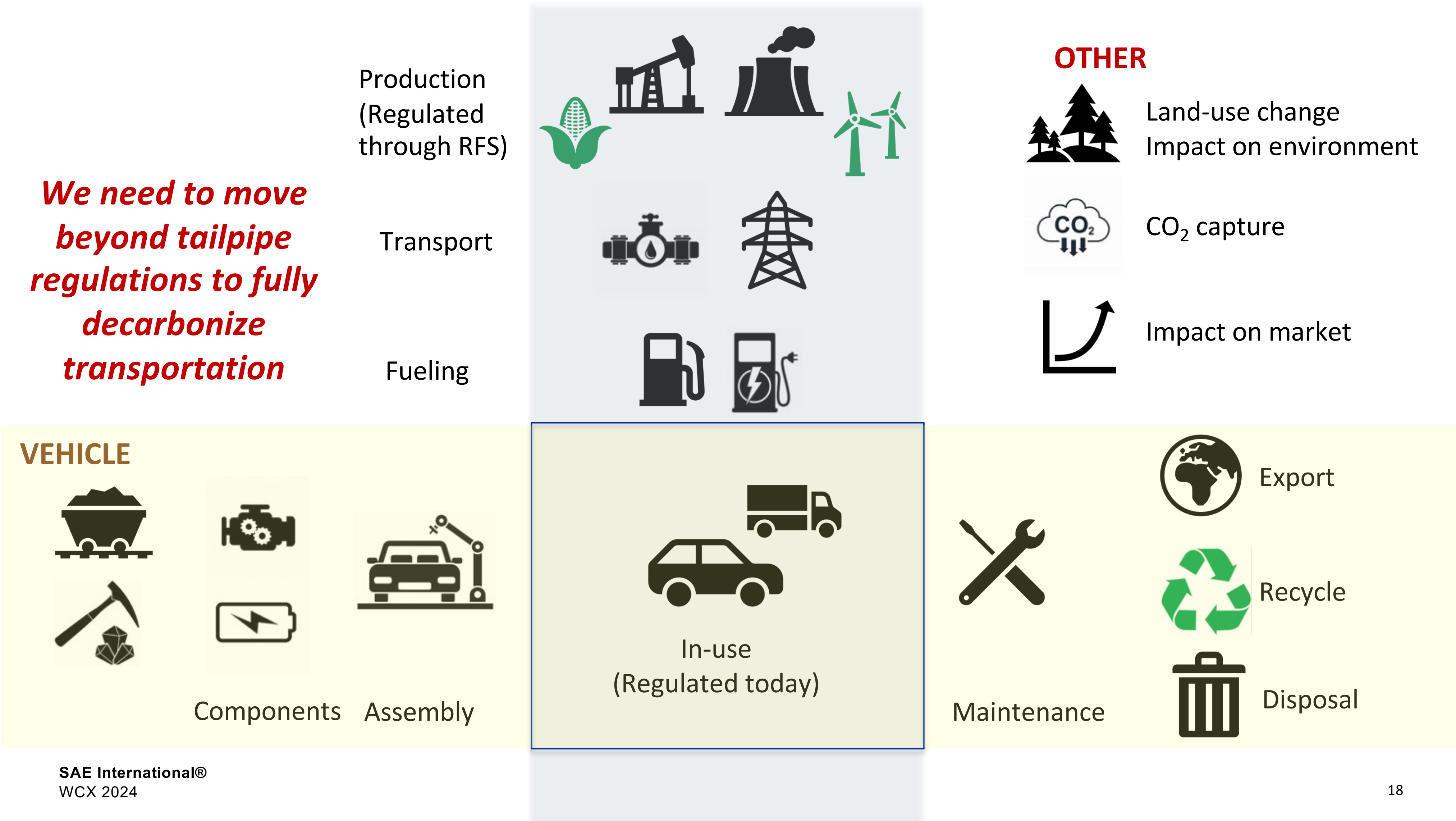
Non-road : CARB Tier 5 proposal
90% reduction in NOx and 75% reduction in PM for 56 – 560 kW engines

Tier 4 Final and Proposed CARB Tier 5

Limits apply to NRTC and Steady -State/RMC. All values in g/kWh.

Engine Rating, kW	Engine Rating, hp	Application	CO		NMHC		NOx			NOx + NMHC		PM		
			Tier 4f	Tier 5f	Tier 4f	Tier 5f	Tier 4f	Tier 5i	Tier 5f	Tier 4f	Tier 5f	Tier 4f	Tier 5i	Tier 5f
0 – 8	0 – 11	All	8.0	8.0	-	-	-	6.0	5.0	7.5	-	0.4	0.3	0.2
8 – 19	11 – 25	All	6.6	6.6	-	-	-	5.5	4.0	7.5	-	0.4	0.2	0.1
19 – 56	25 – 75	All	5.0	5.0	-	0.19	-	3.7	2.5	4.7	-	0.03	0.015	0.008
56 – 130	75 – 750	All	5.0	5.0	0.19	0.08 LLC = 0.19	0.4	0.22	0.04 LLC = 0.06	-	-	0.02	0.005 Same for LLC	
130 – 560		All	3.5	3.5	0.19	0.08 LLC = 0.19	0.4	0.22	0.04 LLC = 0.06	-	-	0.02	0.005 Same for LLC	
> 560	> 750	Gen Sets	3.5	3.5	0.19	0.08	0.67	0.50	0.35	-	-	0.03	0.015	0.008
		Mobile Machines	3.5	3.5	0.19	0.19	3.5	3.50	3.00	-	-	0.04	0.04	

We need to move beyond tailpipe regulations to fully decarbonize transportation



Contact Info

Dr. Ameya Joshi
ClearFlame Engine Technologies
ameya.joshi@clearflame.com

SAE INTERNATIONAL Mobility, Advanced™

Year-in-Review on Emissions, Fuels, and Propulsion

Engines for Heavy-Duty and Off-Road Applications

Sandia National Laboratories

Key Takeaways From the Energy Outlooks

Projections see **diesel** demand worldwide increasing by ~15% by 2050

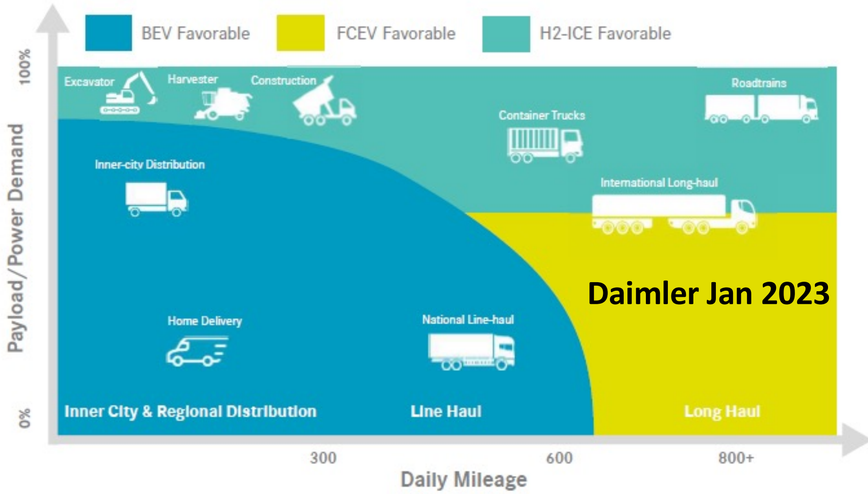
Biofuels are projected to reach up to 10% of petroleum diesel usage

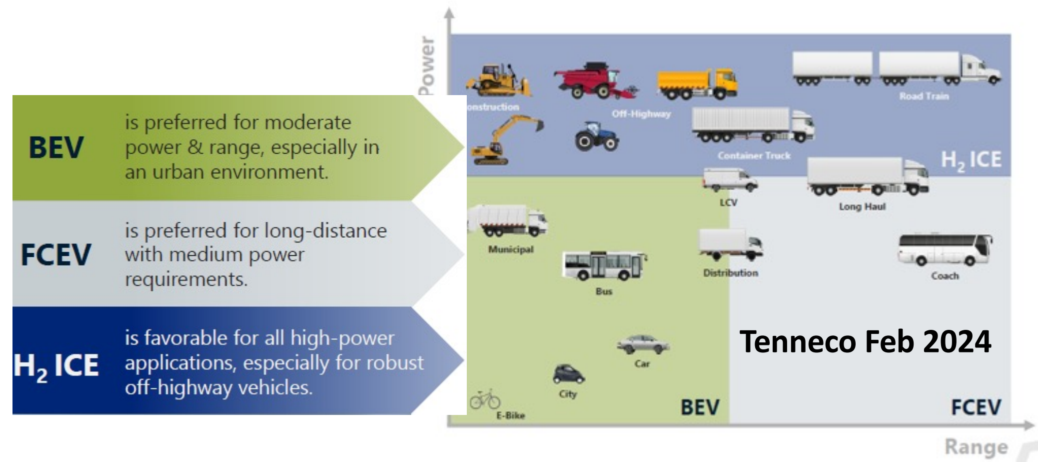
Natural gas in transportation expected to grow by >50%, reaching 7-14% of diesel

H_2 is projected to be of the same magnitude as biofuels & NG, but projections are increasing rapidly

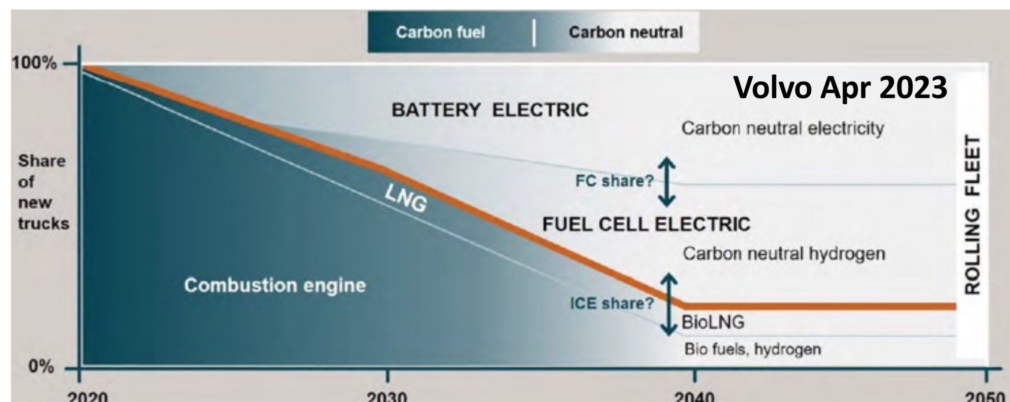
Each of these alternative fuels will see growth rates exceeding diesel, but diesel will continue to dominate the market

Industry visions of the Future HD Transport Technology Mix





- ICEs are a favored technology for long-distance, high power, and extreme ambient environments
- Their power density, fuel energy density, and robustness all point to their continued use in the long-term



Petroleum-Based and Near Drop-In Fuels for CI Engines

Diesel Engine Developments – New Engine Introductions

- Cummins HELM™ X15D
- Up to 605 hp and 2,050 ft-lb
- EPA 2027 and CARB compliant
- Biodiesel to 20%, 100% renewable
- 48V alternator and AT heater solution

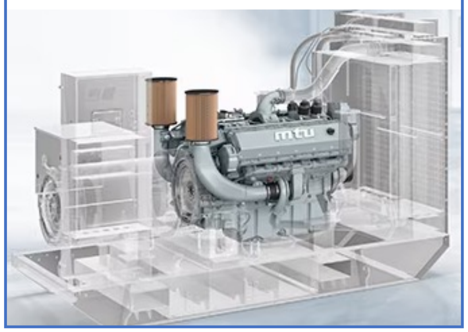
- Volvo D17 Euro 6 for heavy transport
- 780 hp and 3,800 Nm
- Biodiesel to 20%, 100% renewable
- 100% biodiesel for 700hp rating
- Wave piston

- Caterpillar 13D (also Perkins 2600)
- Up to 690 hp & 3,200 Nm
- EU Stage V, U.S. EPA Tier 4 Final, Korea Stage V, Japan 2014, China NRIV
- 100% HVO and up to 100% standard biodiesel for high hp

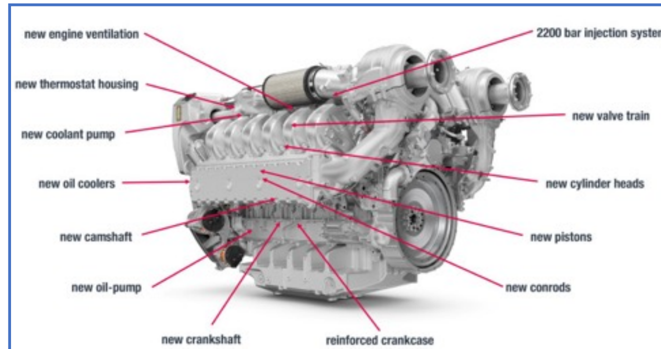
Marine & Stationary Power Diesel Engine Developments

Rolls-Royce mtu Series 1600 engines for stationary power:

- Increased power density
- New TC and FIE
- Renewable diesel



- OXE Marine and Dumarey Automotive Italia collaboration to develop 2.0L diesel outboard
- Scania and MAN expand range of IMO Tier III engines (added SCR AT)
- Perkins 2806J-E18TAG1 ElectropaK –
  - up to B20 or 100% HVO (renewable diesel)
- China Shipbuilding Power Engineering Institute developed new V8, V12, V16 and V20 high-speed H175 engines
- New modular medium-speed EVOLVE family from Anglo Belgian Corporation
- X-S mid-bore 2-strokes from WinGD targets new ship builds by allowing better vessel hydrodynamics (also plans DF version)
- New offerings from Shanghai Marine Diesel Engine Research Institute (SMDERI)



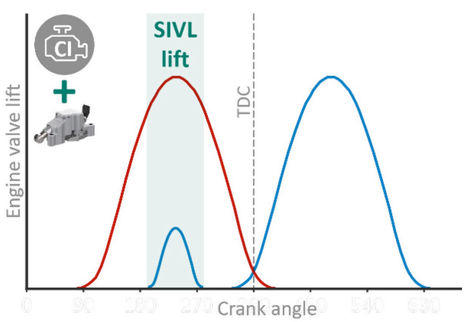
- MAN 1.2 MW D3872 – completely new design
- EPA Tier 4, IMO Tier III
- Approved for HVO

HD Diesel Technology Advances

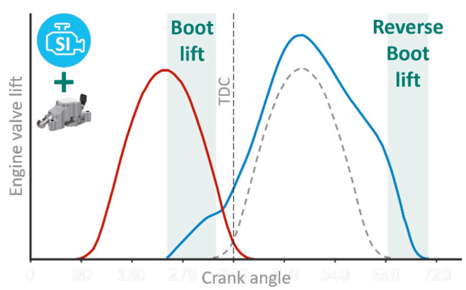
Continuously variable valve timing and lift (CVVL) system

- Fine control of both air charge and EGR rate allowing:
  - Low-load AT temperature management
  - Miller/Atkinson cycle operation
  - Improved transient operation (cycle-by-cycle EGR and A/F control)

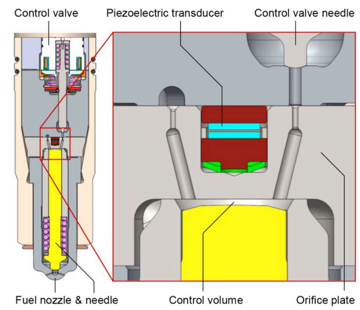
Vienna 2023-43



Secondary intake valve lift for CI EGR control



High overlap SI EGR control

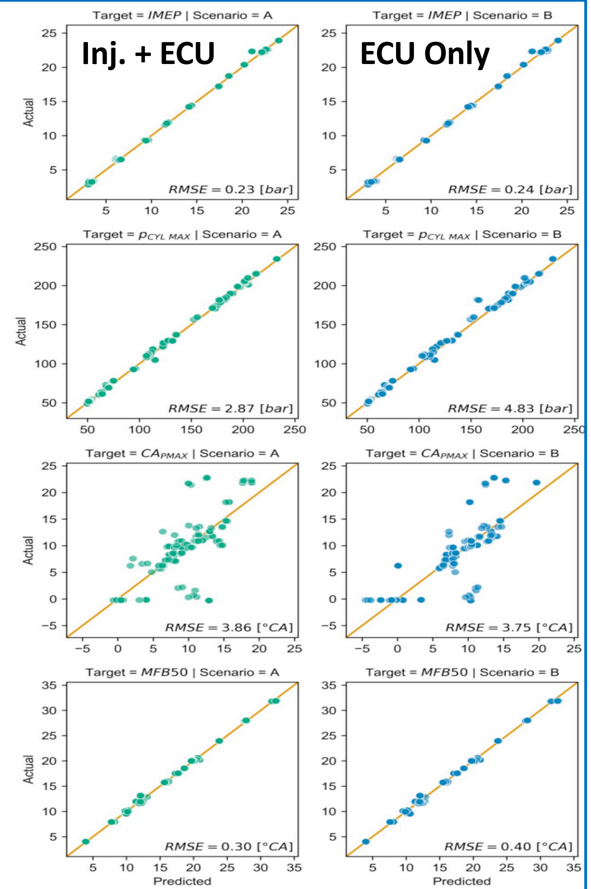


AI/ML applied to engine control

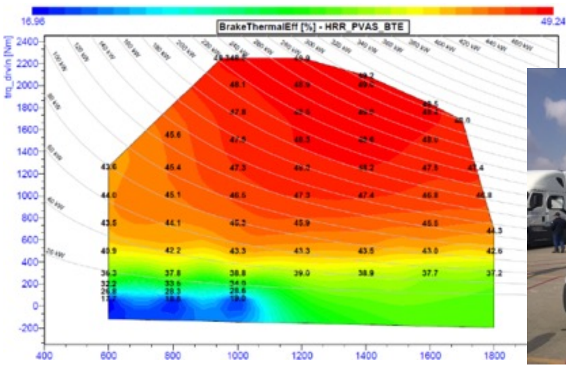
- Intelligent injector with piezo sensor for monitoring IMEP, P_{max}, & B50
- Injector data im-proves prediction over ECU alone

SAE 2023-01-0291

Also see ICEF2023-110524



Advanced Compression Ignition Powertrain Technologies

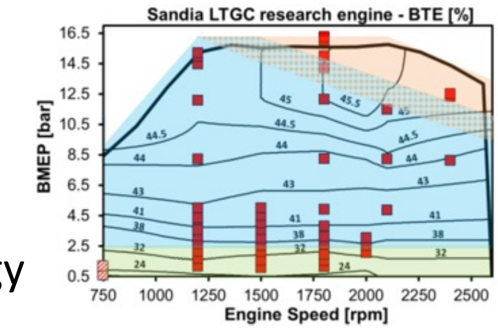


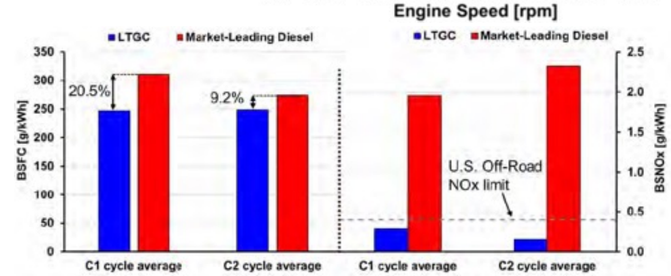
- Walmart fleet tests of 300 kW 10.6L OP
- Large simultaneous reductions in fuel consumption and NO_x
  - 10%+ fuel reduction over best-in-class reference engine (no system optimization)
  - Meets 20 & 35 mg NOx CARB/EPA emissions on all cycles using a conventional AT system

https://achatespower.com/wp-content/uploads/2024/02/Heavy-Duty-Diesel-Engine-Performance-and-Emissions-Summary-UPDATED-1.pdf

Gasoline Compression Ignition

- Additive-mixing injector concept allows kinetically controlled operation across entire load speed map
- Extremely low engine-out emissions
  - PM < 10 mg/kWh
  - NOx < US Tier 4 over ISO 8178 C1/C2
- MCE testing under-way in DOE technology commercial-ization project



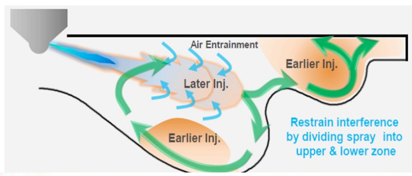


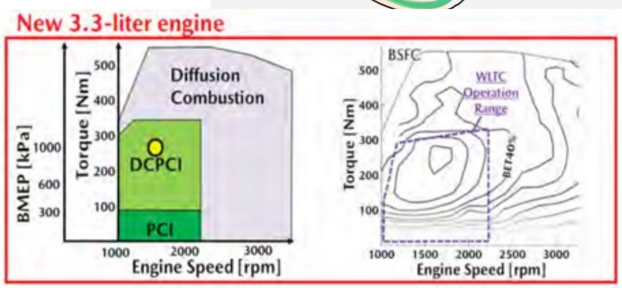
2023 Vienna Motor Symp. Paper #2023-59

Diesel Engine R&D Trends — General Emphasis on Improving Mixing

Vienna Motor Symp. Paper 2023-41; JSAE 20239193

Next generation SkyActivD 3.3L I6



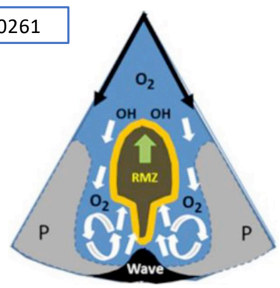


- Adapted previous PCI strategy to split injections
- "Distribution Controlled Partially Premixed Compression Ignition" (DCPCI) provides more CV combustion and reduces heat losses

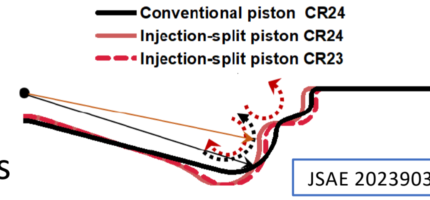
SAE 2023-01-0261

Toward fuel tolerant combustion systems–

Fuel density impacts size of radial mixing zone in Wave piston bowl

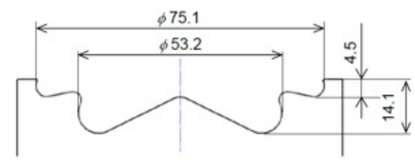


Similar "split-injection" piston investigations



JSAE 20239031

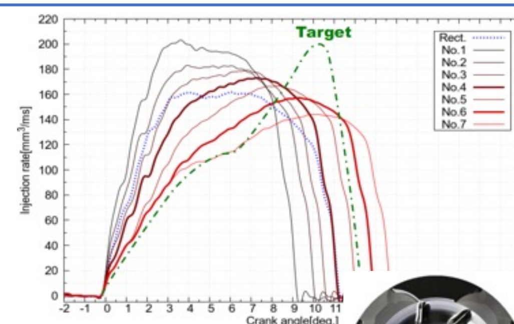
- Focused on high CR engines
- Improve η with high injector flow & improved mixing
- Focused on soot reduction & synergies with low CN fuels



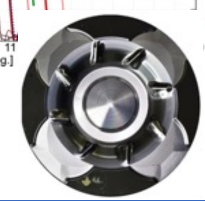
JSAE 20239063

JSAE 20239259

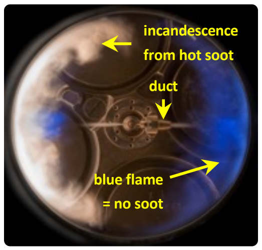
Achieving Sabathe-Seiliger cycle with "high heels" injection rate profile

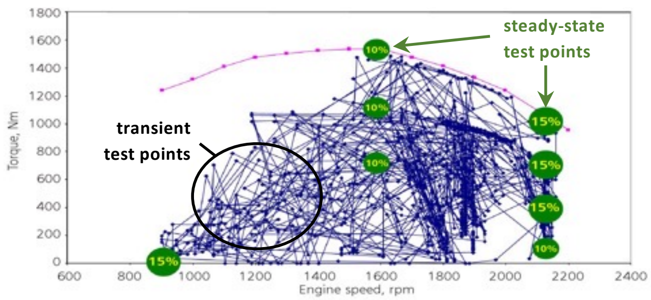


- Unique variable P_{inj} FIE, bowl shapes, tangential injection nozzles



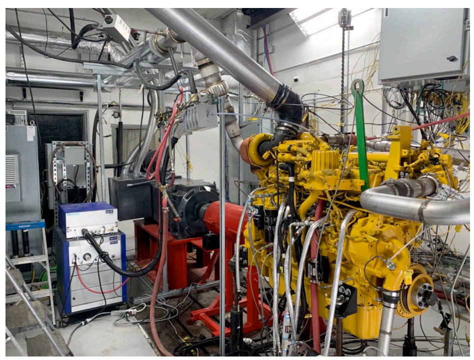
Diesel Engine R&D Trends — General Emphasis on Improving Mixing





Ducted Fuel Injection

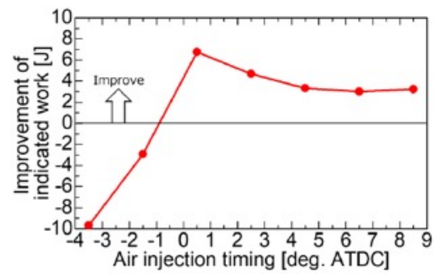
- Demonstrated potential for full-load operation
- Quantified emission reduction potential with low life-cycle CO_2 fuels https://doi.org/10.4271/03-17-01-0001
- Moved to steady-state multi-cylinder demonstration phase

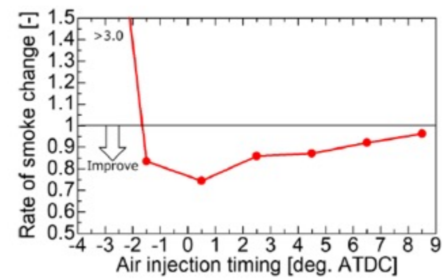


JSAE 20239183

Air injection improves combustion rate, indicated work, & emissions

- Benefits counteracted by increased heat transfer





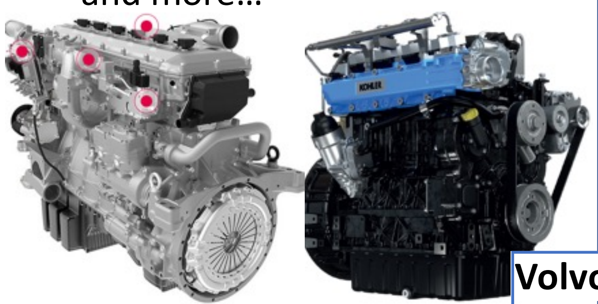
Hydrogen Internal Combustion Engines

H2ICE

H2ICE Introductions and Advanced Demonstrators

Multiple engine introductions at 2023 Agritechnica tradeshow:
- ○ Kohler KDH – 55 kW EU Stage V LPDI w/ no AT
- ○ MAN H4576 16.8L – 368 kW LPDI (40 bar) Euro VII w/ AT

and more…



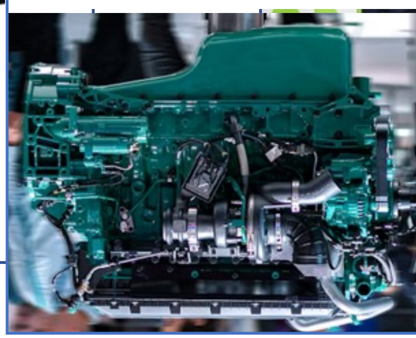
- ○ Deutz ready for volume production with TCG 7.8L
  - ▪ Volume contract with Mahle
  - ▪ 100 pc. GenSet order

