The Future of Heavy-Duty Diesel Engines: Must we Achieve Zero Emissions?

Imad Khalek, PhD, FSAE

Institute Engineer