Westport HPDI demos

Mercedes-Benz Unimog 430 prototype

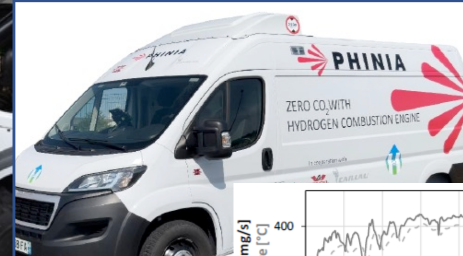
Dumarey Automotive Italia 6.6L Genset; in production March 2025

Volvo Penta 8L dual fuel

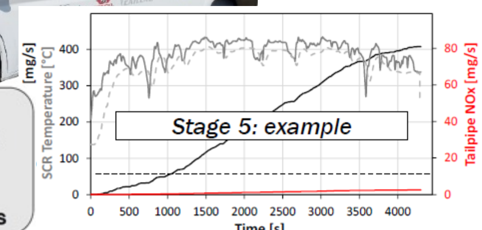


JCB launches numerous demonstrators

Phinia H2ICE Endurance Roadtrip

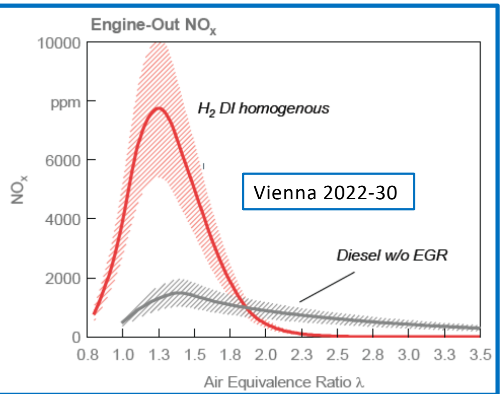


Fully Loaded
Cold Temperatures
12 hours
1000 km
Negligible Emissions

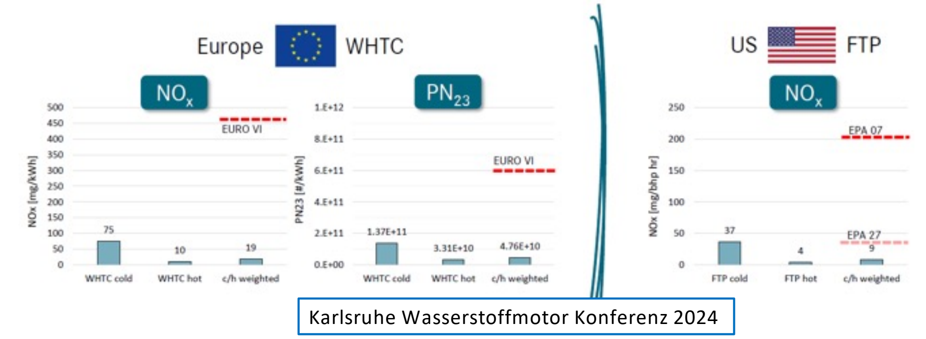


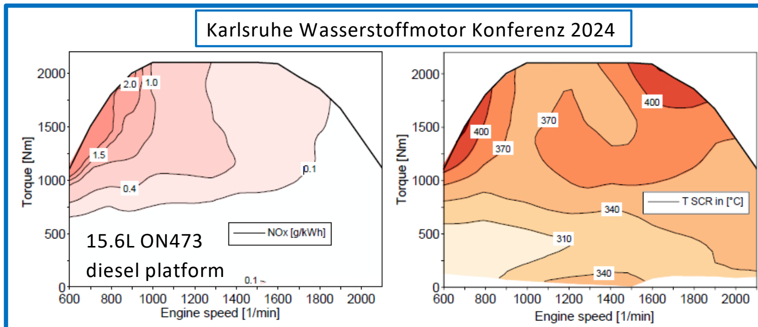
H2ICE – Full Engine Progress in Premixed PFI/LPDI Combustion Systems

H2 flame temperature can lead to high NOx – and a trade-off with power density

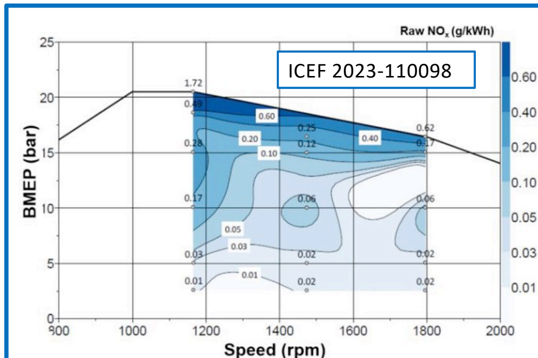


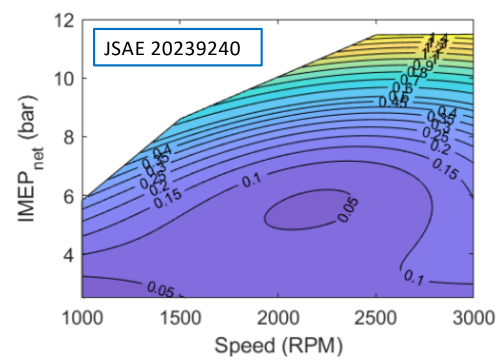
Very low tailpipe emissions with non-optimized ATS





- Peak raw NOx emissions are 5–10 times less than diesel
- EGT for H2ICEs is favorable at low load





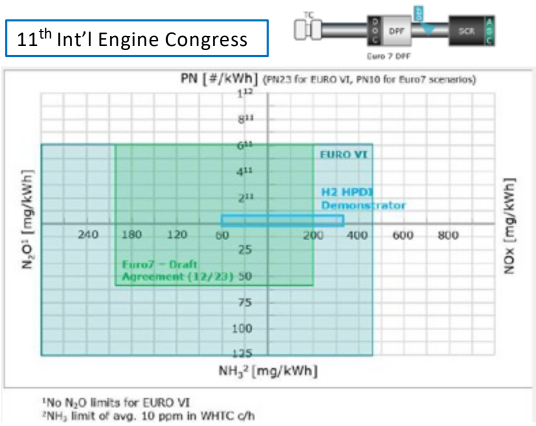
- See also: Vienna papers 2023-37 and 2023-38 showing EO NOx ~ 0.20 g/kWh at 21 and 16 bar load, respectively

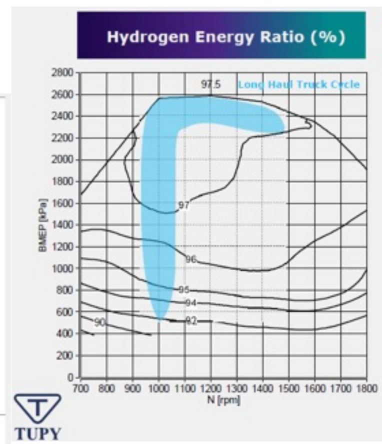
H2ICE – Full Engine Progress in HPDI Combustion Systems

Hydrogen energy ratio maps point to 1 g CO_2e/km-ton potential

- Demonstrated 50.5% BTE is 2.9% higher than baseline diesel

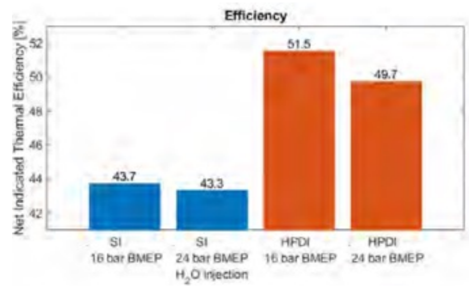
11th Int'l Engine Congress

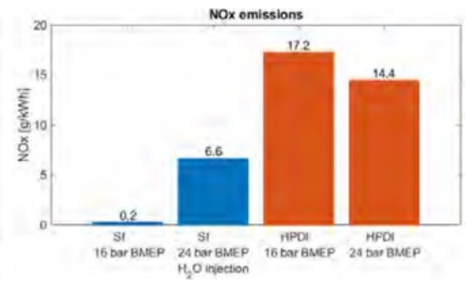




HPDI combustion systems show 7-8% pt improvement in efficiency over PFI – at the expense of higher NOx

Vienna 2023-38

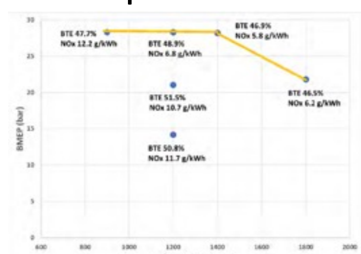


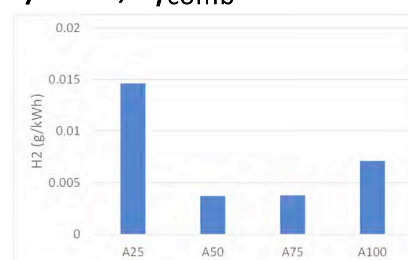


Efficiency and engine-out NOx numbers are consistent across multiple studies

Vienna 2023-39

- H2 slip is also extremely low; η_{comb} > 99.99%



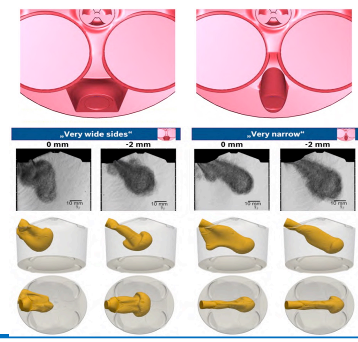


H2ICE – Premixed LPDI or PFI Fundamental R&D

H_2 jet development strongly influenced by injector pocket geometry

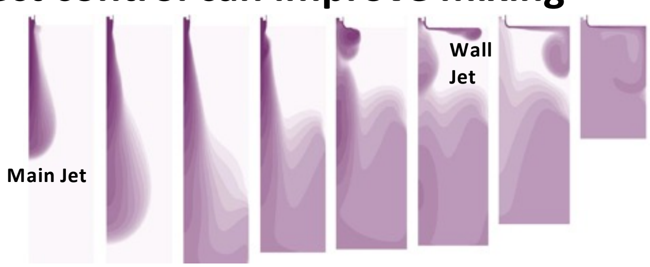
Vienna 2023-35

- Both the width and the injector recess within the pocket impact the jet spreading and penetration
- Narrow jets that concentrate momentum are more effective for enhancing mixing and combustion rate



Coandă effect control can improve mixing

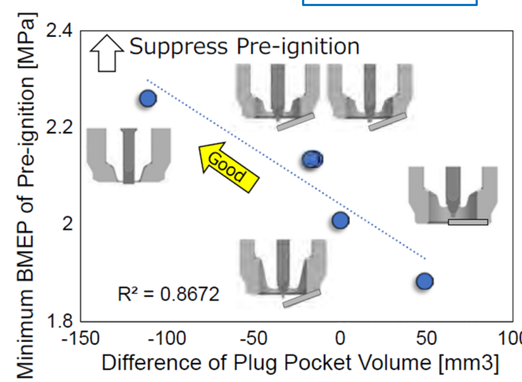
11th Int’l Engine Congress



Spark plug crevice volume shown to be an important source of pre-ignition

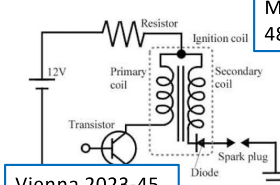
Vienna 2023-36

- Minimize crevice volume around insulator and stagnant flow zones in the cylinder to suppress “sporadic” preignition



Ignition circuitry is also important

- Minimize energy & hence electrode heating and wear
- Eliminate ghost sparks



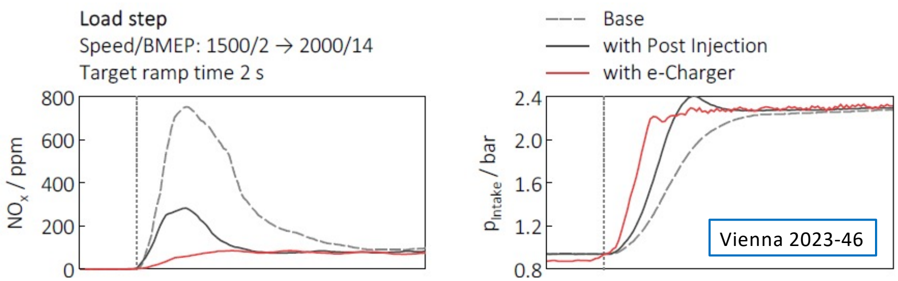
Vienna 2023-45

MTZ Worldw 84, 48–53 (2023)

Energies 2024 17, 1739

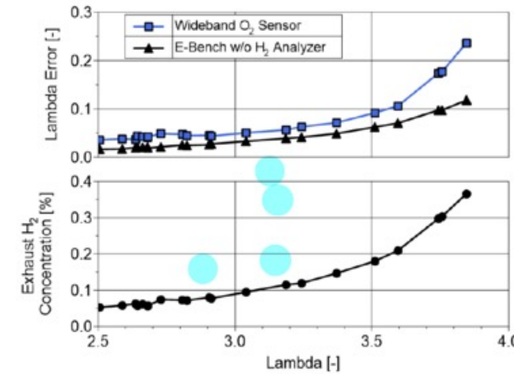
H2ICE – Premixed LPDI or PFI Fundamental R&D II

Post-injection and e-boosting significantly improve transient response and NOx



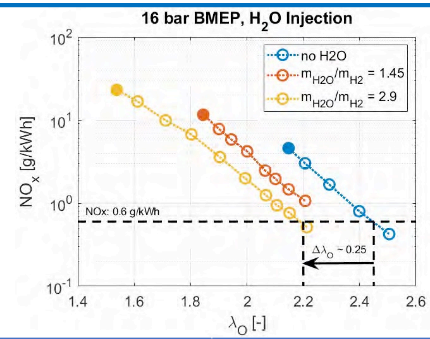
Vienna 2023-46

Cross-sensitivity of O2 sensor to H2 → potential for transient emission spikes with closed-loop control



JSAE 20239181

Water injection is shown to benefit NOx & knock, enabling higher η



Vienna 2023-38

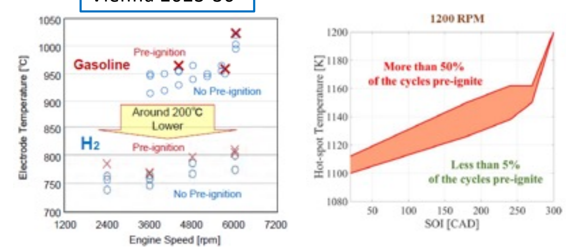
See also JSAE 20235386

BMEP	mH2O/mH2	CA50	ITEn
16 bar	1.5	7.8	40.2
18 bar	2.6	7.6	42.0
20 bar	2.3	7.9	42.4
24 bar	1.7	7.8	43.3

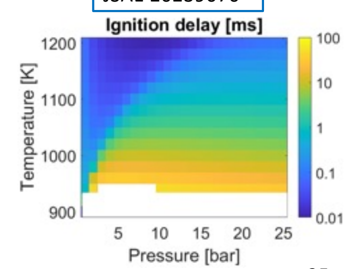
Thermal pre-ignition temperature is lower than HCs; also preferentially occurs at lower pressure

- Kinetics simulations show ignition delay *decreasing* with pressure

Vienna 2023-36

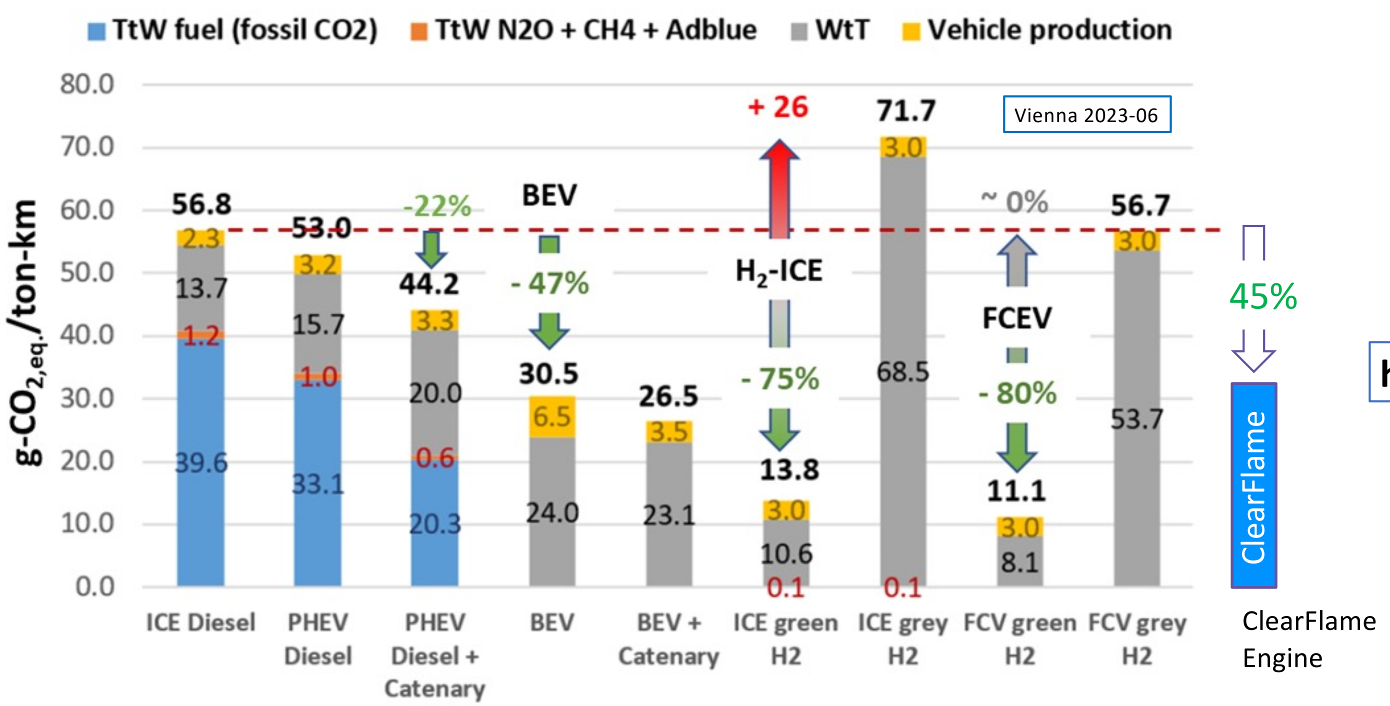


JSAE 20239070



Alcohol Burning Engines
Methanol & Ethanol

Why alcohol combustion?



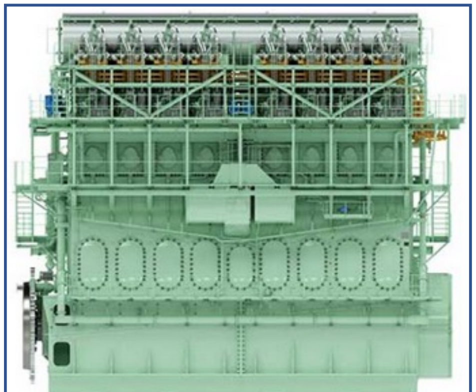
h/t: Ameya Joshi

Alcohol combustion offers rapid decarbonization with minimal modifications to new or existing engines or infrastructure

Alcohol Combustion – Market Introductions, Demonstrations & Development Efforts

ClearFlame sells first truck to Vander Haag's

Ground Vehicle



MAN ES says G95ME-LGIM ready for new Maersk builds; as of Aug 2023 19 orders (initially for 50-cm bore)

Also retrofits & new segment expansion

- Maersk signs contract for main engine retrofits for 11 container ships
- COSCO contracts for retrofit of four main engines for 13,800 and 20,000 TEU ships
- China Merchants Energy Shipping (CMES) orders 80-bore engine for new Very Large Crude Carrier (VLCC)
- MAN announces dual-fuel version of MAN 175D PFI high-speed engine

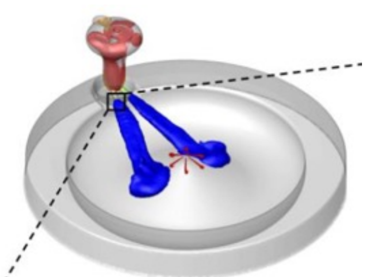
Marine Segment

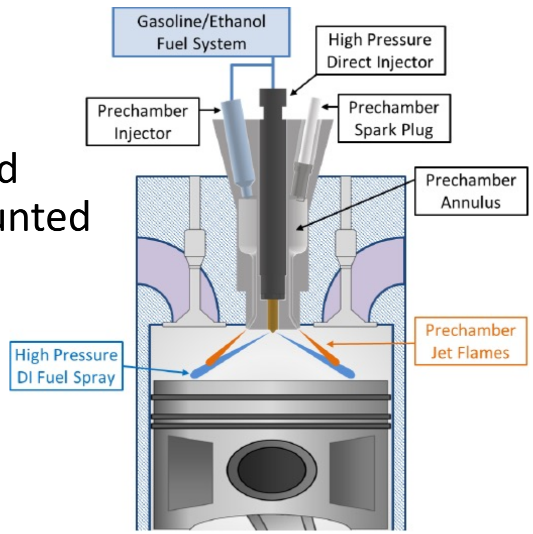
- Hyundai Heavy Industries reports orders for 50 methanol dual-fuel engines
- WinGD reports several orders for will supply X-DF-M methanol dual-fuel engines:
  - 82-bore size for a series of six container vessels to be built at Yangzijiang Shipbuilding in China
  - Four 92-bore size engines to power ultra-large container vessels being built for COSCO

Alcohol Combustion -- Enabling Mixing-Controlled Combustion by Enhancing Ignition I

Flex-fuel Mixing Controlled Combustion System Enabled by Prechamber Ignition

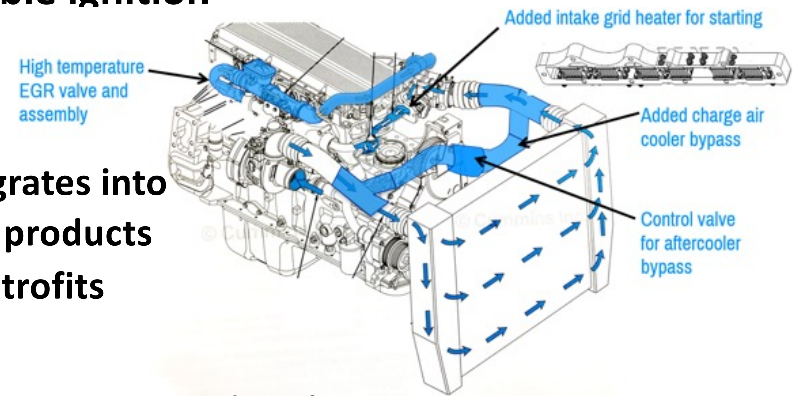
- Collaborative project among 6 organizations – OEM, Tier 1, University, Small Business, Trade Organization
- E15→E100 with Pre-chamber ignition assistance
- Project has evolved toward a side-mounted PC configuration



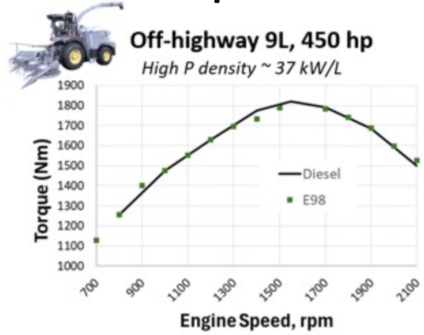


Intake charge heating and hot EGR also enable reliable ignition

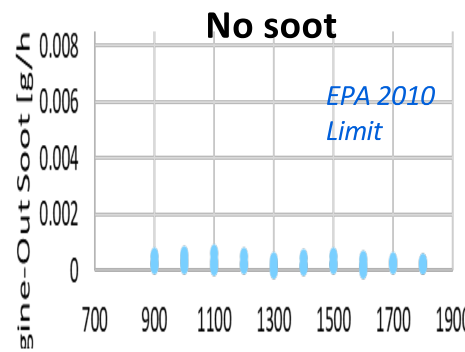
Integrates into new products or retrofits



Same torque as diesel

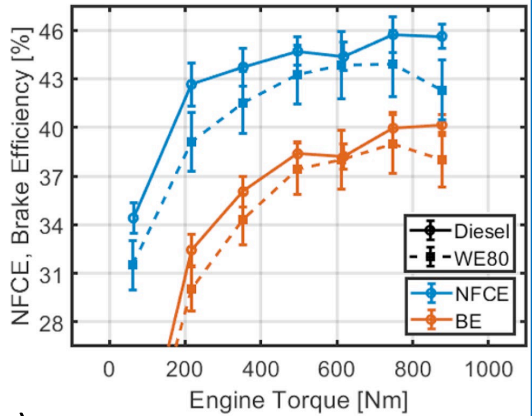


No soot



Alcohol Combustion – Enabling Mixing-Controlled Combustion by Enhancing Ignition II

- **Opposed-piston engines can enable ignition by trapping hot residuals**
- **Full map operation with no other ignition assist** (apart from cold-start)



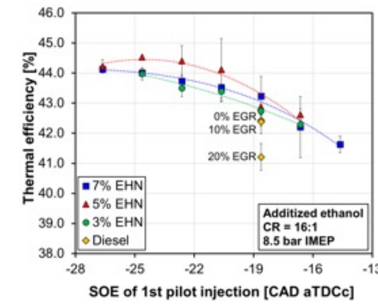
SAE 2023-01-0335

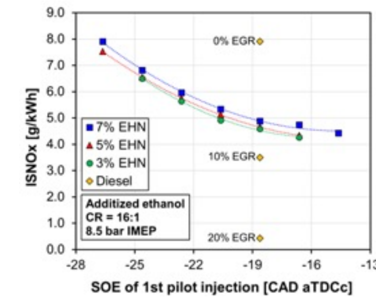
- **Significant benefits realized:**
  - Can burn 'wet ethanol' (WE80, 20% water)
  - Load comparable to diesel obtained
  - WE80 produces near-zero soot and reduces engine-out NOx emissions by 60-80%
- **Efficiency loss recoverable with optimization**

Ignition-enhancing additives are another potential solution

EHN

- Better efficiency than diesel
- Extremely low soot, NOx comparable to diesel
- High additive volume (3% at CR20)





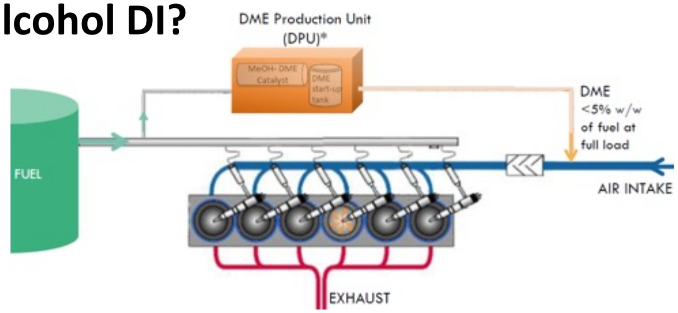
What about ethers? (on-board generation of DME or DEE)

- For blended operation, much higher ether concentrations required – >30% DEE
- For dual-fuel DI there is radical competition during ignition

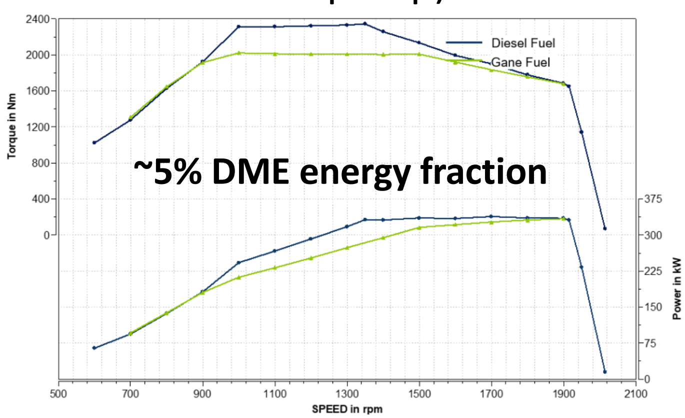
Alcohol Combustion – Enabling Mixing-Controlled Combustion by Enhancing Ignition III

SAE 2023 Heavy-Duty Sustainable Transport Symposium

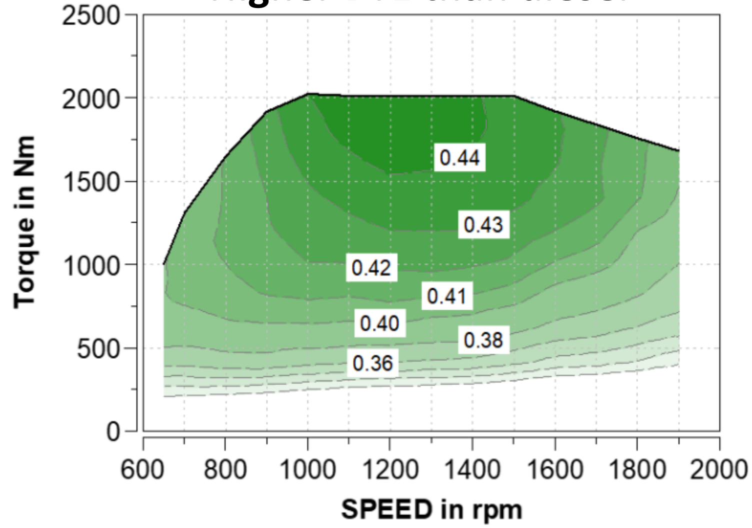
What if you port injected the ether, with alcohol DI?



Diesel torque reproduced (mid-speed deficit due to fuel pump)



Higher BTE than diesel



- **Lowest load operability and cold-start behavior unclear**

Natural Gas Engines

Natural Gas – SI Engine Introductions and Demonstrations

Hybrid NG truck from SwRI Isuzu, Woodward, and SCAQMD provides 25% GHG reduction

Innio Jenbacher –
BTE improved 0.33%
HC emissions reduced 30%

Updated Scania 13L
Marketed as bio-gas
5% fuel savings with range up to 1800 km

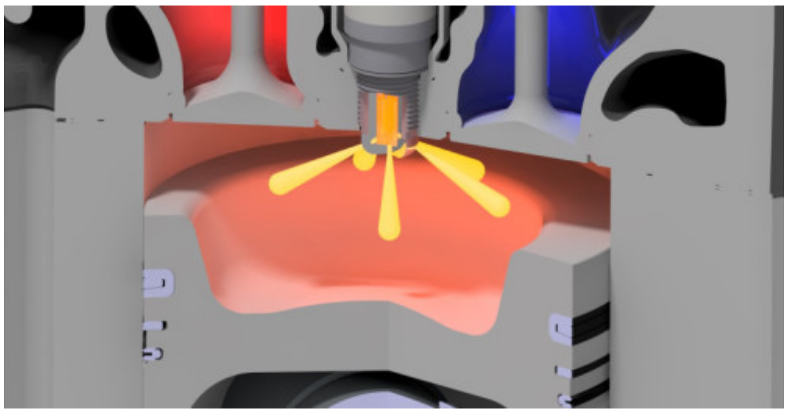
Cummins produces first 9L NG Euro VI Phase E for low emission EU cities

Cummins NG X15N is first HELM™ platform available to customers

MAN B&W Otto-cycle ME-GA gas engine trials completed aboard LNG carrier

NG SI Engine Technology Introductions & Development Efforts

MAN offers pre-chamber spark plugs for NG engine upgrades aimed at CHP market



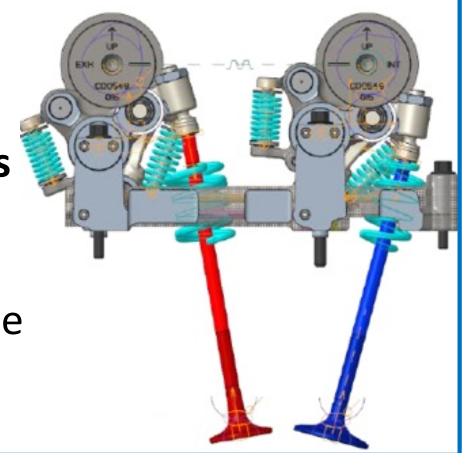
- MAN E3262, E3268, E0836, E0834 series (4.6 – 25.8L) and 29.6L E3872
- Compatible with up to 20% H2
- Improves efficiency (up to 1%), service life, and NVH

Cummins 10L NG engine

- Pent-roof, tumble based combustion system
- DOHC with VVT for high power density and high part-load efficiency
- Performance targets:
  - 400 hp, 1350 ft-lb torque, 42% peak BTE
  - 0.02 g/hp-hr NOx with all other criterial pollutants meeting 2027 EPA/CARB.

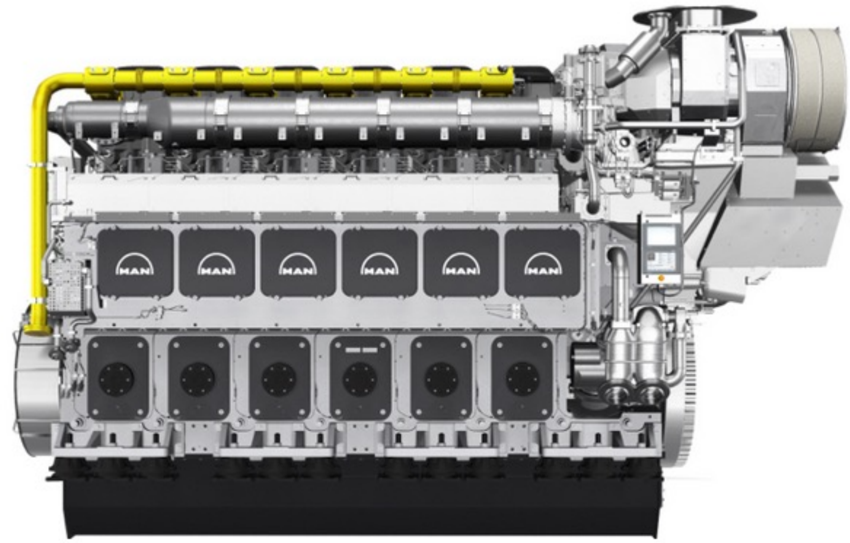
Cummins/Tula/Jacobs advanced NG valvetrains

- Targets VVT enabling dynamic skip-fire, 2-stroke braking mode



Natural Gas – Dual Fuel Engine Introductions and Demonstrations

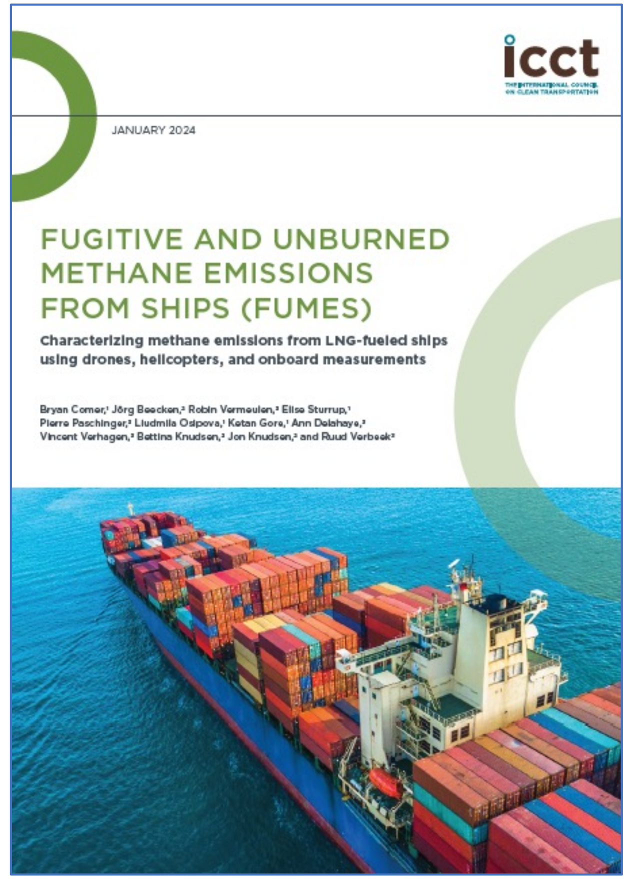
- AVL designing new clean-sheet power cylinder targeting 330 Bar PFP and 35 bar BMEP
  CIMAC 2013|023
- MAN ES 49/60DF engine
  (7.8–18.2 MW; 1.3 MW/cyl)
  - PFI Gas, pilot and main diesel injectors separate, VVT



- MAN 35/44DF CD GenSet Launched
  (also will support dual-fuel methanol operation by 2026)
- Westport Fuel Systems to adapt its Next Generation LNG HPDI™ fuel system to meet Euro VII emission requirements

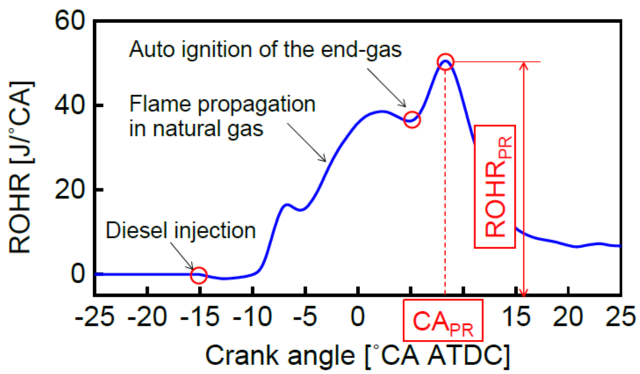
Methane slip reduction – a key challenge for NG engines

- Reducing methane slip continues to be an important research topic
- ICCT measurements of real-world methane slip measured by drones found
    - 4-stroke LNG marine engine averaged 6.4% -- roughly double assumptions used by regulating authorities
    - 2-stroke engines were significantly lower



Dual Fuel Combustion System Development – Addressing methane slip with controlled auto-ignition (CAI)

Controlled end gas autoignition provides high efficiency and reduced methane slip

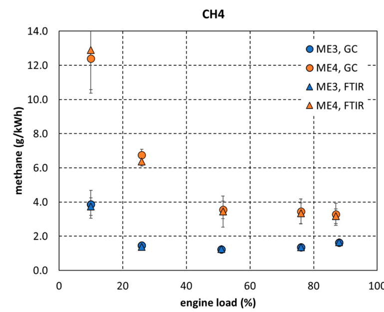


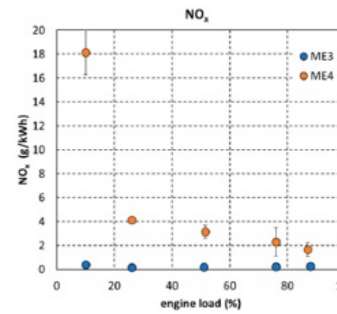
- Challenges to controlled autoignition:
  - Extend operating range
  - Decrease both slip and NOx emissions
- Results extend previous work by examining the use of boosting and EGR

JSAE 20239121, see also JSAE 20239121 / SAE 2023-32-0016

Wärtsilä is putting CAI into practice

Atmosphere 2023, 14, 825





- Significant reduction of methane slip and NOx
- Reduces CO_2e emissions by ~10-20%, depending on load
- High η associated with rapid burn can also be expected to increase BTE
- Similar strategies have been piloted by Woodward

CIMAC 2023

Ammonia Engines

Ammonia Dual-Fuel Engines – Industry Trends

- Ammonia Ship engines offered from multiple manufacturers:
  - Wärtsilä 25 Ammonia
  - WinGD X-D High-pressure DI
  - MAN 2-stroke High-pressure DI by 2027
- Industry orders broadening beyond NH_3 bulk carriers to container ships (MSC order)
- Approvals in Principle (AIPs) for design awarded by American Bureau of Shipping and Lloyds Register & Bureau Veritas (Wärtsilä WARMS safety concept)
- Azane fuel solutions providing first bunkering solutions – terminals and vessels
- MAN sees 27% of fuel used in large merchant vessels to be NH_3 by 2050

Table 5-1: Ammonia engine development schedule

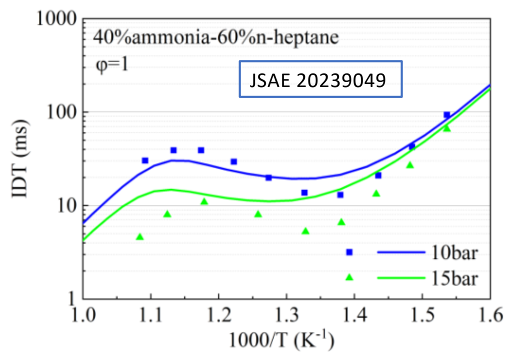
Engine type	MIM/MIDS	GTD*	Safety Concept	Full documentation set	Earliest expected first engine delivery date**
6X52DF-A-1.0	Available	Available	Available	Q2/24	Q2/2025
6X72DF-A-1.0	Available	Available	Available	Q4/24	Q3/2025
X62DF-A-1.0	Available	Q4/24	Available	Q3/25	Q1/2026
X82DF-A-1.0	Available	Q1/25	Available	Q1/26	Q3/2026
X62DF-A-S1.0	Available	Q2/25	Available	Q3/26	Q1/2027
X52DF-A-S1.0	Available	Q3/25	Available	Q1/27	Q3/2027

Ammonia Engines – R&D Progress I

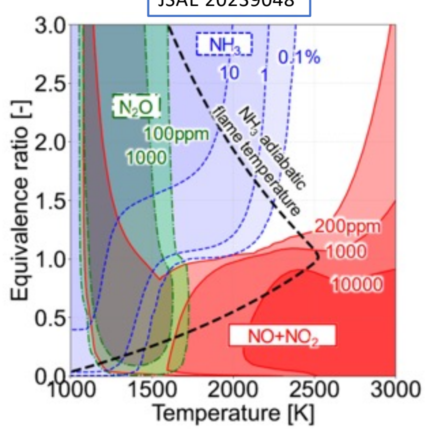
Dual-fuel kinetic mechanism development

- Mechanisms for HC/NH_3 blends still require work to capture fuel interactions

Also see SAE2023-01-0204



JSAE 20239048



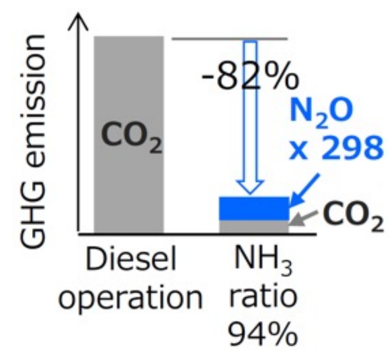
- ϕ-T plots indicate a fundamental trade-off between NH_3/N_2O emissions and NO_x

Also see JSAE 20239124

Exploration of emissions tradeoffs

See JSAE 20239094, 20239192, SAE 2023-01-1629, & ICEF2023-109103

- Engine tests confirm the trade-off:
  - NH_3 and N_2O emissions are improved by advancing combustion, reducing excess air, or adding H_2
  - NH_3 and N_2O emissions from cool wall layers remain important, and can dominate over bulk gas sources



- Nonetheless, sizeable total GHG reductions can be achieved

JSAE 20239197

Contact Info

Thank you

- Paul Miles
- Sandia National Laboratories
  Combustion Research Facility
  Livermore, CA
- 925 294-1512
- pcmiles@sandia.gov

Source: kevbeirne.substack.com

SAE INTERNATIONAL Mobility, Advanced

Year In Review Panel
Year in Fuels

Low carbon fuel effects on emissions

Jim Szybist
Oak Ridge National Laboratory

April 16, 2024

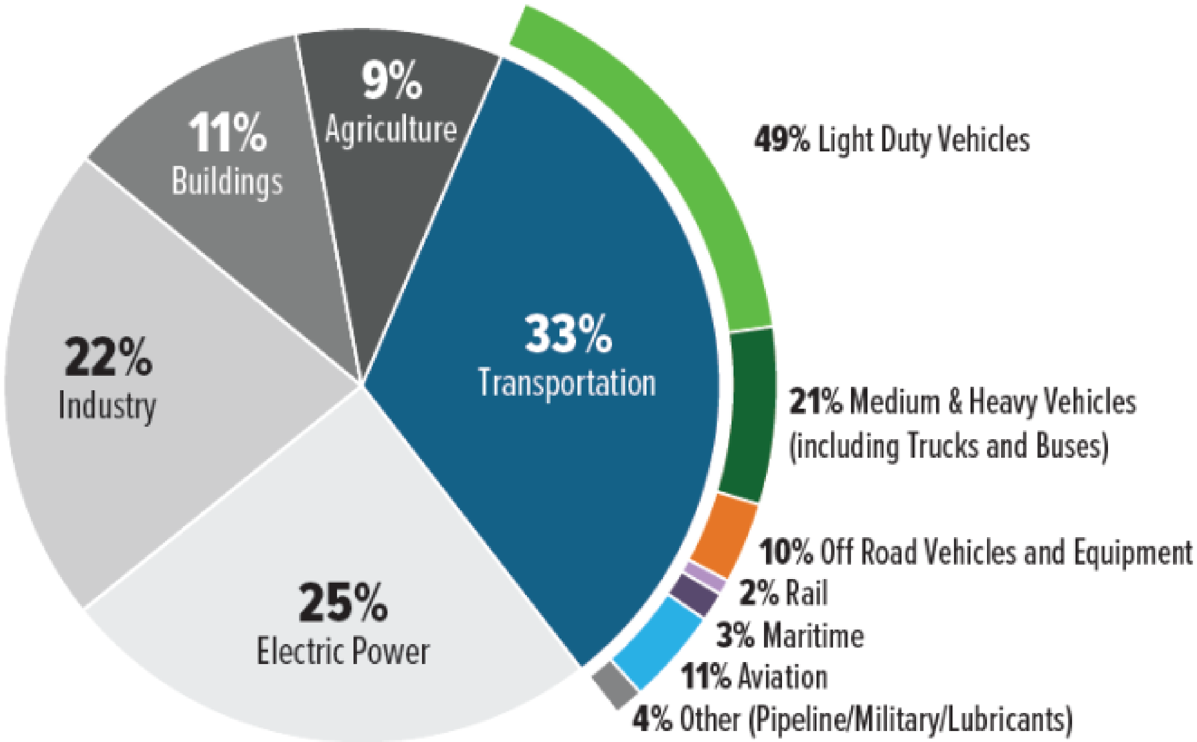
OAK RIDGE National Laboratory

Acknowledgements

- DOE Vehicle Technologies Office: Gurpreet Singh, Kevin Stork, Siddiq Khan, Nick Hansford

- ORNL Colleagues: Josh Pihl, Scott Curran, Mike Kass, Brian Kaul, Derek Splitter

U.S. National Blueprint for Transportation Decarbonization Sets Sector-Wide Strategy for 2050



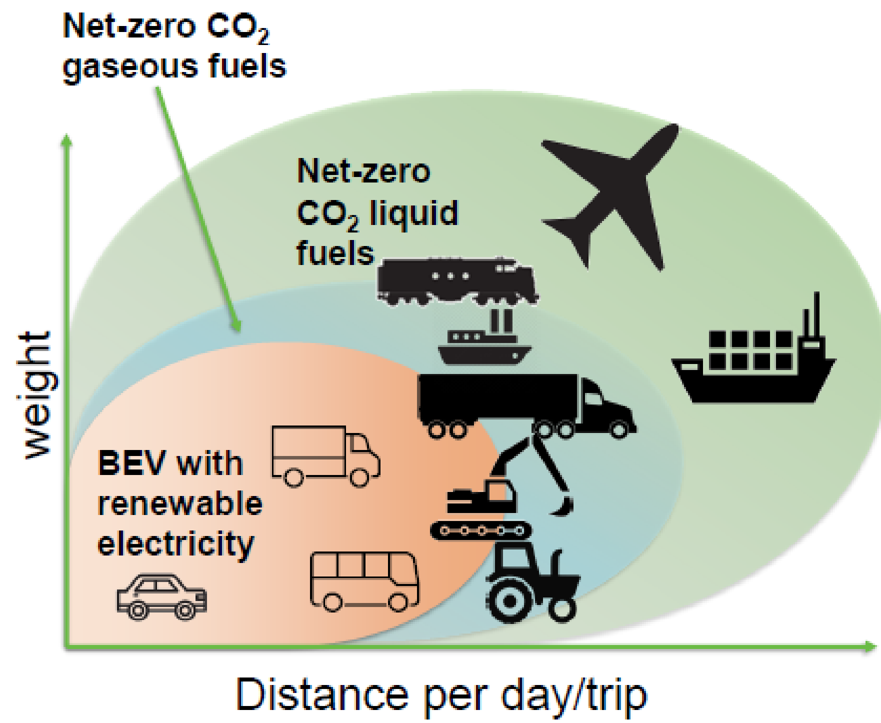
From the U.S. National Blueprint for Transportation Decarbonization

https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf

- Transportation is the largest emitter of greenhouse gas (GHG) emissions
- 70% of GHG emissions are attributed to on-road application
- Non-road GHG emissions are expected to increase in importance

Electrification is a Critical Path to Reduced GHG Emissions, but Other Solutions are Also Required

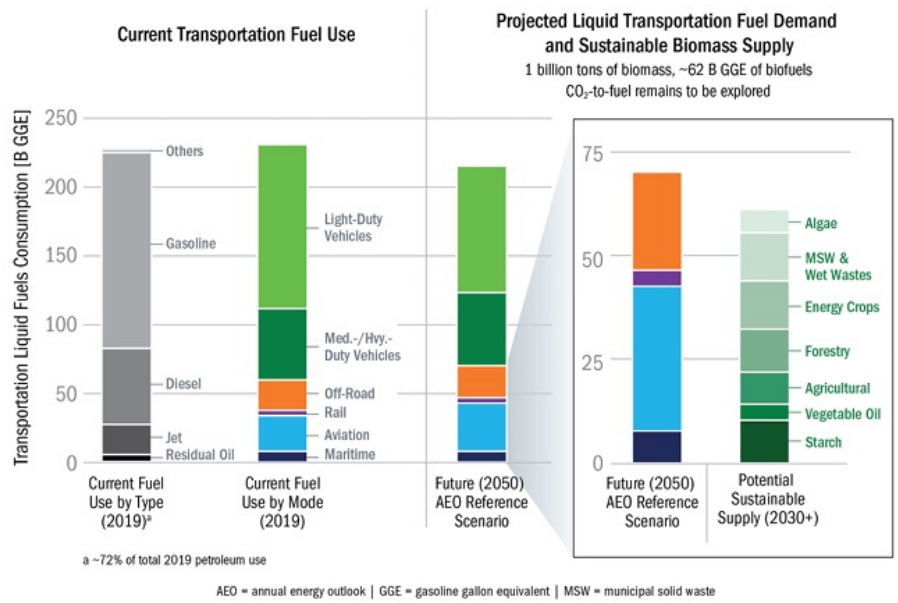
- On-road transportation will be largely electrified
  - LD vehicles will largely battery electric
  - MD/HD vehicles will be a mix of battery electric and fuel cells
- Electrification more challenging for non-road due to
  - Heavy loads
  - Long distances
  - Insufficient time for charging
  - Lack of charging infrastructure
- Other solutions are needed for off-road, rail, marine, and aviation



M. Weismiller, "Decarbonization of Hard to Electrify Vehicles," presentation to ASME ICEF 2021

Insufficient Biomass Resources to Support All Non-Road Decarbonization Needs

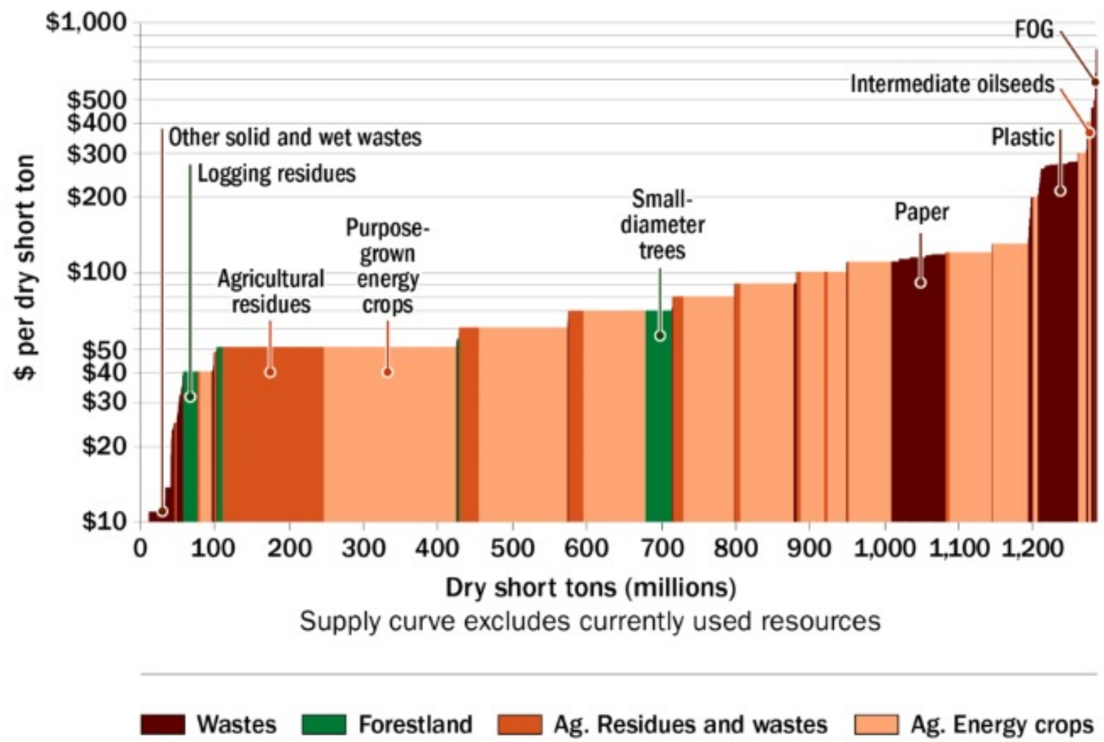
- DOE Billion Ton 23 estimates future biofuel availability in the U.S.[1]
  - 60 billion gasoline gallon equivalent (GGE) of renewable fuels could be available
  - Nonroad energy demand is projected to exceed 70 billion GGE
- DOE assumes Sustainable Aviation Fuel (SAF) is top priority for biomass
  - Aviation is hardest to electrify
  - Reliant on energy density of hydrocarbon fuel
- SAF production targets[2]
  - 3 billion gallons per year by 2030
  - 35 billion gallons per year by 2050



1. https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources
2. https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

Economics may Incentivize Non-Biomass-Derived Sustainable Fuel Before Biomass Resources are Fully Exploited

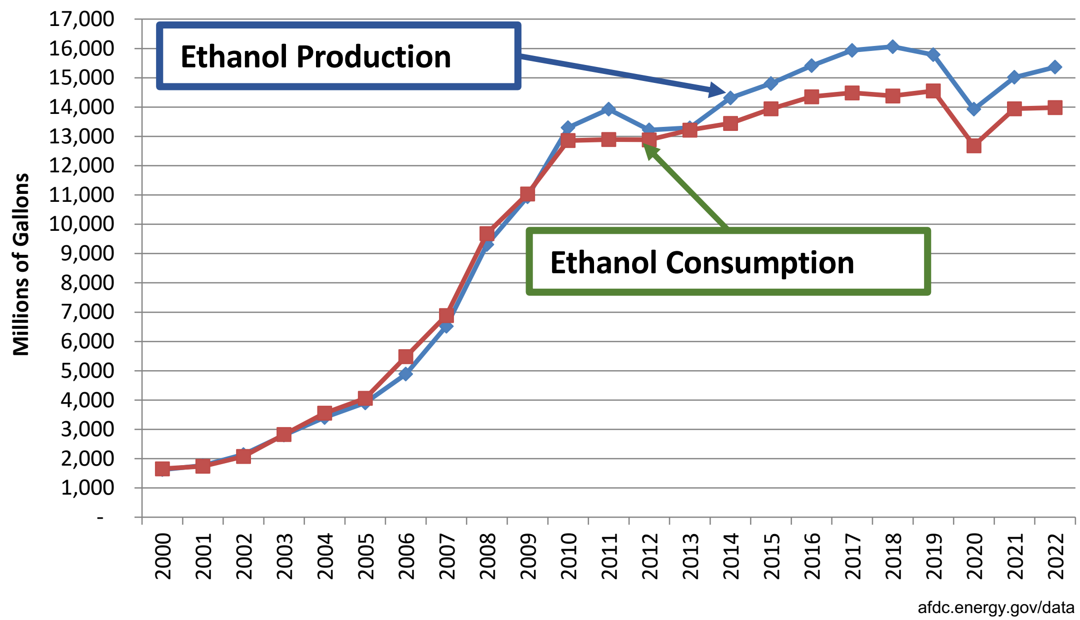
- Increasing incremental cost of biomass feedstock
- Amount of biofuel produced is a function of market prices
- Synthetic fuels of the hydrogen economy are promising alternatives
  - Hydrogen
  - Methanol
  - Ammonia



https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources

Ethanol is the Largest Production Biofuel, but Production and Consumption has Leveled Off in the U.S.

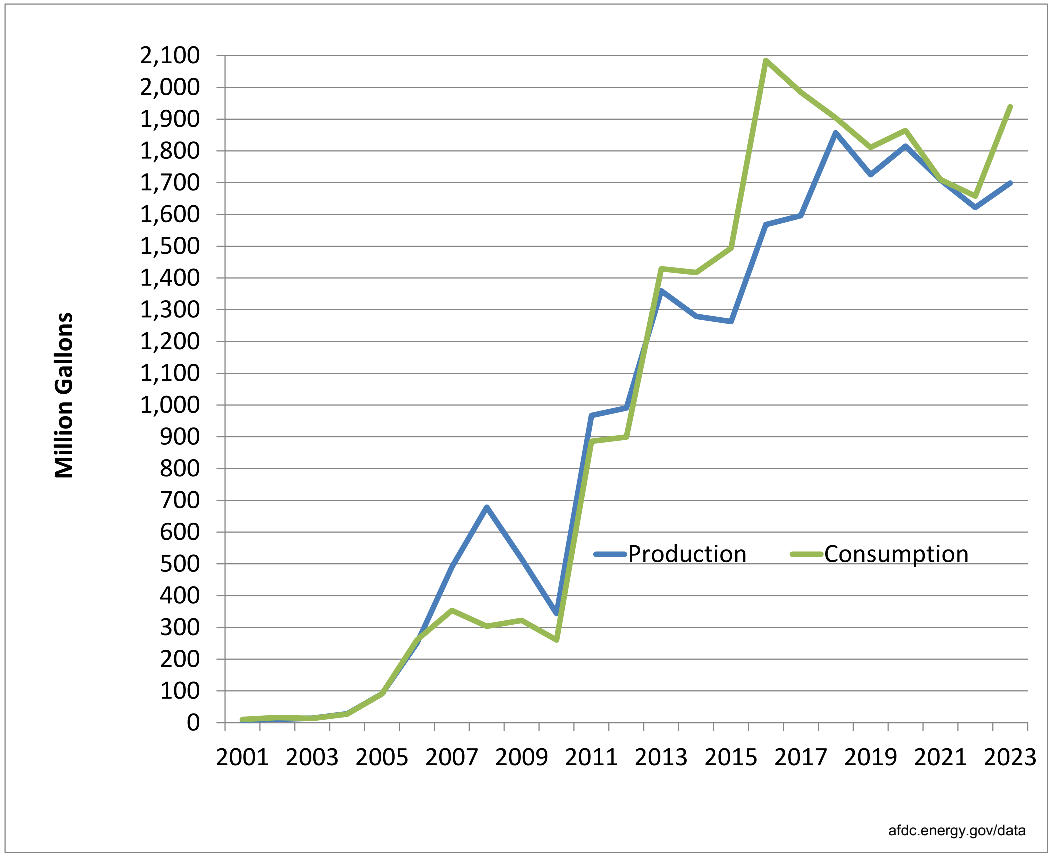
- Vast majority of ethanol consumed as E10
- Trend in ethanol consumption reflects gasoline
- Multiple pathways to produce SAF from ethanol
  - Approved alcohol-to-jet ASTM pathway
  - SAF Grand Challenge Roadmap lists 6 companies pursuing alcohol-to-jet technologies



Data from the DOE Alternative Fuels Data Center afdc.energy.gov/data

Biodiesel Production and Consumption Has Plateaued

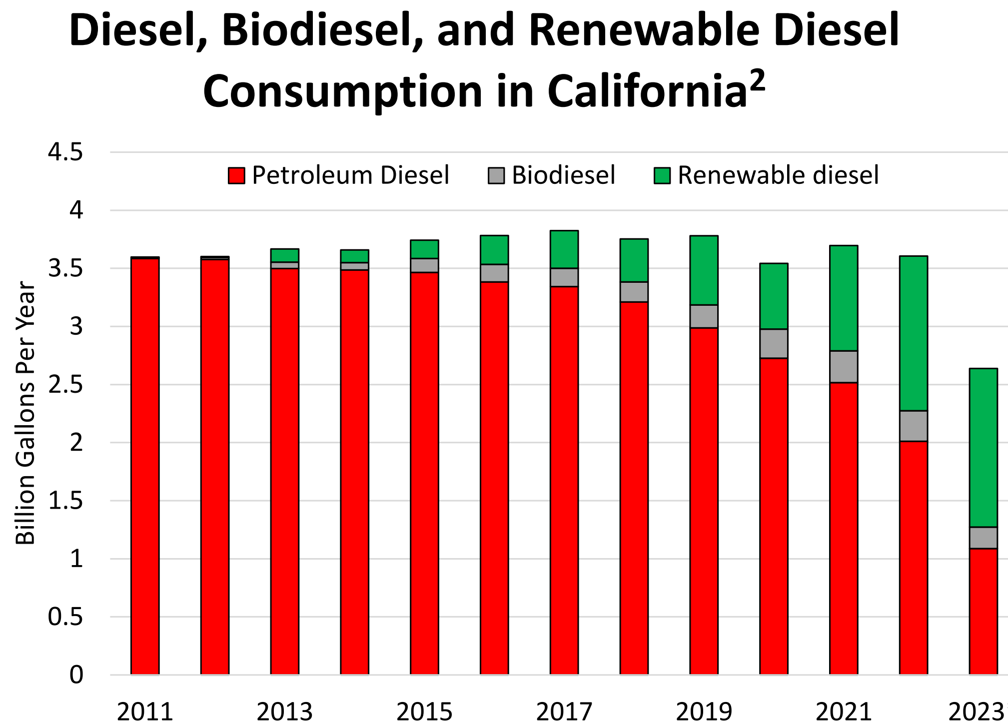
- Peak biodiesel consumption occurred in 2016
- Consumption levels have plateaued at near-peak levels
- Additional growth for diesel market primarily focused on renewable disel



Data from the DOE Alternative Fuels Data Center afdc.energy.gov/data

Renewable Diesel (RD) Production and Consumption have Boomed in (parts of) the U.S.

- RD production increased from 1.75 to 3.88 billion gallons per year from Jan 2022 to Nov 2023[1]
  - RD production exceeds biodiesel
  - 30% growth projected in both 2024 and 2025[1]
- RD consumption concentrated California
  - Accounts for >50% consumption
  - Tax incentives aid growth

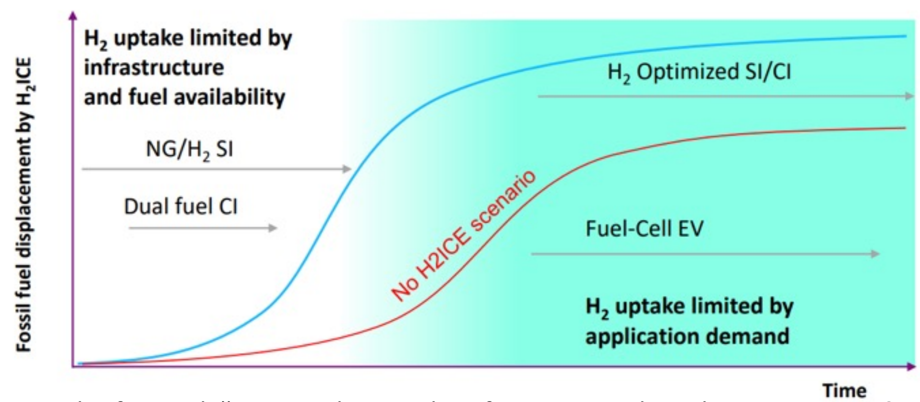


*Excludes Q4 of 2023

1. Energy Information Agency: https://biomassmagazine.com/articles/eia-renewable-diesel-production-to-expand-by-30-annually-in-2024-2025
2. Data from UC Davis: https://asmith.ucdavis.edu/

Large Investments being made in Hydrogen Economy; Dramatic Growth is Projected Worldwide

- U.S. National Clean Hydrogen Strategy Aims[1] aims to produce at least 10 million metric tons per year (MMT/Y) by 2030
  - DOE investing $8B in regional hydrogen hubs[2] in addition to applied programs
- Hydrogen targets for EU are even more ambitious
  - Produce 10 MMT/Y and Import 10 MMT/Y by 2030
- Hydrogen uses in transportation include both engine and fuel cell
  - Engine use can accelerate adoption
- Industry estimates that hydrogen will be 5-15% of diesel by 2050, but changing rapidly

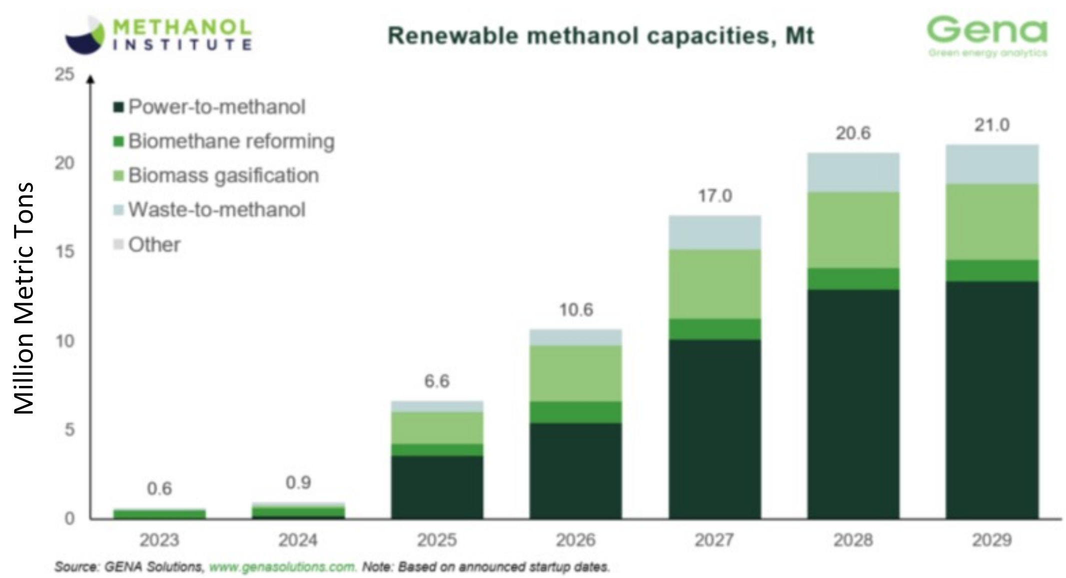


Plot from: Aleš Snra, Is there a place for H_2 internal combustion engines?, HFTO webinar series, February 2023.

1. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf?sfvrsn=c425b44f_5
2. https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0
3. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/key-actions-eu-hydrogen-strategy_en

Investments in Green Methanol Production and Bunkering for Marine Use are on the Rise Worldwide

- Green methanol can be made through multiple pathways
  - Biofuel
  - E-fuel: hydrogen and CO_2
  - Produced from waste
- Worldwide capacity expected to increase >20x by 2029
  - Based on announced startup dates
  - Current global production is about 100 MMT/Y
- Storage and bunkering throughout Europe, Asia, North America



Plot taken from the Methanol Institute: https://www.methanol.org/renewable/

Investments in Green Methanol Consumption for Marine Use are on the Rise Worldwide

- More than 100 methanol-compatible vessels have either been delivered or ordered[1]
  - Nearly all are dual-fuel technology
- Maersk alone has ordered 24 methanol-compatible vessels
  - First vessel, Ane Maersk, sailed maiden voyage on methanol in March, 2024
- Growing list of methanol-related demonstrations, orders, and deliveries

1. https://www.methanol.org/wp-content/uploads/2024/02/2023-MIs-On-the-Water-and-on-the-Way-1-1.pdf

Ammonia is Garnering Significant Investment for use as a Carbon-Free Hydrogen Carrier and Marine Fuel

- Suez Canal Zone has seen numerous projects to produce green ammonia
  - Egypt alone has a project pipeline worth \$83 billion in green hydrogen and ammonia[1]
- Fortescue has demonstrated world's first ammonia vessel in Singapore in March 2024[2]
- Wartsilla currently offering a 4-stroke ammonia engine for marine[3]
- MAN to offer 2-stroke ammonia engine for new vessels starting in 2027[4]

Fortescue Green Pioneer, world's first ammonia-powered vessel[2]

1. https://www.hydrogeninsight.com/production/egypt-has-an-83bn-pipeline-of-green-hydrogen-projects-that-could-produce-millions-of-tonnes-of-green-ammonia/2-1-1495879
2. https://fortescue.com/news-and-media/news/2024/03/15/world-s-first-use-of-ammonia-as-a-marine-fuel-in-a-dual-fueled-ammonia-powered-vessel-in-the-port-of-singapore
3. https://www.wartsila.com/media/news/15-11-2023-wartsila-continues-to-set-the-pace-for-marine-decarbonisation-with-launch-of-world-first-4-stroke-engine-based-ammonia-solution-3357985
4. https://www.reuters.com/business/energy/man-energy-solutions-offer-ammonia-fuelled-ship-engines-after-2027-2024-03-04/

DOE Decarbonization of Off-Road, Rail, Marine, and Aviation (DORMA) Portfolio is Working on Challenges with Synthetic Fuels

Hydrogen

ORNL CRADA with Wabtec: rail decarbonization

ANL CRADA with Wabtec: rail decarbonization

SNL projects on jet and combustion fundamentals

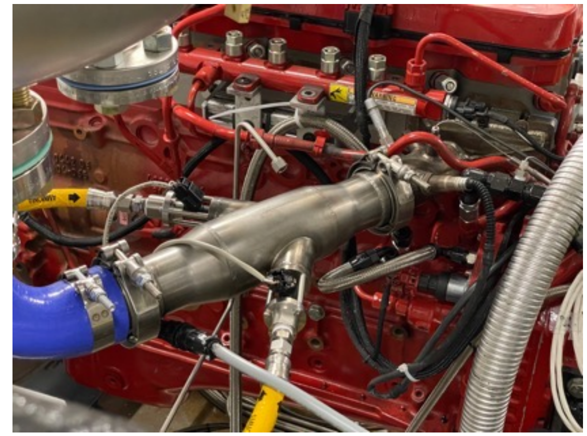
Methanol

ORNL CRADA with Caterpillar: marine decarbonization

SNL CRADA with Caterpillar: decarbonization with methanol

ANL projects on enabling methanol and hydrogen combustion

Ammonia



ORNL project: Ammonia combustion and emissions

Full DOE VTO DORMA Portfolio Update Available at Merit Review Meeting, June 3-6

Decarbonization of Heavy Transportation Technologies are in the Early Stages

- Electrification is the primary path for on-highway decarbonization
- Biomass is critical to non-road decarbonization
  - Insufficient biomass for this to be the only path
- Synthetic fuels supported by the hydrogen economy are seeing significant growth
  - Hydrogen
  - Methanol
  - Ammonia

Backups

Blueprint Identifies Long Term Fuel/Technology Opportunities by Transportation Sector

1 icon represents limited long-term opportunity
2 icons represents large long-term opportunity
3 icons represents greatest long-term opportunity

	BATTERY/ELECTRIC	HYDROGEN	SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)*	(3 icons)	—	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	(2 icons)	(1 icon)	(1 icon)
Long-Haul Heavy Trucks (~7%)	(1 icon)	(3 icons)	(2 icons)
Off-road (10%)	(2 icons)	(1 icon)	(1 icon)
Rail (2%)	(2 icons)	(2 icons)	(2 icons)
Maritime (3%)	(1 icon)	(2 icons)†	(3 icons)
Aviation (11%)	(1 icon)	(1 icon)	(3 icons)
Pipelines (4%)	(2 icons)	TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

Figure B. Summary of vehicle improvement strategies and technology solutions for different travel modes that are needed to reach a net-zero economy in 2050 (more details provided in Section 5).

Light and medium duty will be largely electric

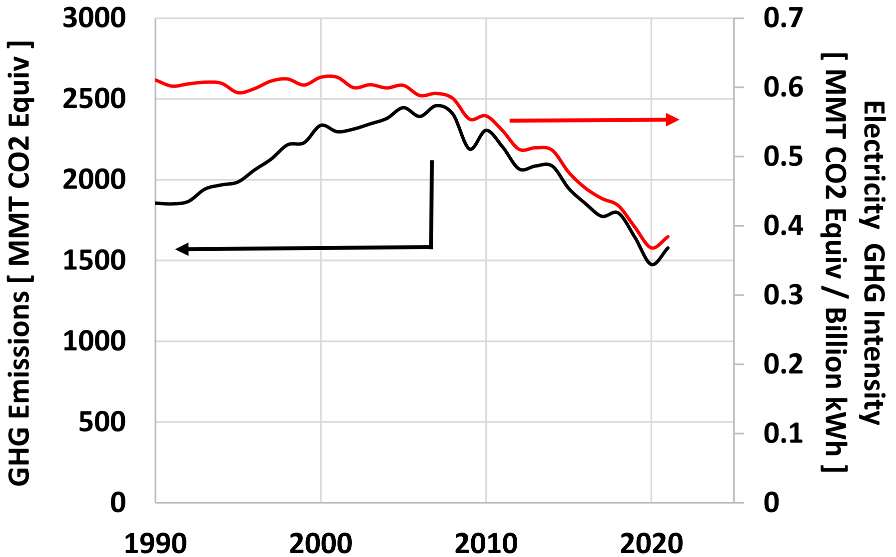
Off-road, rail, and marine will be a combination of battery electric, hydrogen, and sustainable liquid fuels

Aviation will be the most reliant on liquid fuels; sustainable aviation fuel is a high priority

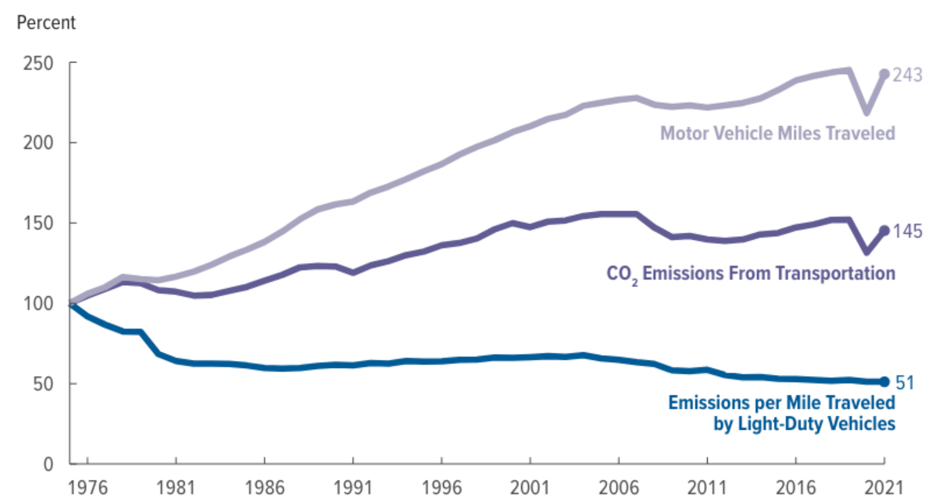
Sustainable fuels for existing internal combustion engines is an important need for decarbonization

On-Highway Shift to Electrification is Supported by Carbon Emissions and Carbon Intensity Trends

GHG Intensity from Electricity has Decreased by >1/3 Since 2005



Transportation CO_2 Emissions have Remained Nearly Constant Since 2005



GHG Data From: EPA (2024) Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022. U.S. Environmental Protection Agency, EPA 430-D-24-001. https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions and-sinks-1990-2022.
Electricity Generation Data From EIA: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

Congressional Budget Office, Emissions of Carbon Dioxide in the Transportation Sector, publication 58566, December 2022. http://www.cbo.gov/publication/58566

WCX April 16–18 2024
Detroit, Michigan, USA

Panel Discussion:
Year in Review on
Emissions,
Fuels, and Propulsion

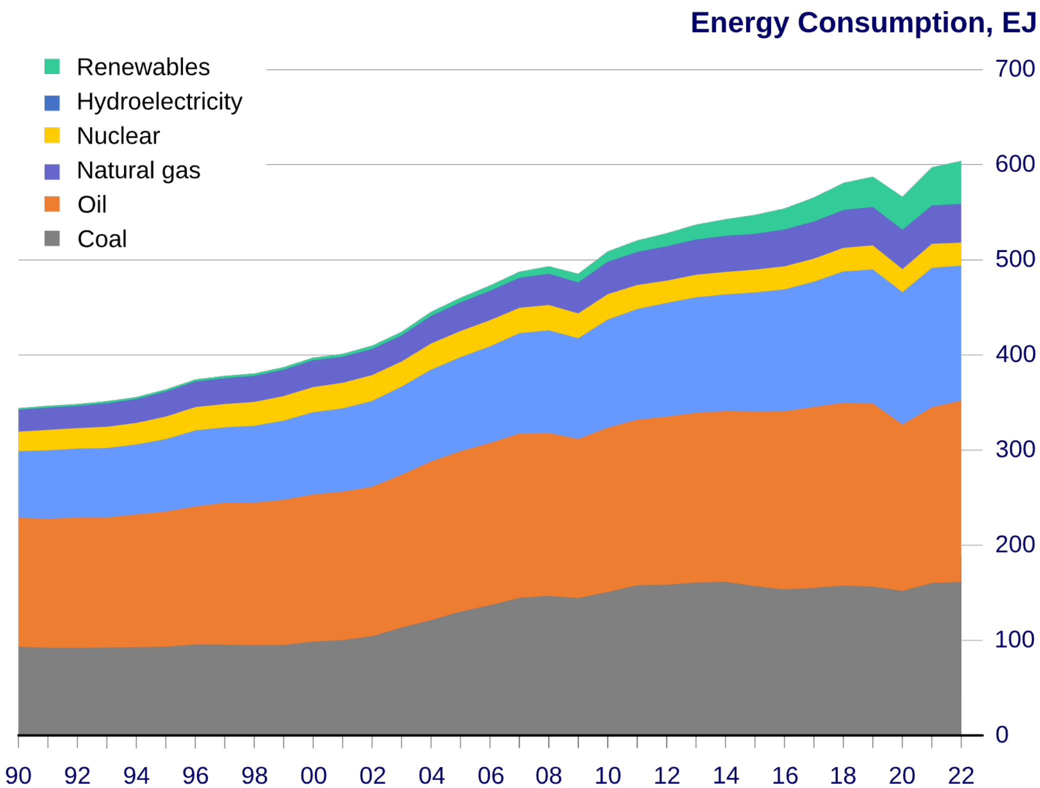
Energy Transition & Electric Vehicles Status Update

W. Addy Majewski

DieselNet.com

DieselNet

World's primary energy consumption, 1990-2022



Data: Energy Institute Statistical Review of World Energy 2023

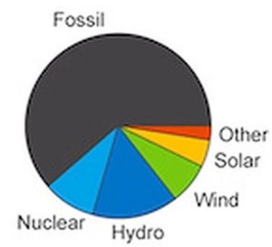
Renewables are being added on top of growing fossil energy demand

Renewables = wind + solar + geothermal + wave power.

Electrical energy (renewables, hydro, and nuclear) is converted into EJ on an 'input-equivalent' basis, assuming about 38% conversion efficiency in a thermal power station.

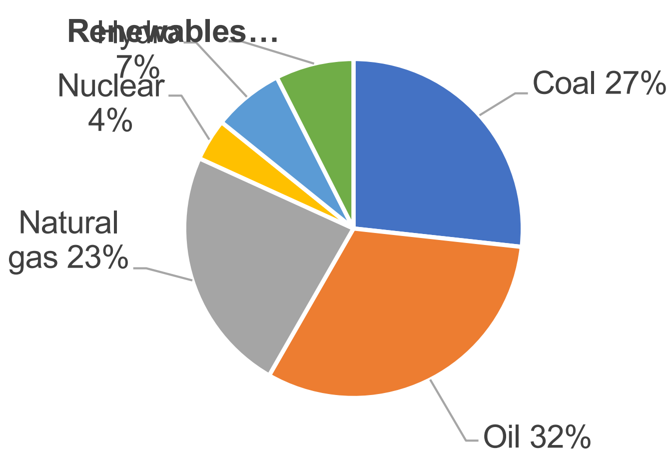
Renewables and global energy supply

- Contribution of renewables (wind & solar) to *global electricity* production (2022)
    - Wind: 7.2%
    - Solar PV: 4.5%
    - Renewables met 84% of net electricity demand growth in 2022



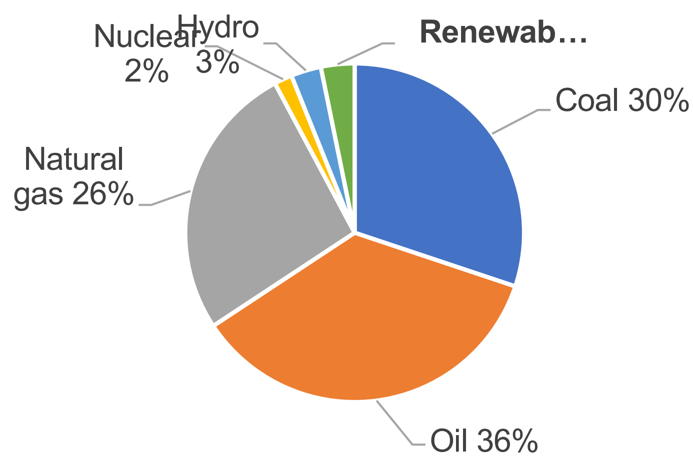
- Contribution of renewables to *global primary energy* supply

  - Input-equivalent (substitution) method: 7%

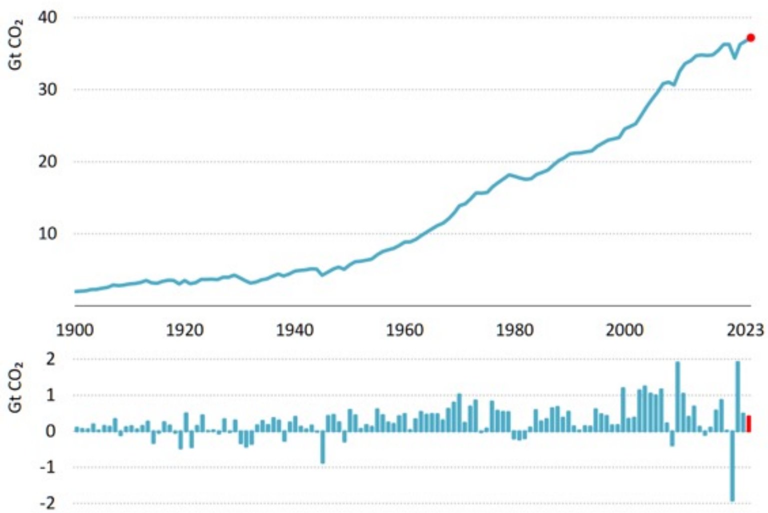


Data: Energy Institute Statistical Review of World Energy 2023

  - Heating value method: 3%

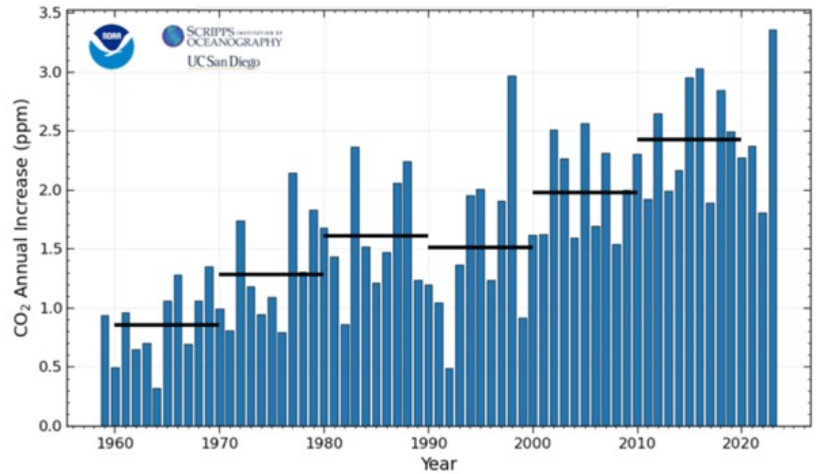


Energy-related CO2 emissions



Global energy-related CO2 emissions and their annual change

https://www.iea.org/reports/co2-emissions-in-2023/



Annual increase of CO2 concentration at NOAA Mauna Loa observatory

Black lines represent 10-year averages

https://gml.noaa.gov/ccgg/trends/gr.html

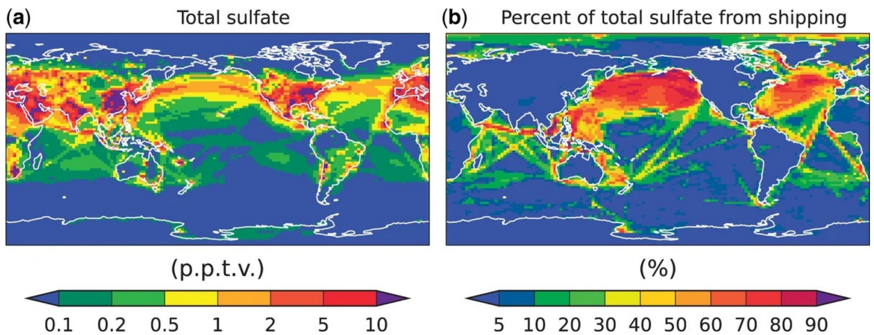
- CO2 emissions from fossil fuels increased by 1.1% in 2023
- CO2 emissions decrease during periods of decreased economic activity (Covid-19 lockdowns, 2008 GFC, recession in the 1980s)

- Ambient CO2 concentrations increased by a record high 3.3 ppm in 2023
- CO2 reached 425 ppm in March 2024

Decreasing aerosols accelerate global warming

- Decreasing human-made aerosols—such as due to the reduction of sulfur content in marine fuels—accelerated global warming in the past decade
- Global warming in 2010-2023 is 0.30°C/decade, 67% faster than 0.18°C/decade in 1970-2010
- The large warming over the North Pacific and North Atlantic coincides with regions where ship emissions dominated sulfate aerosol production prior to IMO fuel sulfur regulations
- The impacts of aerosols may outweigh the effects of greenhouse gases

Local and global temperature trends (°C) in two periods



Total sulfate (parts per trillion by volume) and percentage of total sulfate provided by shipping prior to IMO regulations on sulfur content of fuels

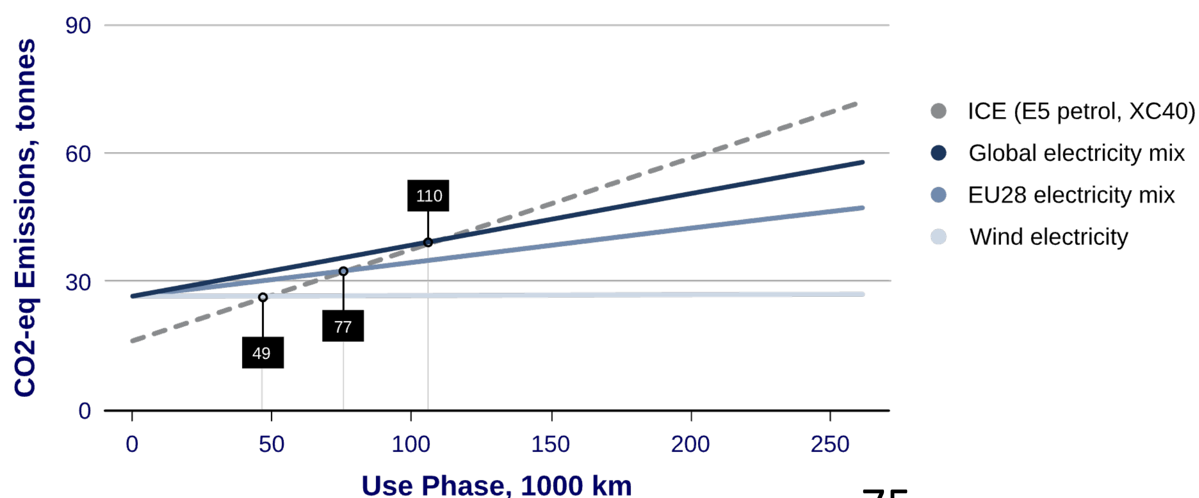
James Hansen 2024, Global Warming Acceleration: Hope vs Hopium

Electric vehicles: Emissions from BEVs (life cycle)

Carbon footprint for Volvo XC40 ICE and C40 Recharge (tonnes of CO_2eq; total distance 200,000 km)

Vehicle	Materials Production & Refining	Li-ion Battery Modules	Volvo Cars Manufacturing	Use Phase Emissions	End-of-Life	Total
XC40 ICE (E5 petrol)	14	-	1.7	43	0.6	59
C40 Recharge (global electricity mix)	18	7	1.4	24	0.5	50
C40 Recharge (EU-28 electricity mix)	18	7	1.4	16	0.5	42
C40 Recharge (wind electricity)	18	7	1.4	0.4	0.5	27

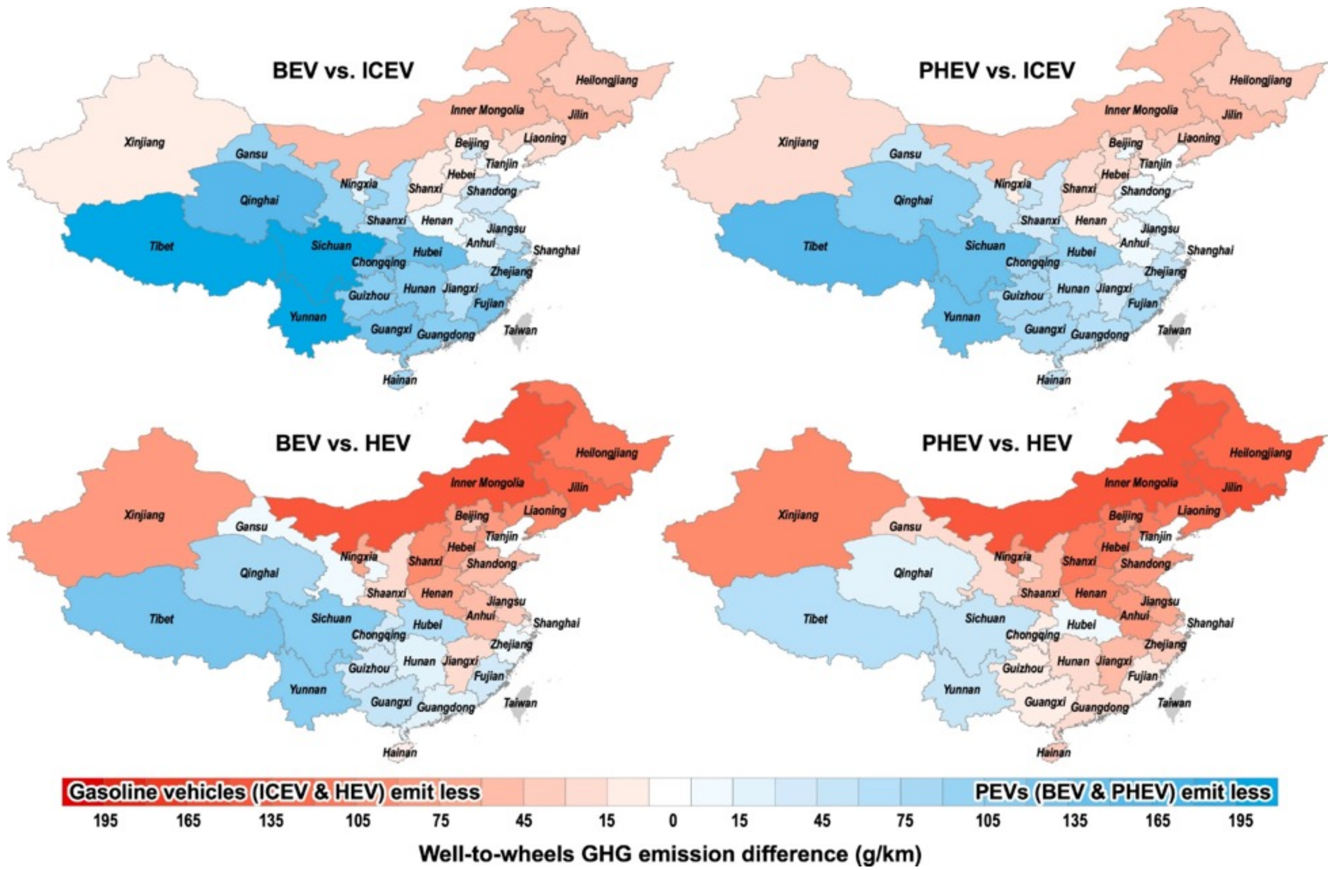
Emissions break-even diagram for Volvo C40 Recharge BEV



Volvo Cars 2021

WTW emissions from ICEVs, HEVs, PHEVs, and EVs

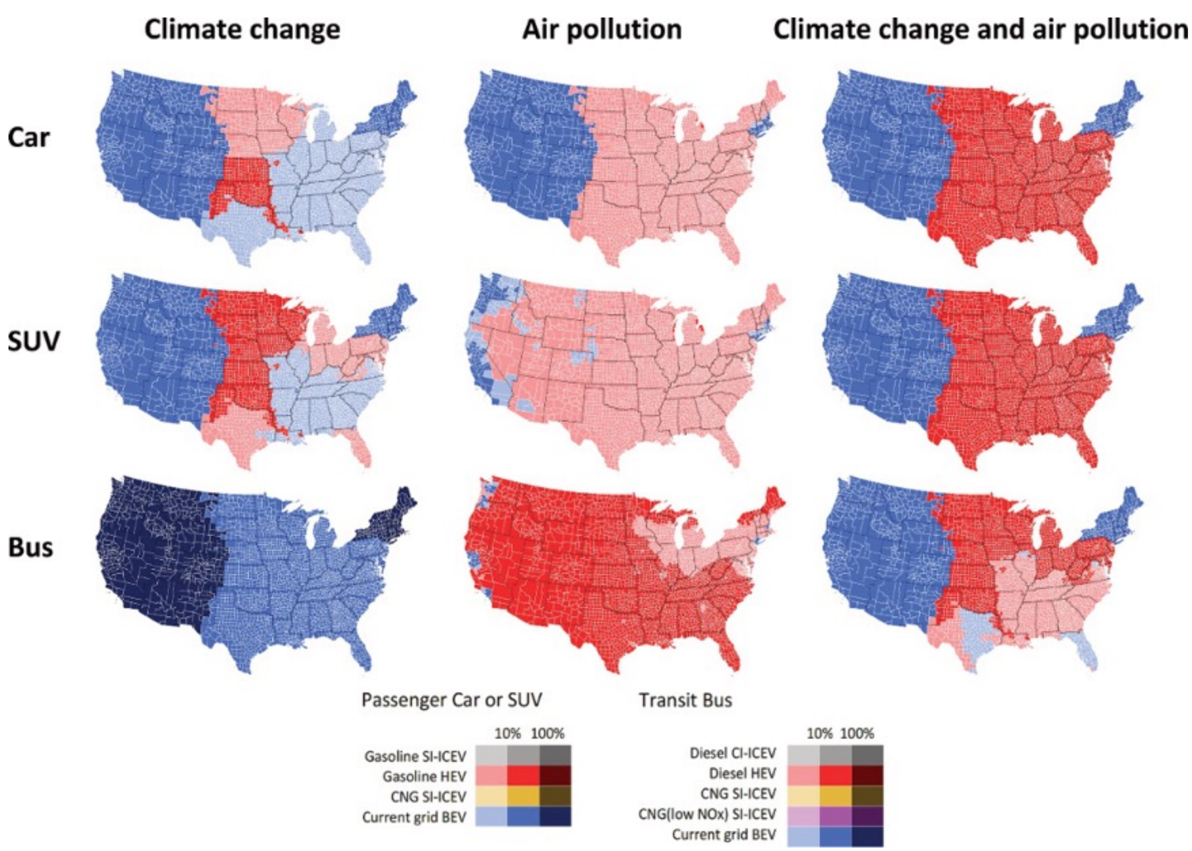
Comparison of WTW GHG emissions between gasoline vehicles (rows) and PEVs (columns) at the provincial level in China—the impact of grid electricity mix and climate



Argonne 2021

WTW emissions from ICEVs & EVs—US conditions

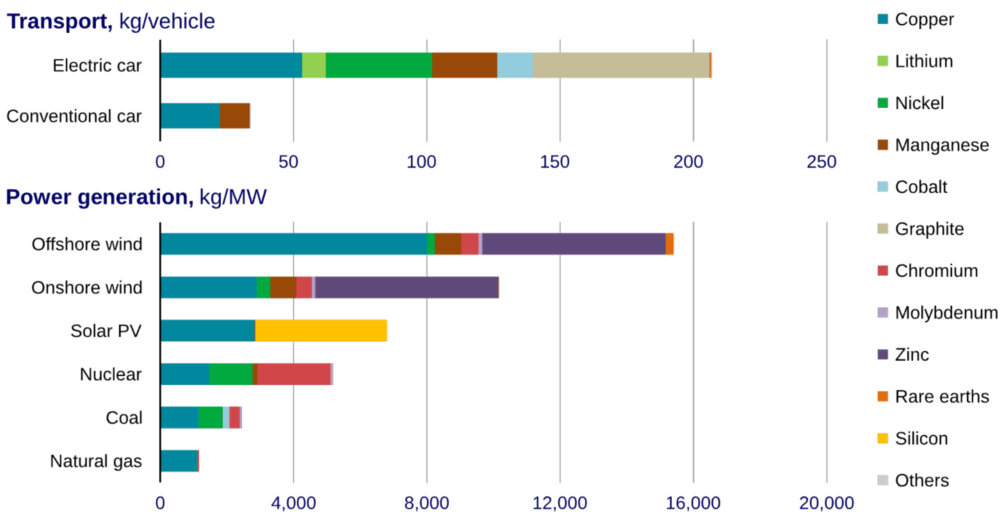
Fuel-vehicle technologies that have the lowest "monetized damages" in each county for passenger cars, SUVs, and transit buses



Color shades represent relative differences in damage estimates across technologies—for instance, a 100% relative difference means that all the other fuel-vehicle technologies lead to 100% higher damages than the shown technology for any county.

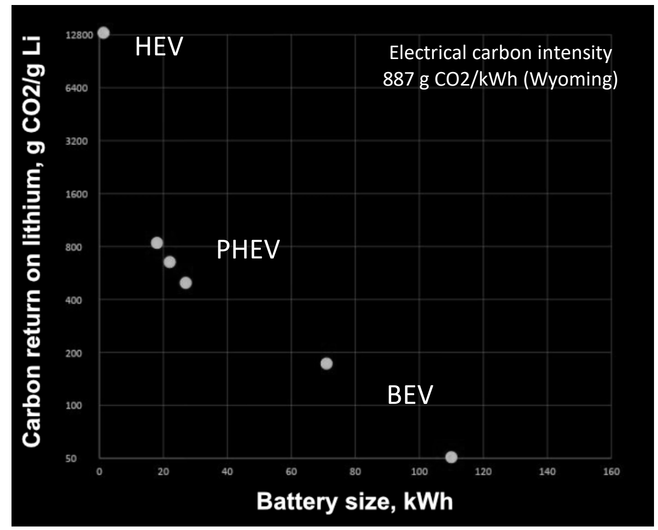
Tong 2020

HEVs can provide better resource utilization than BEVs



Minerals used in selected clean energy technologies

IEA 2021



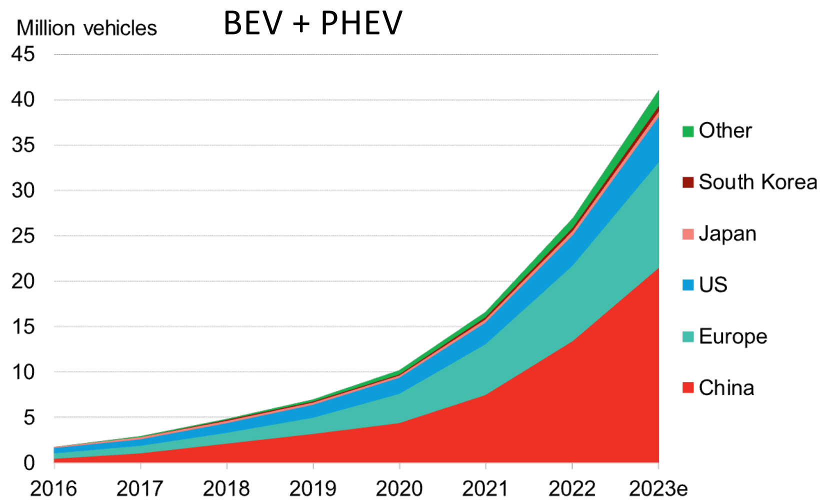
Carbon return on lithium (CROL)

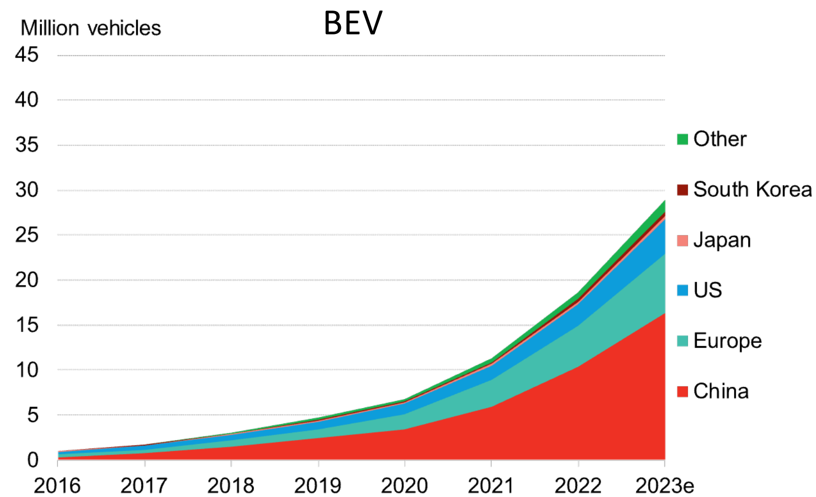
g CO2 avoided per g Li used

[Toyota / carghg.org]

- BEV policies may lead to a wasteful allocation of critical metal and mineral resources such as those used for battery production
- Hybrids are more effective than BEVs for reducing CO_2 per kWh of battery capacity

Electric vehicle markets: Global EV vehicle fleet

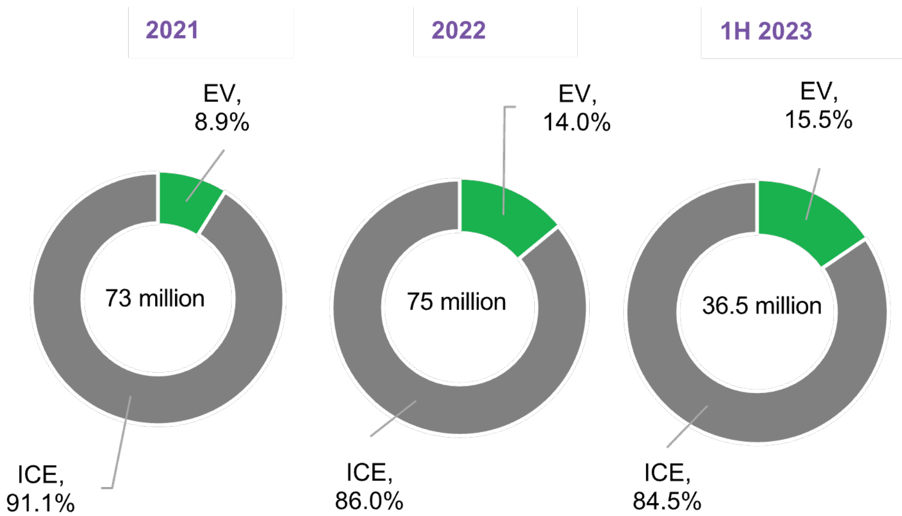




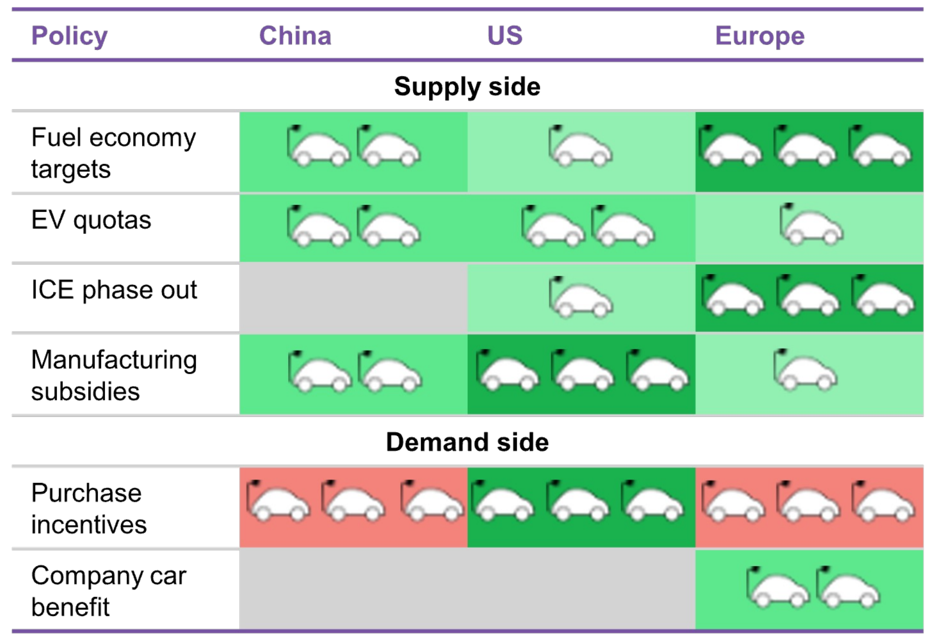
BloombergNEF 2023

- A cumulative total of 41 million EVs—including 29 million BEVs—were sold by the end of 2023, up from just 10 million at the end of 2020.
- Most of these vehicles are still on the road, which means that EVs now make up about 3% of the global fleet of passenger vehicles.
- China and Europe are home to 80% of that EV fleet.

Global EV sales



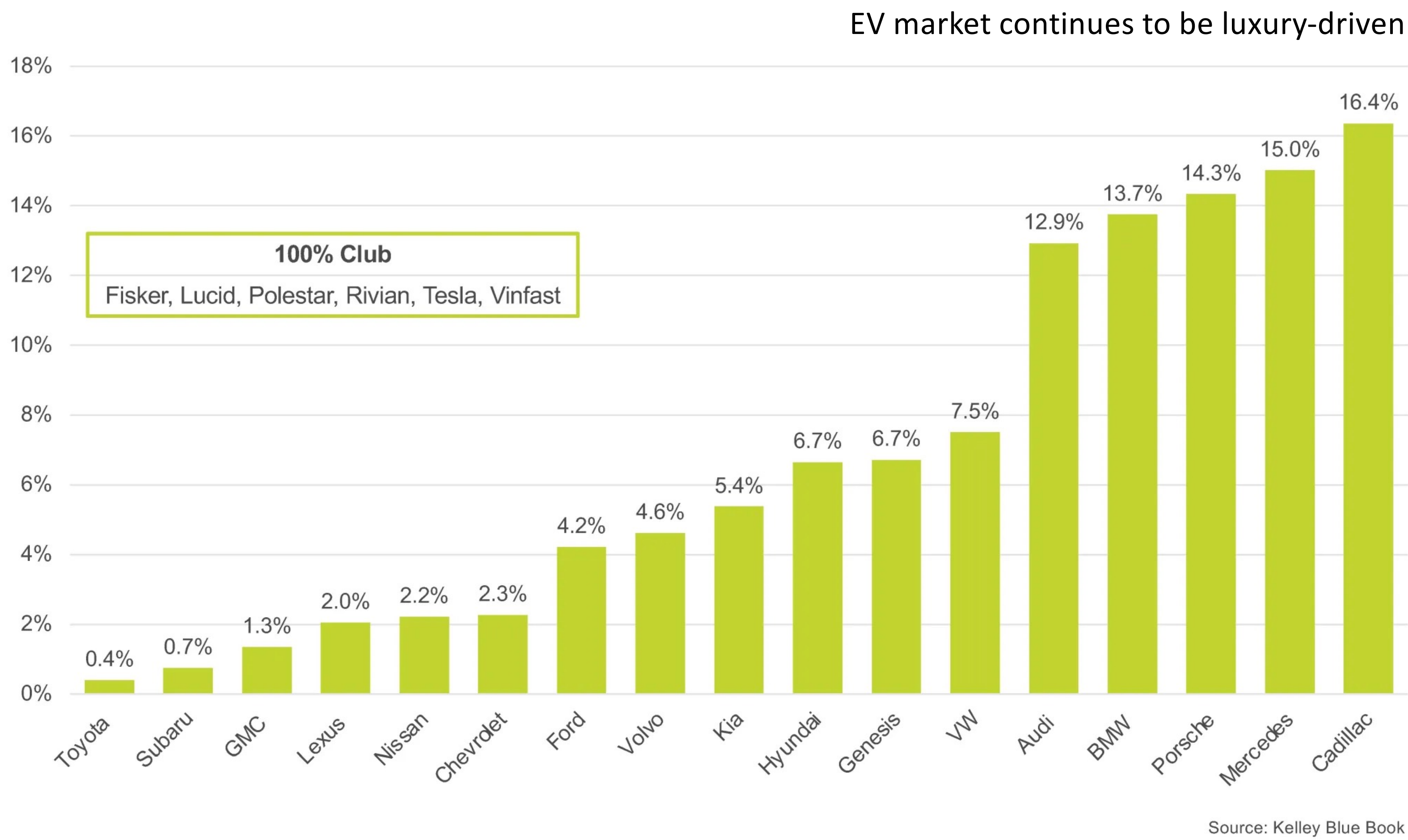
Major EV policies in three key EV markets



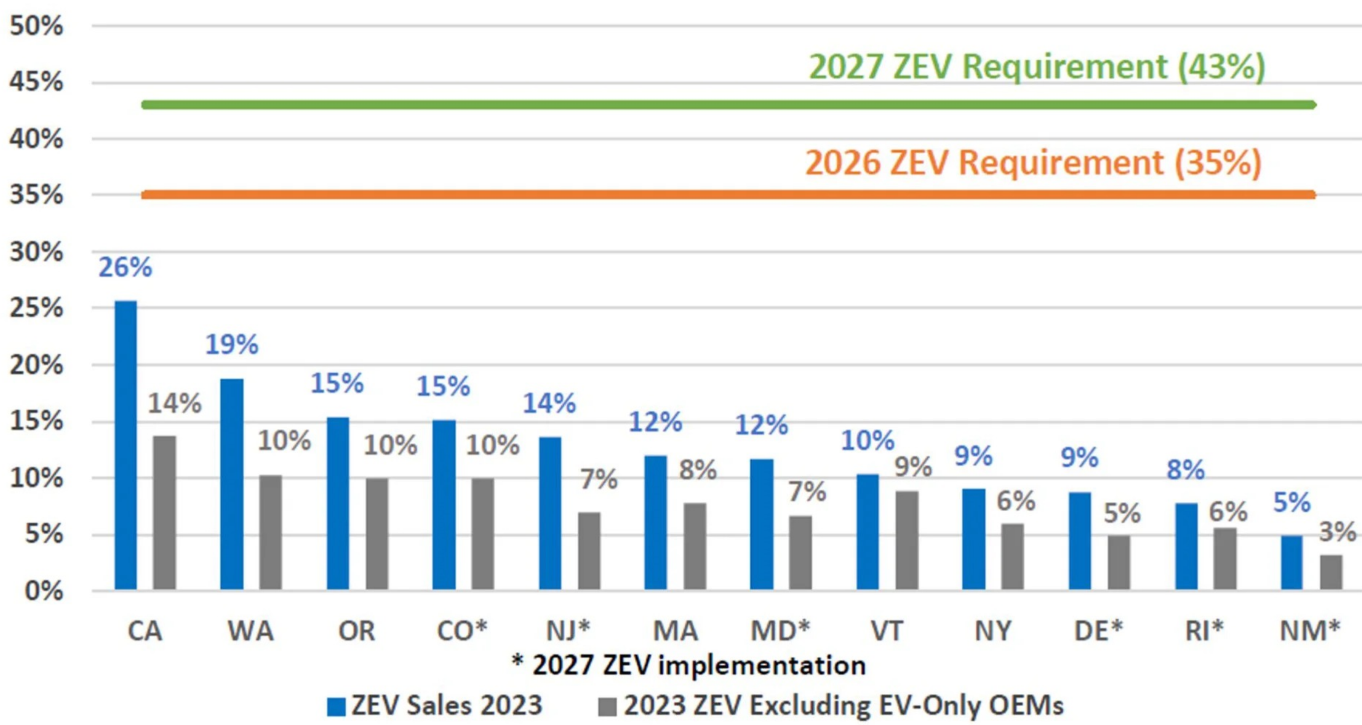
- EVs include BEVs and PHEVs
- Sales driven by EV policies

BloombergNEF 2023

EV sales share by brand, Q1 2024



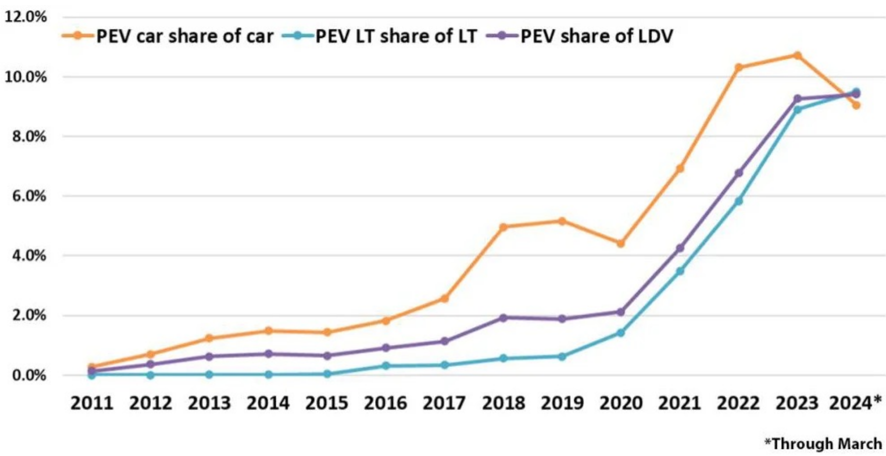
EV sales by state (Section 177) vs 2026-27 ZEV sales mandates



2023 Calendar Year ZEV Sales Rates in California and Section 177 States Compared to ACC II Requirement in MY2026 and MY2027. Note: ZEV sales requirements increase to 50% in 2029, 76% in 2031 and 100% in 2035 leaving little time to make up sales deficits.

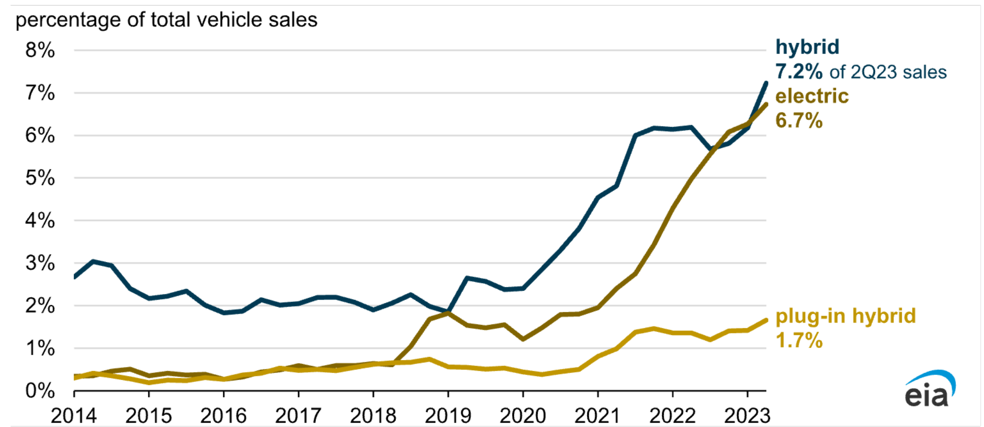
Source: Automotive Alliance

EV market trends



US yearly car and light truck (LT) PEV shares

[Argonne]()



US quarterly light-duty vehicle sales by powertrain

[US EIA]()

New BEV market share in Europe-28

[Jato Dynamics]()

Customer signals

Hertz is selling 20,000 EVs—about one-third of its electric car rental fleet—due to lackluster customer demand and high repair and maintenance costs.

[J.D. Power](): Consumer interest in EVs declines for fourth consecutive month
(March 29, 2024)

Manufacturers adjust EV plans, turn to hybrids

FORD

Ford to expand hybrid vehicles, push back launch of 3-row EVs to stay competitive

Phoebe Wall Howard
Detroit Free Press

Published 10:01 a.m. ET April 4, 2024 | Updated 5:20 p.m. ET April 4, 2024

CAR AND DRIVER RESEARCH CARS SIGN

SUBSCRIBE REVIEWS NEWS WHAT'S MY CAR WORTH? BUYER'S GUIDE

Home / News

GM Bringing Back Plug-In Hybrids, Chevy Equinox Could Be the First

CEO Mary Barra said the upcoming PHEV powertrain for the U.S. is already in production elsewhere, suggesting it could come from existing China-market models.

BY ERIC STAFFORD PUBLISHED: FEB 16, 2024

REUTERS World Business Markets More Register

My View Following Saved

Autos & Transportation | ADAS, AV & Safety | Sustainable & EV Supply Chain | Workforce

Tesla to lay off more than 10% of staff globally as sales fall

By Victoria Waldersee

April 15, 2024 9:46 AM EDT · Updated an hour ago

Forbes

FORBES > LIFESTYLE > CARS & BIKES

Mercedes-Benz Shelves EV-Only Plan In Favor Of More Gas-Powered Cars

Peter Lyon Contributor

Based in Tokyo for over 30 years I focus on all things automotive.

Feb 28, 2024, 12:12pm EST

COMPANY NEWS | ARTICLE

COMPANY NEWS | News Wire Sep 26, 2023

Volkswagen Cuts EV Production at German Sites as Demand Craters

Monica Raymunt, Bloomberg News

CARSCOOPS

ELECTRIC

U.S. Dealer EV Inventories Have Doubled, No Wonder Automakers Are Scaling Back Production

Dealers are holding 114 days of supply of electric vehicles, up from only 53 days a year ago

Ford Halves 2024 Electric F-150 Production Plans on Slowing Demand

December 14, 2023 EnergyNow Media

CARSCOOPS

REPORT

Audi Scales Back EV Rollout, Will Continue To Introduce PHEV, ICE Cars In The Near Future

Electric, internal combustion, and plug-in hybrid vehicles will help keep Audi afloat in the next couple of years

by Sebastien Bell December 18, 2023 at 16:34

Bloomberg Subscribe

Apple Car: Mark Gurman Live Q&A | Electric Car Abandoned | How App

Technology

Apple Dials Back Car's Self-Driving Features and Delays Launch to 2028

- After board meetings, car downgraded to Level 2+ autonomy
- Company pushes back launch from 2026 to 2028 at the earliest

Apple Scales Back Self-Driving Ambitions, Delays Launch

By Mark Gurman
January 23, 2024 at 1:40 PM EST

Contact info

- Thank you!

  - Addy Majewski
  - DieselNet.com
  - +1 905-399-4198
  - wam2@dieselnet.com

Heavy Duty and Nonroad Emission Controls Progress in 2023

Christopher Sharp - SwRI

Southwest Research Institute

Initial Thoughts on HD and NR Emissions

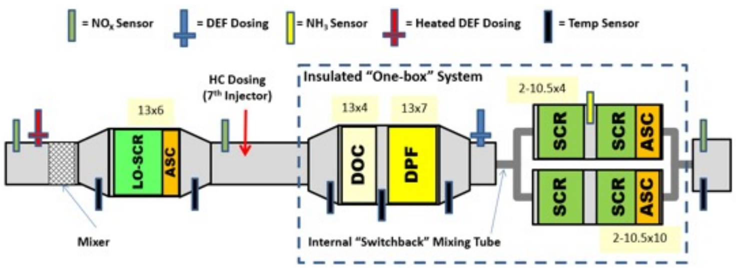
- On-highway commercial vehicle emission standards in U.S. and EU have pushed for more tailpipe NO_X reductions, but they have diverged
  - U.S. EPA / CARB **50-70** mg/kw-hr (**lab**) and **75-100** mg/kw-hr (**field**)
  - Euro VII **200** mg/kw-hr (**lab**) and **260** mg/kw-hr (**field**)

- Regulatory push for Decarbonization has accelerated
  - EPA Heavy Duty Phase 3 GHG (25-60% CO_2 reduction by 2032)
  - EU Parliament approve targets (45%/65%/90% CO_2 reduction by 2030/2035/2040)

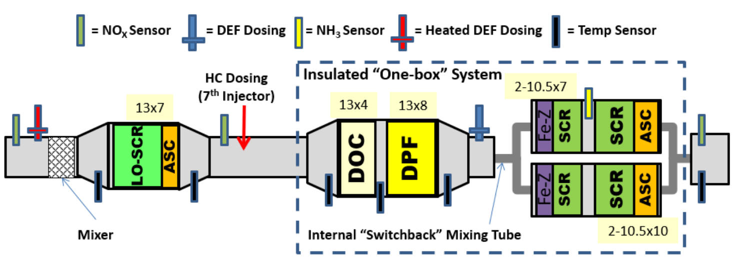
- **Continued innovation in IC engines will be important for meeting these goals**

Continued Low NO_X Technology Demonstration – On Highway

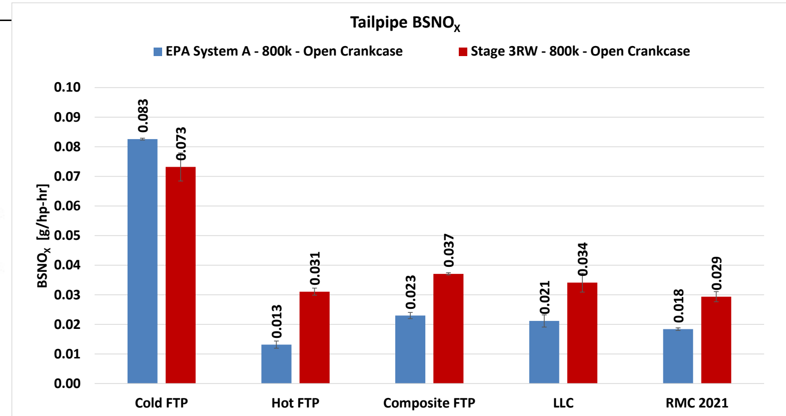
Stage 3RW

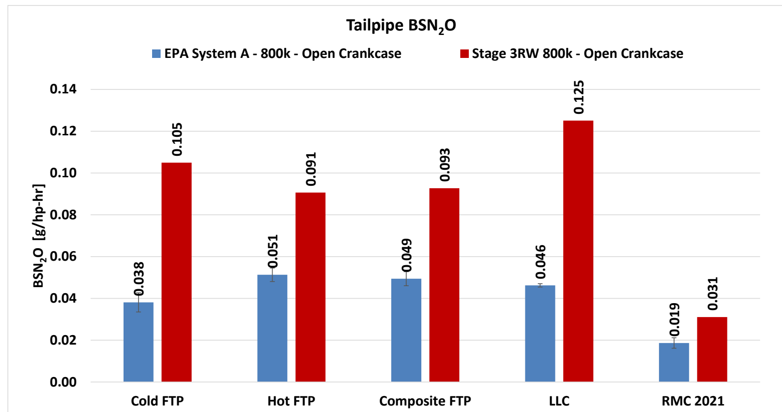


System A



- System improvements
  - Move to Fe-Cu hybrid formulation
  - Improved coatings – low temp durability
  - Slightly higher displacements for margin



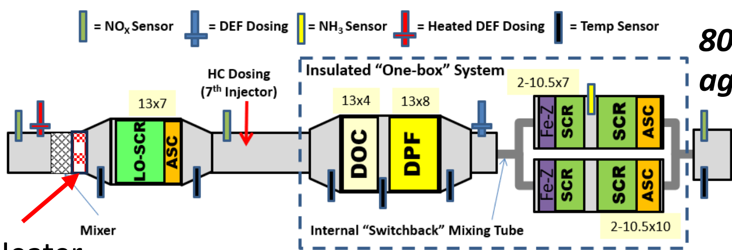


Results after 800,000 miles equivalent DAAAC aging

- Improved Tailpipe NO_X emissions at end-of life
  - 11-14 mg/hp-hr lower than previous system design
- Further 6-8 mg/hp-hr available if closed crankcase is used
  - Warmed-up emissions < 0.01 g/hp-hr at end-of-life
- Significantly lower Tailpipe N_2O emissions beyond end-of-life
  - Half of EPA standard

2024-01-2129

Aftertreatment e-Heater as a Technology Lever



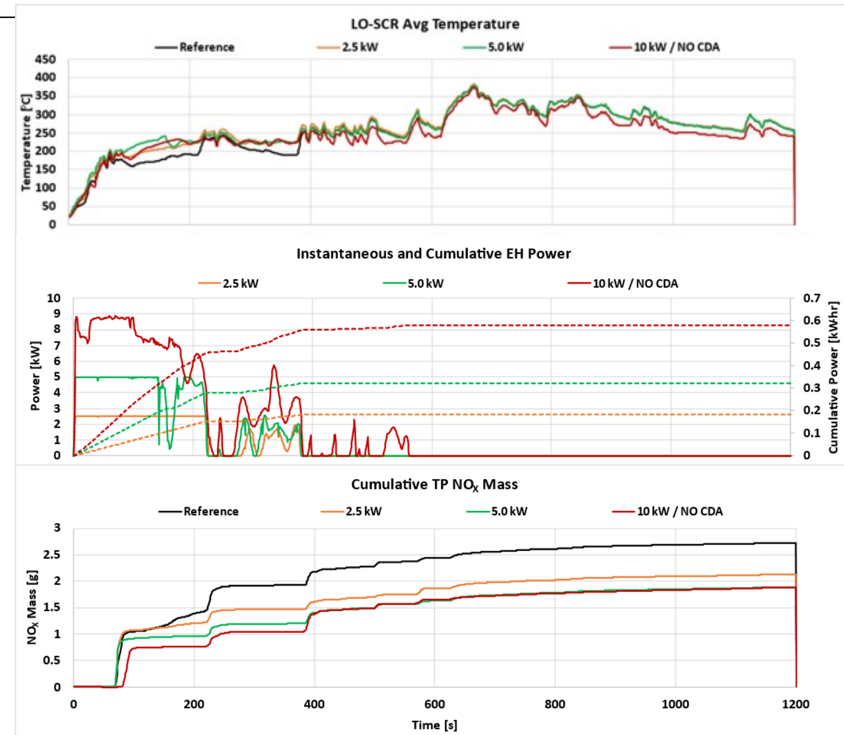
e-Heater

800,000 mile, DAAAC aged AT system

2024-01-3011

(Eaton, Emitec, SwRI)

Cycle	CDA Enable	Power Level	TP NO_x [g/hp-hr]	$BSCO_2$ [g/hp-hr]	CO_2 Savings %
Composite HD-FTP	ON	No Heater	0.026	520	-
		2.5 kW	0.020	519	0.2
		5.0 kW	0.019	520	0.0
	OFF	10 kW	0.022	527	(-1.3)
Cycle	**CDA Enable**	**Power Level**	**TP NO_x [g/hp-hr]**	**$BSCO_2$ [g/hp-hr]**	**CO_2 Savings %**
LLC	ON	No Heater	0.025	617	-
		2.5 kW	0.017	621	(-0.7)
		5.0 kW	0.014	622	(-0.8)
	OFF	10 kW	0.018	680	(-10.2)



EH power needed	Base truck power	Total power	Practical max current	Minimum system voltage
2.5kW	3kW	5.5kW	250-275A	24V
5kW	3kW	8kW	250-275A	36V
10kW	3kW	13kW	250-275A	48V

e-Heater enhances performance at FUL, higher power (10kw) met 2027 standards without CDA (but low load CO_2 impacted without CDA)

Super-Truck II : 55% BTE & 2X freight efficiency ✓

Daimler	Volvo	Cummins / Peterbilt	Navistar	PACCAR / Kenworth

A. Joshi, COMVEC 2023

https://www.energy.gov/eere/vehicles/annual-merit-review-presentations

Improved combustion

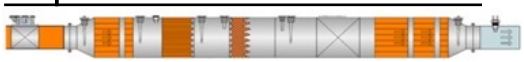
High CR + 0.3 – 0.8 BTE
Thermal barrier coatings - 1 % BSFC
Lower friction +0.5% BTE

Improved air handling


Eaton

EGR pump (+0.9 BTE)
Miller cycle LIVC
High efficiency turbochargers

Improved after-treatment

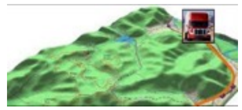

Navistar

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

Waste heat recovery

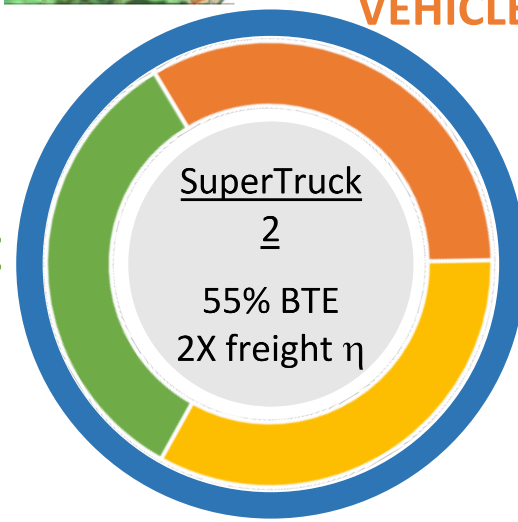
~ +3 – 4.5% BTE
ORC with cyclopentane
Dual entry turbine

Model-based control



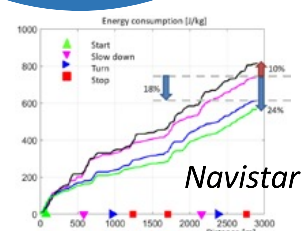
ENGINE

VEHICLE



TRANSMISSION, ELECTRIFICATION

Predictive cruise control



Navistar

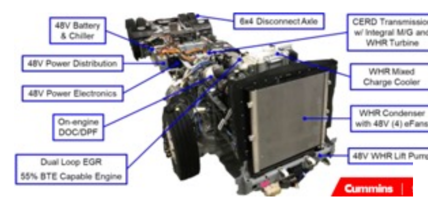
Weight reduction

Navistar: ~ 4,000 lbs (trailer, frame)
Cummins: ~4,700 lbs (+ trailer solar panels)
PACCAR: 28%

Aerodynamics & tires

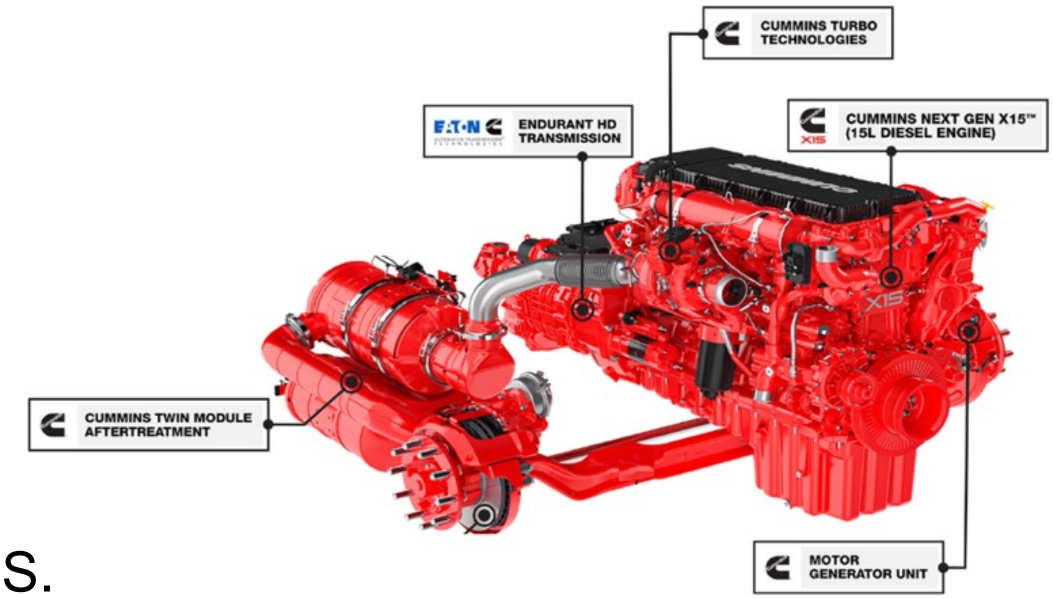
Aero drag reduced by ~ ~60% by NAV, Kenworth, Cummins, PACCAR
Rolling R : NAV 22% ↓, Cummins 33% ↓

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



Cummins

Low NO_X Technologies are Moving Towards Production



- LO-SCR is in production in U.S.
- Navistar S13 engine dual-stage aftertreatment system
  - Dual SCR Dual Dosing

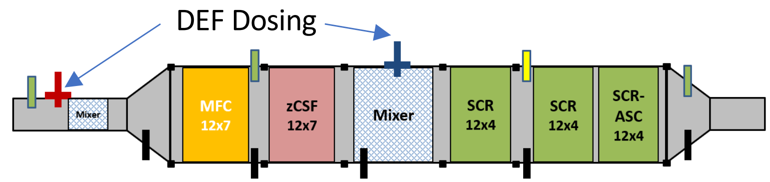
- Cummins announced use of 48V E-Heater solution for 2027

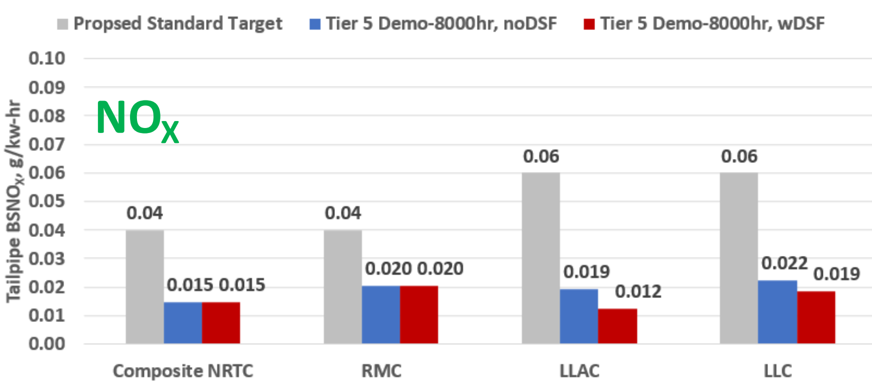
CARB Nonroad Tier 5 Low NO_X Demonstration Program

- Overall goal of Nonroad Low NO_X effort is to demonstrate feasibility of off-road diesel emission control technologies to reduce emissions to the levels given below:
  - NO_X by 90% from Tier 4f (nominal target of 0.04 g/kw-hr)
  - PM by 75% Tier 4f (nominal target of 0.005 g/kw-hr)
  - Demonstration Cycles = NRTC, RMC C1, LLAC (eventually Nonroad LLC)
  - 8000-hour FUL DAAAC-aged (matches current requirement)
- CARB is pursuing GHG reductions as added element to program
  - Target 5-8.6 % GHG reduction while meeting NO_X target

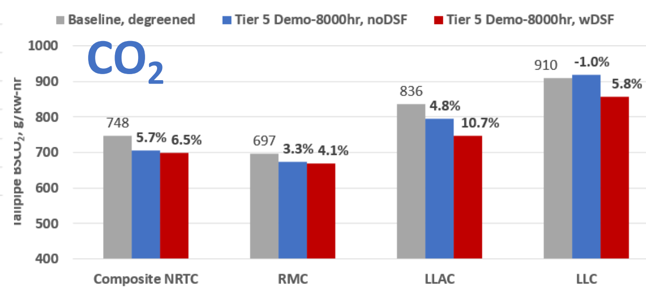
John Deere 6068 (6.8L) Tier 4f Engine (187kw)

Final AT System (Dual SCR-Dual Dosing)





Results are CCV, Open crankcase +0.01 g/kw-hr

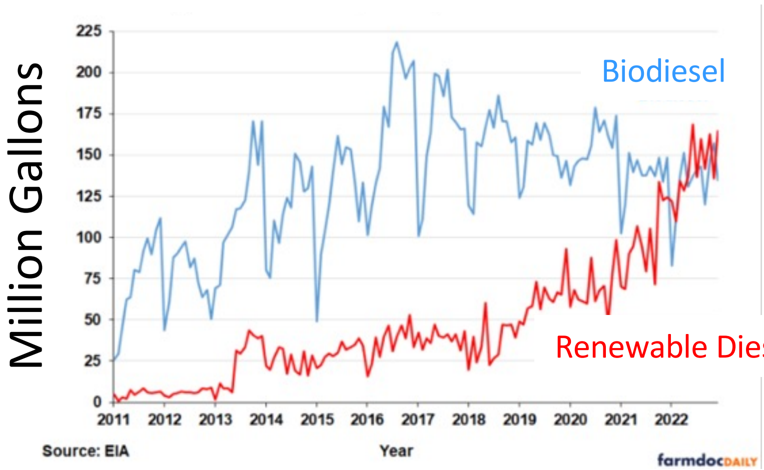


MFC *= Multi Function Catalyst (LO-SCR with in-situ oxidation)*
zCSF *= Zone coated catalyzed soot filter*
DSF *= Dynamic Skip Fire (Cylinder Deactivation)*
CCV *= Closed Crankcase Ventilation*

Renewable Diesel and Biodiesel

Diesel Consumed by Transport in 2022 : ~ 46B gal
Renewable Diesel & Biodiesel consumption
~ 1.8B gal per year (each)
→ So ~ 7% conventional diesel displaced

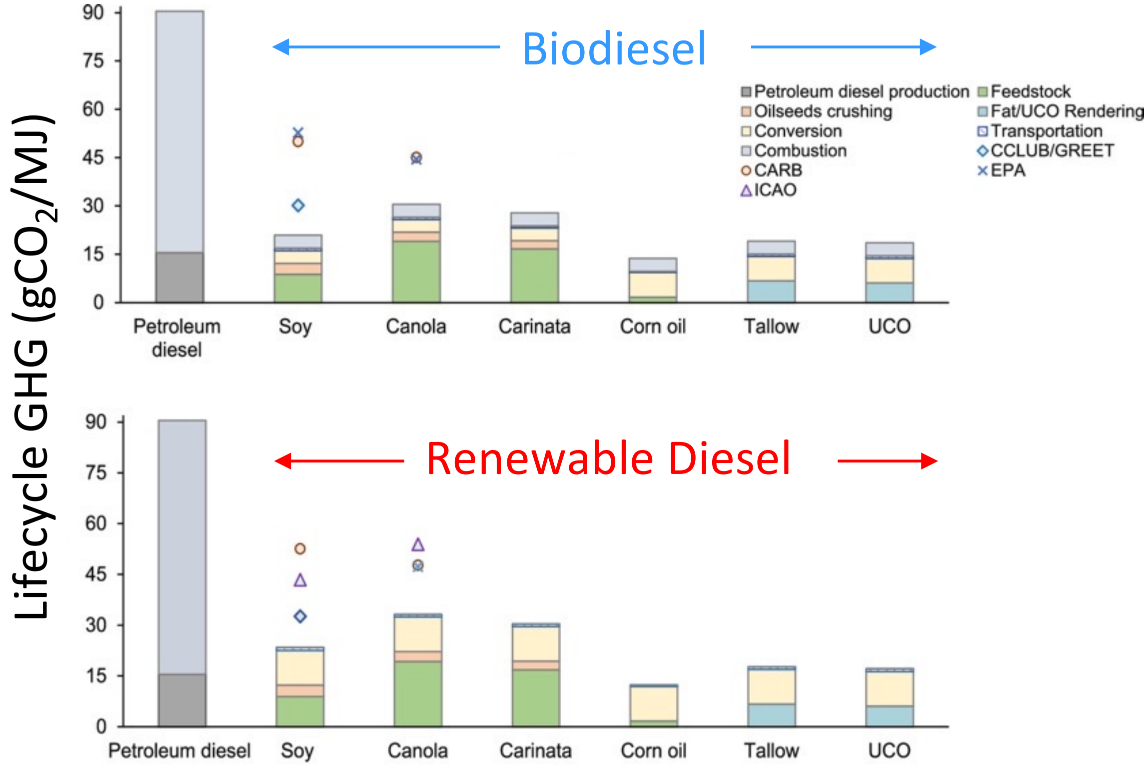
Monthly fuel consumption



farmdoc daily (13):72, Department of Agricultural and Consumer Economi
University of Illinois at Urbana-Champaign, April 19, 2023

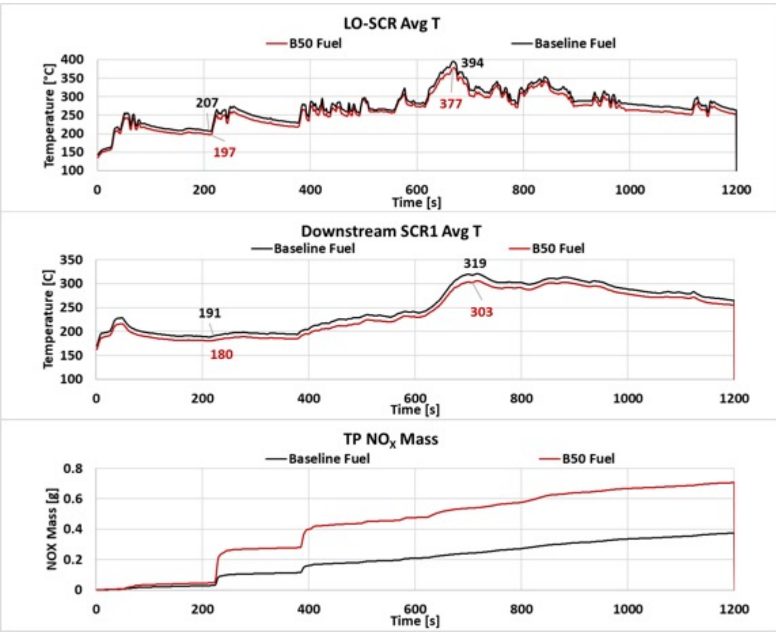
A. Joshi, COMVEC 2023

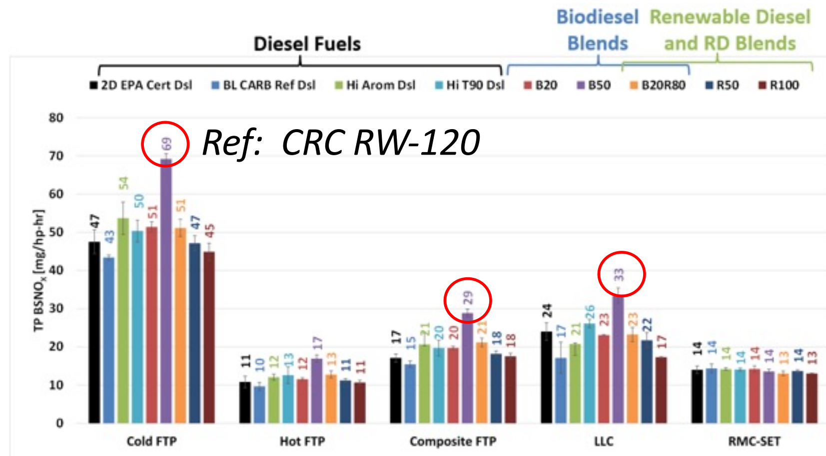
Lifecycle Analysis : BD & RD emissions ~ 63 – 77% lower vs. diesel

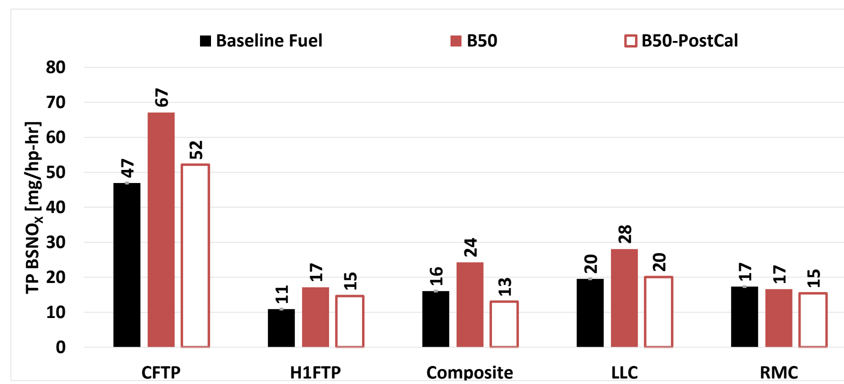


Argonne National Lab, Environ. Sci. Technol. 2022, 56, 12, 7512–7521

Adapting to Renewable Diesel Fuels – Big Potential GHG Reductions But Not Challenge Free…

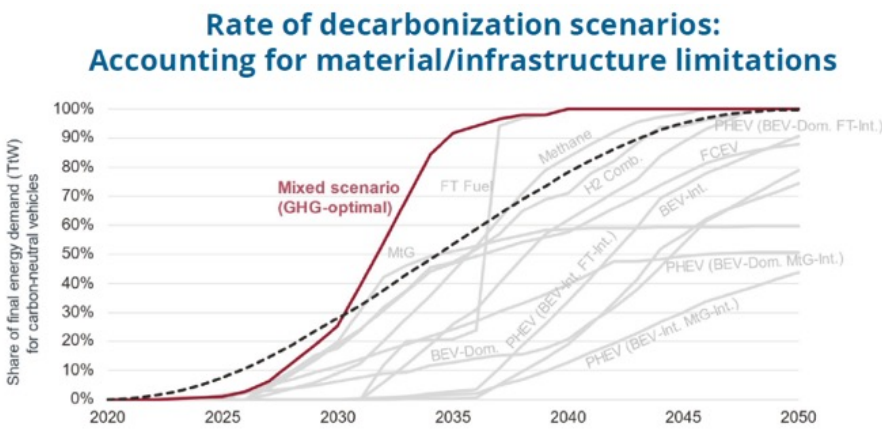






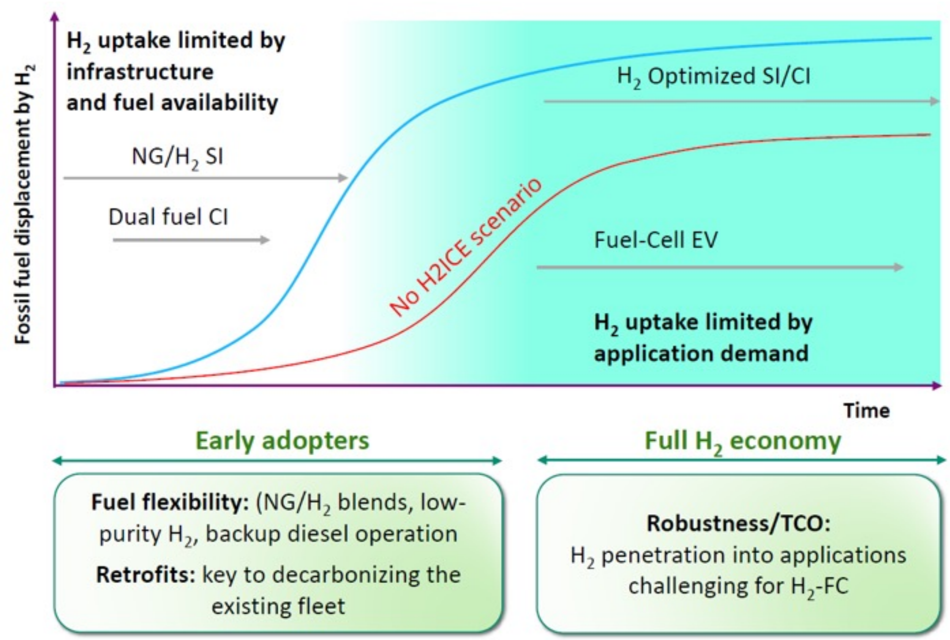
- B50 Blend on Stage 3 Engine showed significant tailpipe impact
- Primary root cause is lower exhaust temperatures due to loss of fuel energy
- Engine recalibration can adapt IF fuel change can be sensed

The Case for H2-ICE…



BEV	Battery-Electric Vehicle	PHEV	Plug-In Hybrid Electric Veh.
FCEV	Fuel-Cell Electric Vehicle	Dom.	EU domestic sourcing
FT	Fischer-Tropsch	Int.	International sourcing
MtG	Methane to Gasoline		

Source: FVV Future Fuel Study IVb, Project Nr. 1452, Final Report, 2022; https://www.fvv-net.de/fileadmin/Storys/Wie_schnell_geht_nachhaltig/FVV_H1313_1452_Future_Fuels_FVV_Fuel_Study_IVb_2022-12.pdf

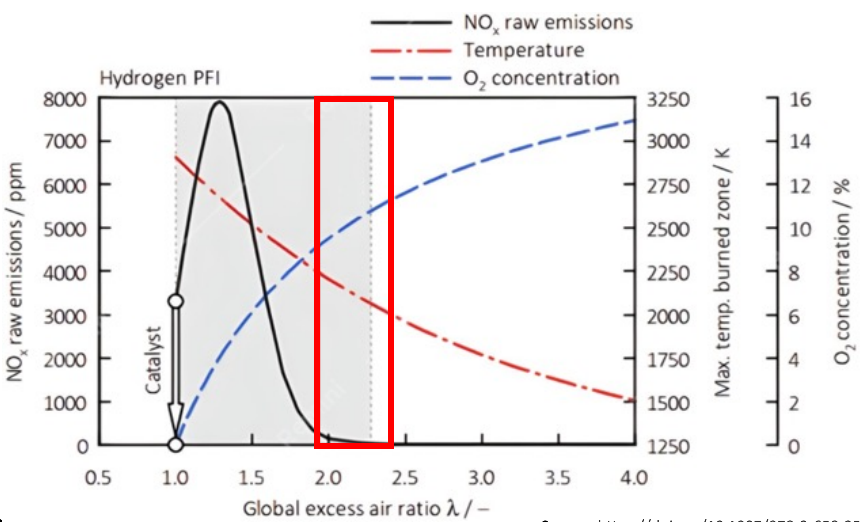


Source: energy.gov – h2IQ hour Feb 2023

- Lower cost, nearer term availability than FCEV and BEV for MHD/HHD
- H2-ICE creates more demand for H_2 – and is not limited by H_2 purity

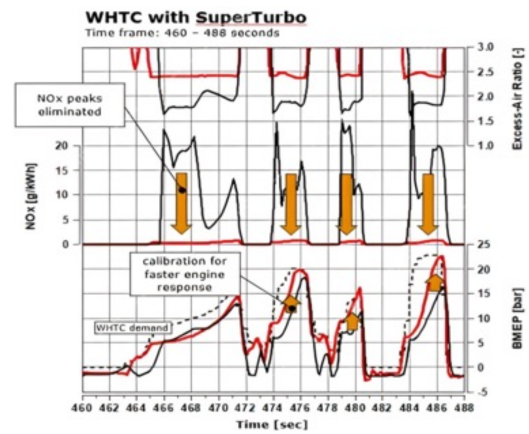
H2-ICE Exhaust Trade-offs

- H_2 combustion is stable to λ > 3
  - Near-zero NO_X
  - Increasing potential for H_2 slip
  - Heavy boosting requirements
- Significant decrease in exhaust temperature
  - Less enthalpy available for turbocharger
  - Less heat available for aftertreatment



Source: https://doi.org/10.1007/978-3-658-35061-1

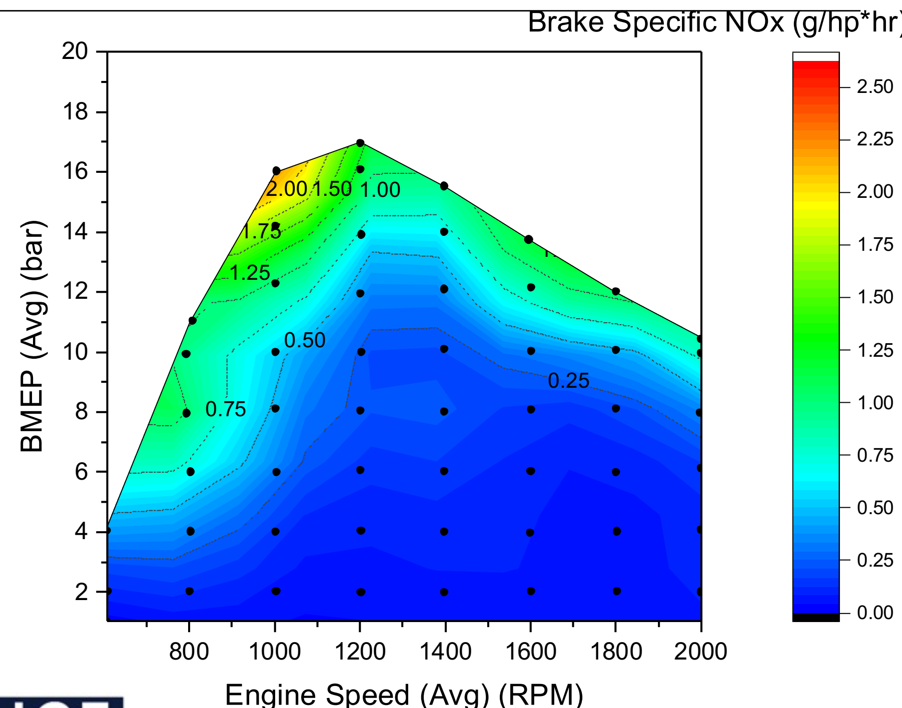
- Potential for NO_X < 0.2 g/kw-hr engine-out BUT…
  - This is still not low enough to meet U.S. standards
  - Performance is an issue
  - Exhaust temperatures are too low
- A better approach might be λ ~ 2.1 – 2.3
  - Target 0.5 to 1 g/kw-hr NO_X
  - Better transient performance
  - Higher exhaust temperatures for AT system

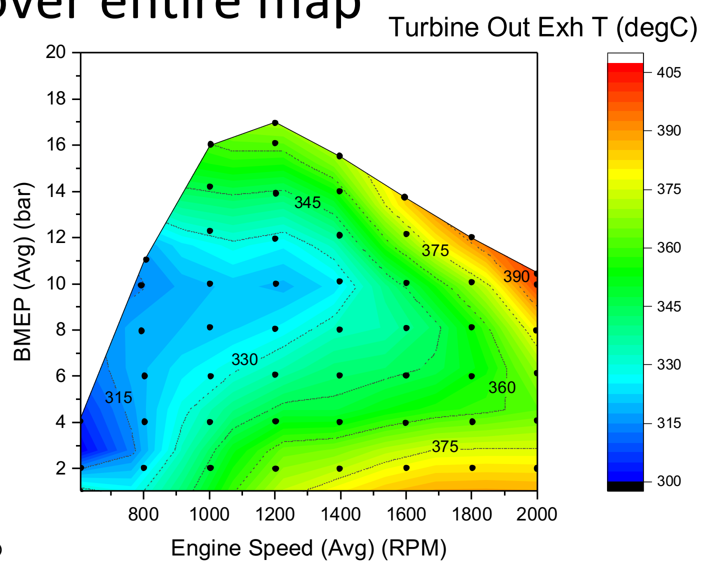


Source: SuperTurbo

H2-ICE – NO_X and Temperatures

- Target λ=2.2 to λ=2.4 range
- EO NO_X is well below diesel range (cycle NO_X in 0.5-1 g/kw-hr range)
- Turbine out exhaust temperatures > 300°C over entire map



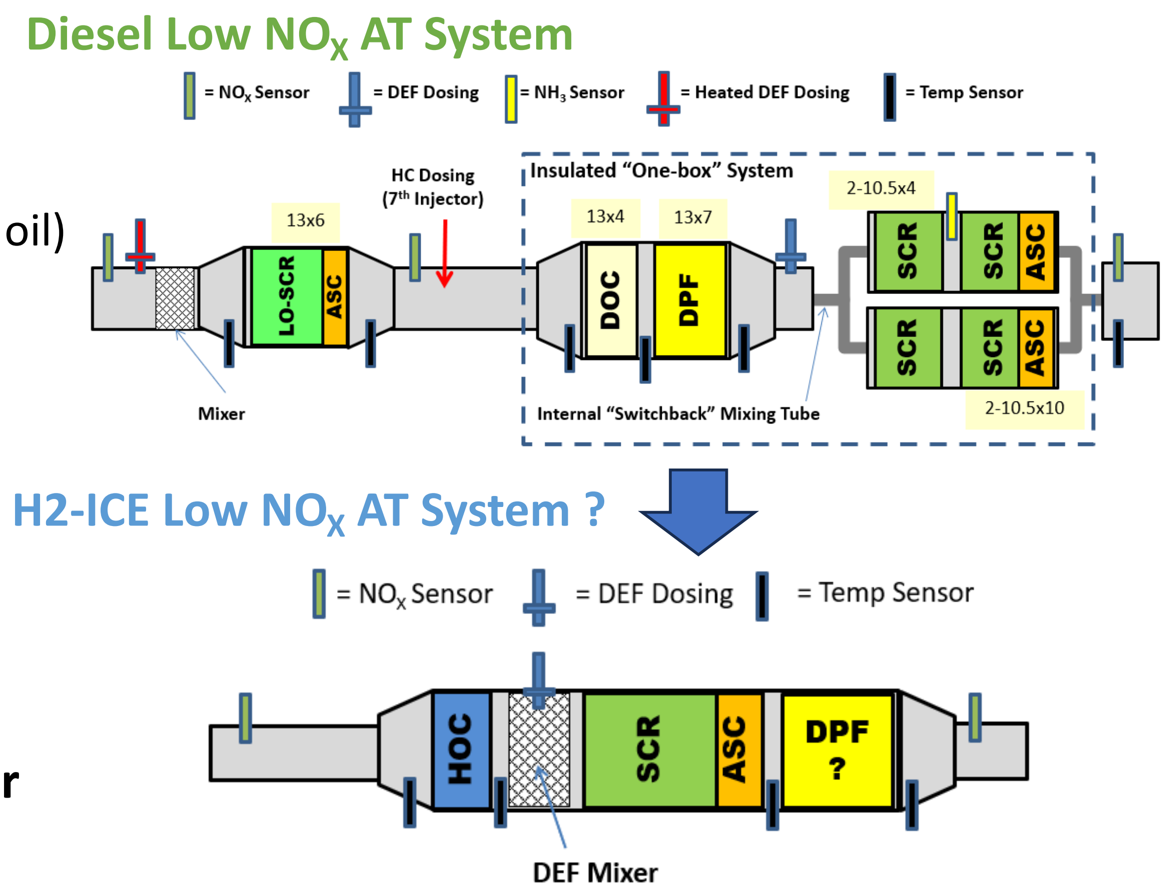


This is better for aftertreatment than lowest possible EO NO_X

From SwRI H2-ICE Consortium Demonstration

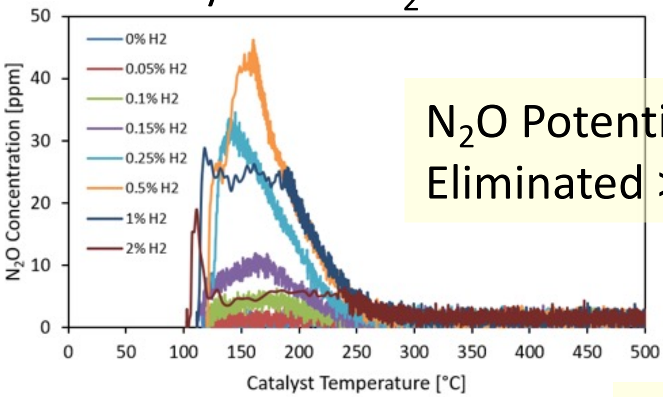
H2-ICE Aftertreatment

- **Opportunities with H2-ICE**
  - Lower engine-out NO_X
  - No soot
  - Near-zero sulfur (only from lube oil)
  - No HC
- **Challenges with H2-ICE**
  - High water content
  - Hydrogen slip
  - Lower exhaust temperatures (?)
  - Selectivity (N_2O)
- **Potential for AT Simplification**
- **H2-ICE tailpipe NO_X can be lower than Diesel Low NO_X**

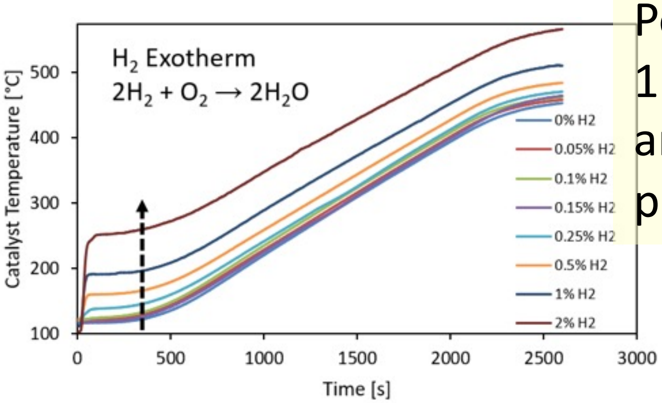


H2-ICE Aftertreatment Details

DOC/HOC – N_2O and Exotherm

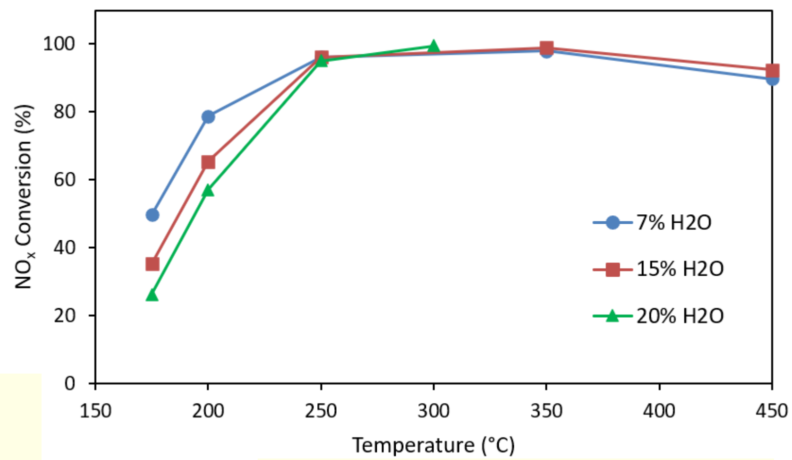


N_2O Potential Eliminated > 250°C



Potential exotherm at 110°C for rapid warmup and elimination of N_2O problem

Water Impact on Cu-Zeolite SCR



Water Impact eliminated > 250°C

- If aftertreatment is used, operating closer to λ=2.2 results in temperatures > 250°C, removing many potential H2-ICE issues

Low Lifecycle Carbon Fuel Effects on Emissions

Josh Pihl

Oak Ridge National Laboratory

Acknowledgments

- **For sharing insights and results:**
  - Mike Bunce (MAHLE Powertrain)
  - Brian Kaul (Oak Ridge National Laboratory)
  - Will Northrop (University of Minnesota)
  - Christine Rousselle (Universite d'Orleans)
  - Sebastian Verhelst (Lund University, Ghent University)
- **For inviting me to participate in this panel:**
  - Andrea Strzelec (USCAR)
  - Ron Silver (retired)
- **For funding:**
  - Nick Hansford, Siddiq Khan, Kevin Stork, Gurpreet Singh (U.S. Department of Energy Vehicle Technologies Office)
- **For feedback:**
  - Jim Szybist, Scott Curran, Todd Toops (Oak Ridge National Laboratory)

Overview

- Low lifecycle carbon fuels will be needed to achieve substantial greenhouse gas emissions reductions in:
  - Legacy IC engine vehicles in the near term
  - Hard-to-electrify sectors in the long term
- Engines running on low lifecycle carbon fuels still must meet emissions regulations
  - Emissions regulations will continue to get more stringent
- Biofuels are easier to implement than other options
  - Renewable diesel, renewable gasoline: no expected emissions challenges
  - Biodiesel, bio-oils: may require changes to engine calibrations, updated fuel specs
  - Probably not enough biomass to fuel all transportation sectors in the long term
- E-fuels/synthetic fuels (hydrogen, methanol, ammonia):
  - May be needed in some transportation sectors
  - Have very different emissions profiles compared to traditional fuels

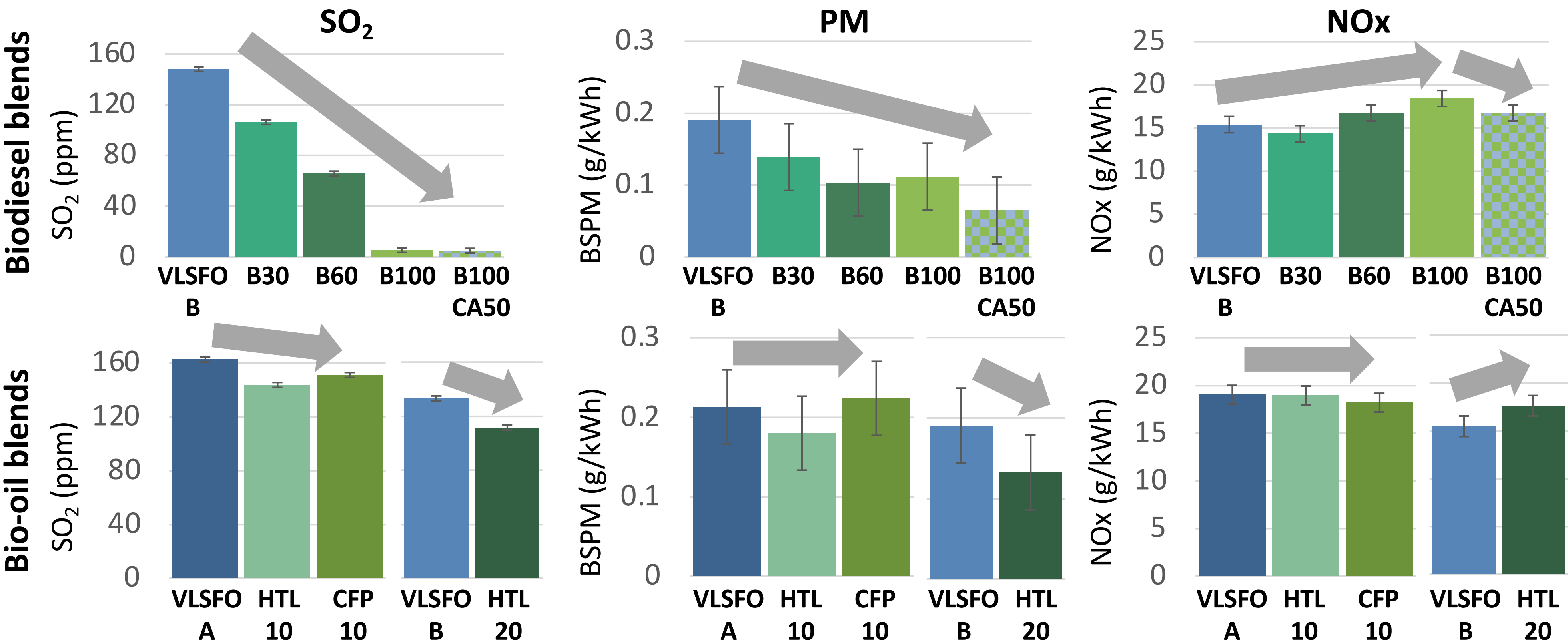
Summary of potential emissions challenges and benefits with LLCFs

Fuel	S	PM	CO	UHC	NOx	Other questions
Biodiesel	↓	↓	—	—	?	Aftertreatment durability[1]
Bio-oils	↓	↓	—	—	?	Compatibility (blends, hardware)
Methanol	⇩⇩	⇩⇩	?	?	?	Formaldehyde
Hydrogen	⇩⇩	⇩⇩	⇩⇩	⇩⇩	?	
Ammonia	⇩⇩	⇩⇩	⇩⇩	⇩⇩	↑	NH_3, N_2O

[1]See Steve Howell's presentation "Recent Changes in ASTM Biodiesel Quality Standards to Support B20 in New Technology Diesel Engines and Data Testing Needs for Supporting up to B100 in 2027-2031 Ultra Low Emissions Diesel Engines"
PFL 330 Thu 10:00 Room 259

Biodiesel and Bio-oils

Biofuel blends reduce SO_2 and PM in a 1:10 scale 2-stroke marine research engine, while NOx emissions increases can be mitigated through engine calibration

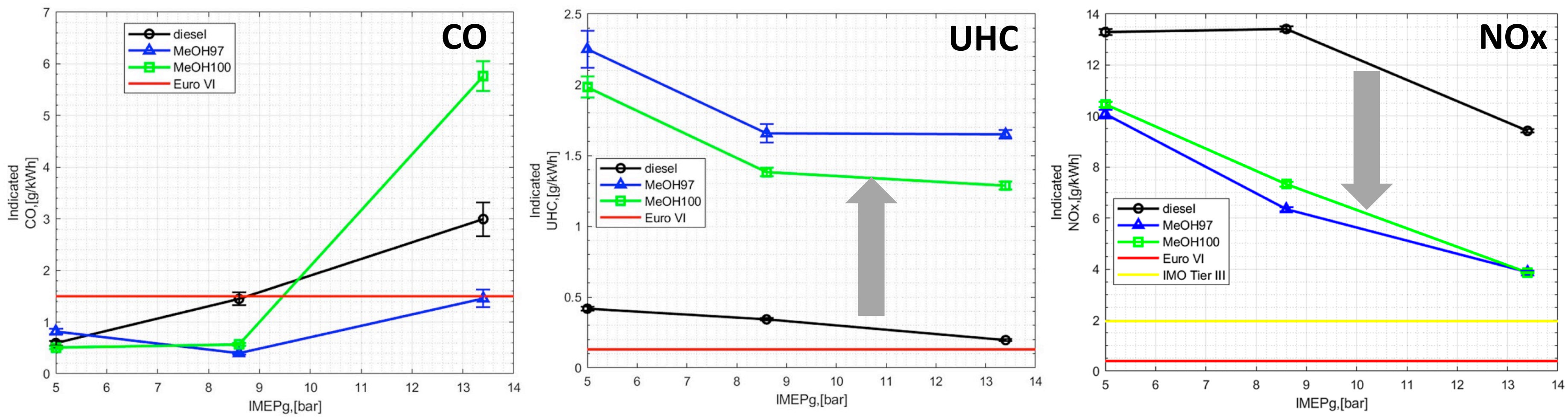


B. Kaul et al., presentation to CRC Real World Emissions Workshop, March 13, 2024

Methanol

Substantially reduced NOx emissions demonstrated in a direct injection methanol-fueled compression ignition engine (SAE 2024-01-2122, Tue 11:00 310A)

- Lund University modified a Scania D13 diesel engine (26:1 CR, high flow injector, intake heater) to run on 100% MeOH or 97% MeOH with PEG ignition improver



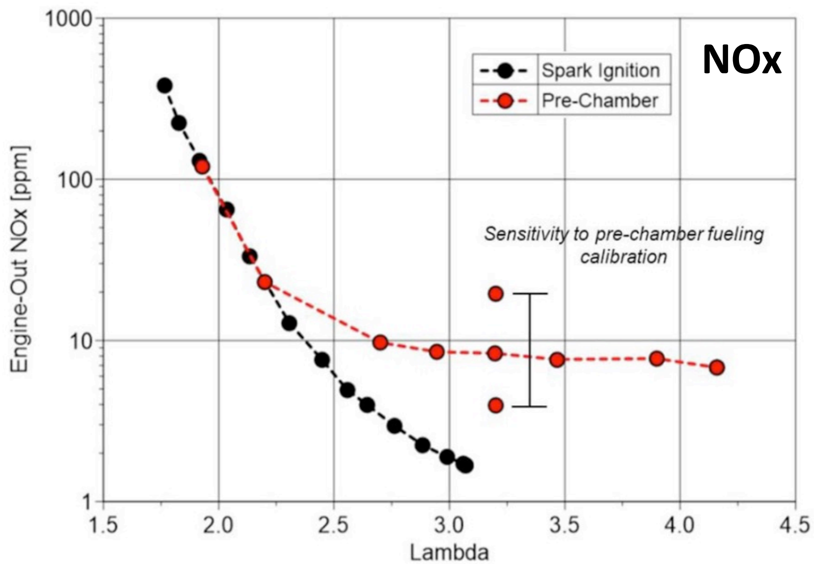
- Compared to baseline diesel operation, **UHC was higher, but NOx was lower**
- ***Minimal formaldehyde was detected*** (PFI studies showed increased formaldehyde)

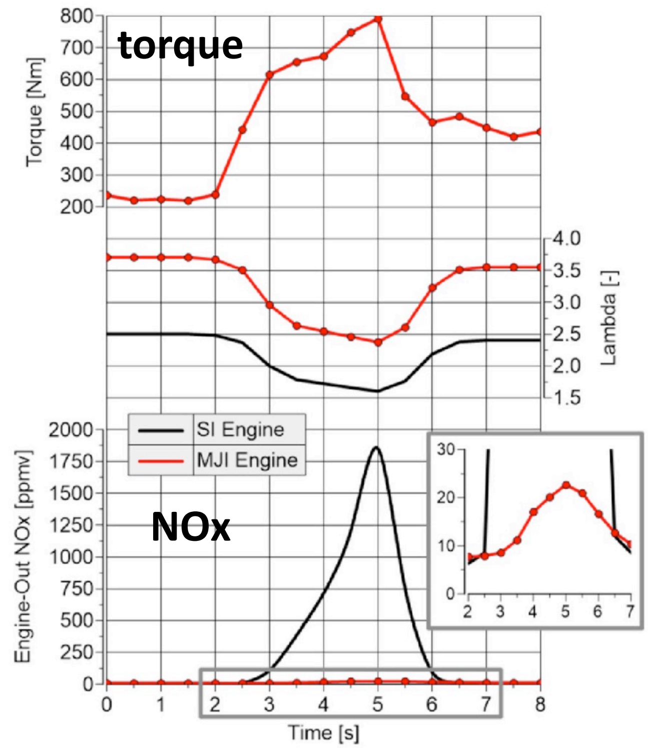
Svensson, M., Tuner, M., and Verhelst, S., “Investigation of Combustion Characteristics of a Fuel Blend Consisting of Methanol and Ignition Improver, Compared to Diesel Fuel and Pure Methanol,” SAE Technical Paper 2024-01-2122, 2024, doi:10.4271/2024-01-2122.

Hydrogen

Ultralean SI combustion results in very low steady state engine out NOx emissions (SAE 2024-01-2610, Wed 1:30 140D)

- MAHLE Powertrain & Liebherr modified a HD diesel engine to run on H_2 with SI and PCSI
- Ultralean (λ > 2.5) operation leads to very low engine out NOx for both SI and PCSI
- Transients can still result in significant NOx emissions
- UEGO error due to H_2 slip may contribute
- **H_2 could be leveraged for lower NOx emissions relative to diesel depending on combustion strategy**

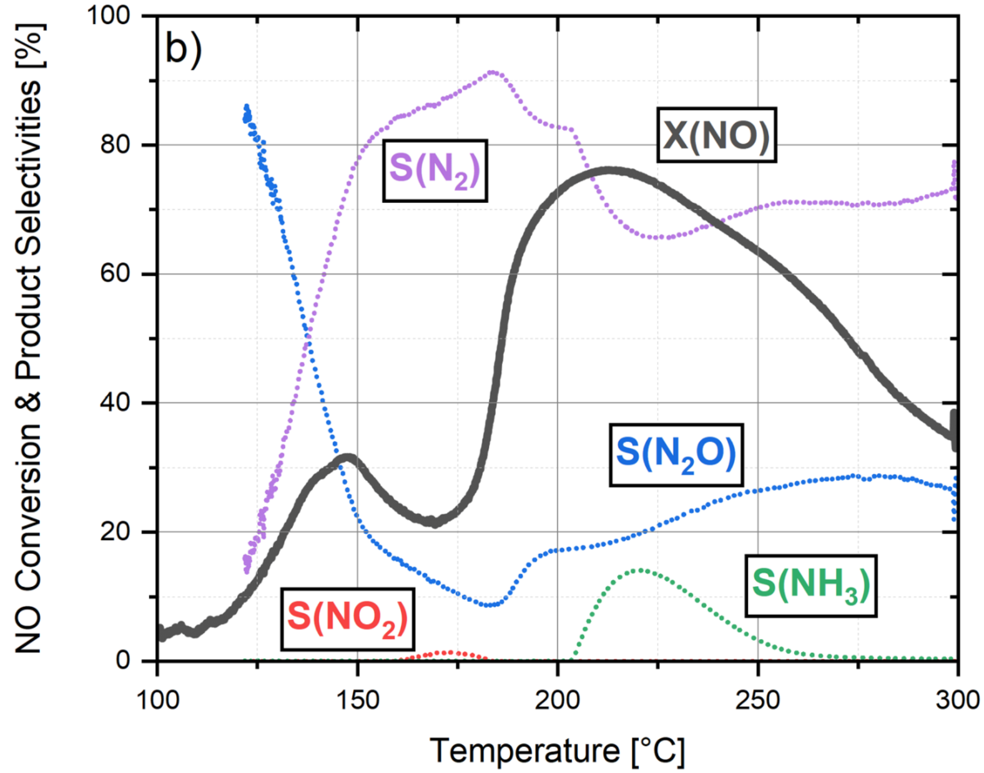




Bunce, M., Seba, B., Andreutti, R., Yan, Z. et al., "Development of a High Power, Low Emissions Heavy Duty Hydrogen Engine," SAE Technical Paper 2024-01-2610, 2024, doi:10.4271/2024-01-2610.

NO SCR by H_2 faces several critical challenges: temperature window, NOx conversion efficiency, N_2O selectivity

- Interest in H_2 IC engines has brought a renewed focus to NO SCR by H_2
- PGM/zeolite catalysts are showing improved performance, but **critical challenges remain:**
  - Limited temperature operating window (~100 °C)
  - Limited peak NOx conversion efficiencies (80-90%)
  - N_2O selectivity is high
    - N_2O GWP = 300 x CO_2
    - 100 ppm N_2O = 3% CO_2

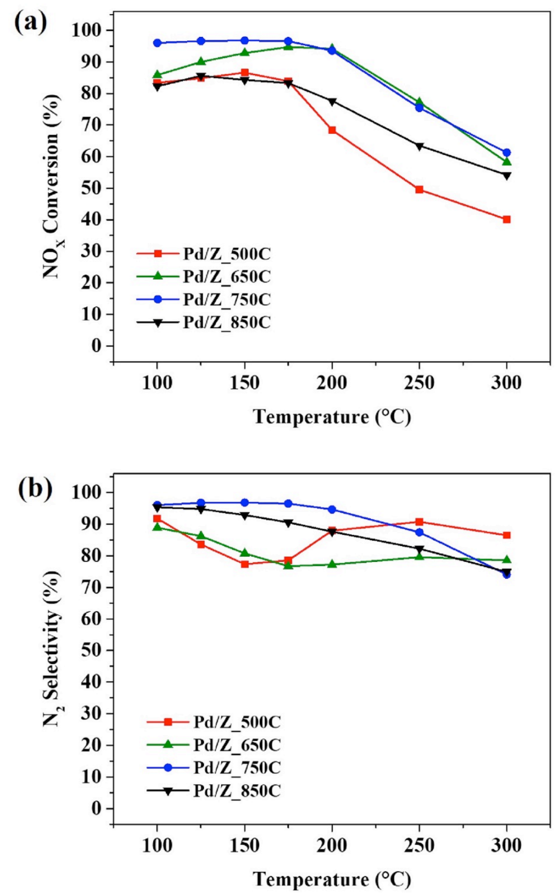


M. Borchers, P. Lott, O. Deutschmann, Topics in Catalysis 2022 doi.org/10.1007/s11244-022-01723-1

Consider experimental conditions when evaluating H_2 SCR data sets

- Questions to ask when evaluating H_2 SCR data:
  - Fresh, degreened, or aged catalyst?
  - Relevant O_2 concentrations?
  - Relevant H_2O concentrations?
  - How much H_2 (fuel penalty)?
    - 2% H_2 in exhaust > 10% fuel penalty
  - N_2O selectivity?
  - Catalyst pretreatment?
    - Example: 30 min under 4% H_2/N_2 at 300 °C

- **Urea SCR is a more likely lean NOx control technology for H_2 IC engines**



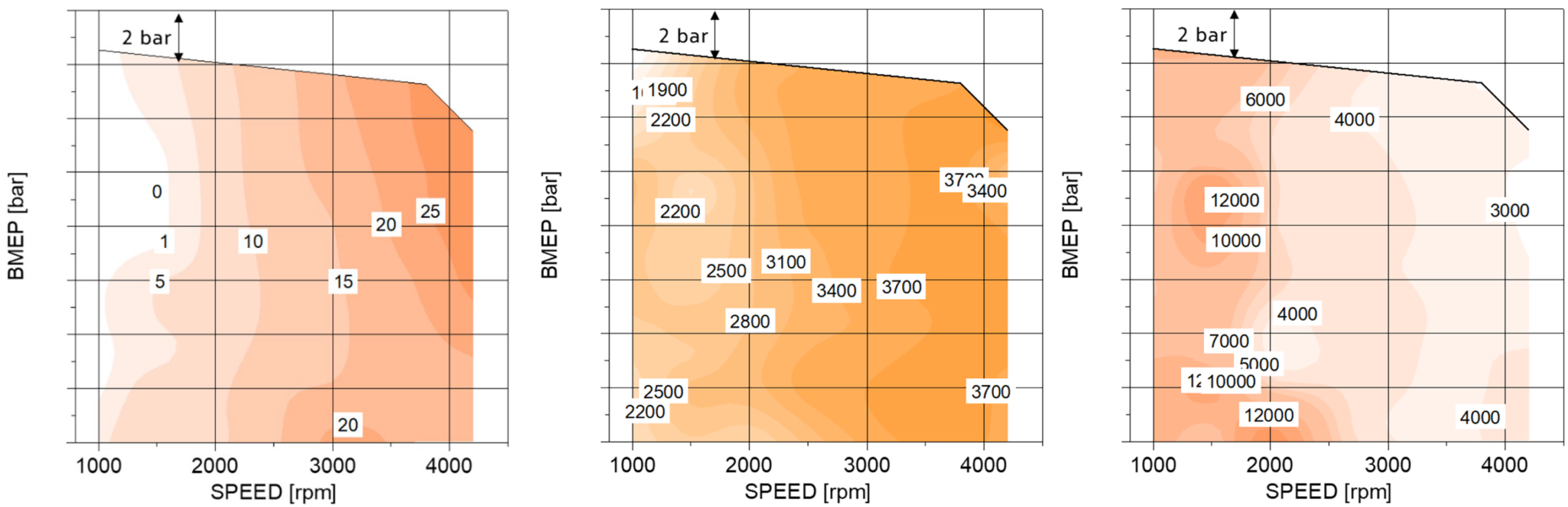
S. Moon et al., Environmental Research 227 (2023) 115707 doi.org/10.1016/j.envres.2023.115707

Ammonia

NH_3 SI engine requires H_2 addition for stable combustion and generates substantial NOx and NH_3 emissions (SAE 2024-01-2818, Thu 2:30 140D)

- Hyundai created an NH_3 turbo DI engine with advanced hardware and controls

H_2 (% energy) **NOx (ppm)** **NH_3 (ppm)**

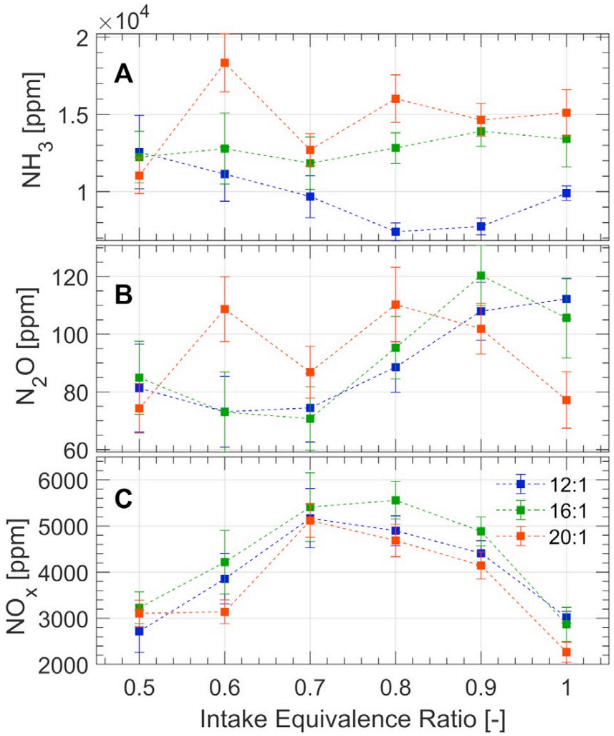


- **NH_3 and NOx emissions high over the entire operating map**; N_2O not reported
- A TWC was insufficient to mitigate both NH_3 and NOx emissions

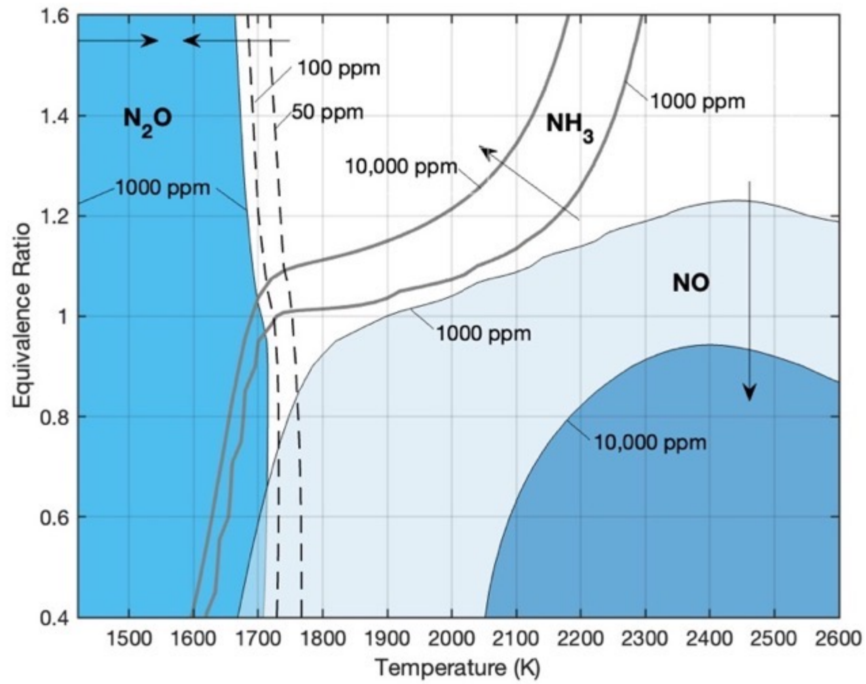
Min, C.K., Lee, S.W., and Baek, H.-K., "Development of Ammonia Direct Injection 4-Cylinder Spark-Ignition Engine," SAE Technical Paper 2024-01-2818, 2024, doi:10.4271/2024-01-2818.

NH_3 combustion experiments consistently show high NOx, NH_3, and N_2O emissions; modeling clarifies emissions reduction challenges (SAE 24PFL-0532, Thu 3:00 140D)

- NH_3 experiments conducted in a CFR engine exhibited high levels of NH_3, NOx, N_2O
- Modeling shows difficulty of finding operating regimes that minimize NH_3, NO, and N_2O, but points to potential strategies



S.A. Regetti, W.F. Northrop, Frontiers in Mechanical Engineer (2024), doi: 10.3389/fmech.2024.1368717



W.F. Northrop, Applications in Energy and Combustion Science 17 (2024) 100245, doi.org/10.1016/j.jaecs.2023.100245

Summary of potential emissions challenges and benefits with LLCFs

Fuel	S	PM	CO	UHC	NOx	Other questions
Biodiesel	↓	↓	—	—	—	Aftertreatment durability
Bio-oils	↓	↓	—	—	—	Compatibility (blends, hardware)
Methanol	⇩⇩	⇩⇩	?	↑	↓	Formaldehyde
Hydrogen	⇩⇩	⇩⇩	⇩⇩	⇩⇩	?	
Ammonia	⇩⇩	⇩⇩	⇩⇩	⇩⇩	⬆	NH_3, N_2O

- Engine calibration can mitigate NOx increases from biodiesel and bio-oils
- Methanol typically decreases NOx, but increases UHC and possibly CO
- Questions remain regarding NOx from H_2, particularly for transients
  - H_2 SCR for lean NOx control still faces significant hurdles
- NH_3 combustion leads to challenging levels of NOx, N_2O, and NH_3

Thanks!

- All opinions and assessments expressed in this presentation are the sole responsibility of me and not the individuals that did the work

- Please attend the referenced presentations for more details!

Josh Pihl
Oak Ridge National Laboratory
pihlja@ornl.gov

Download this panel's slides here: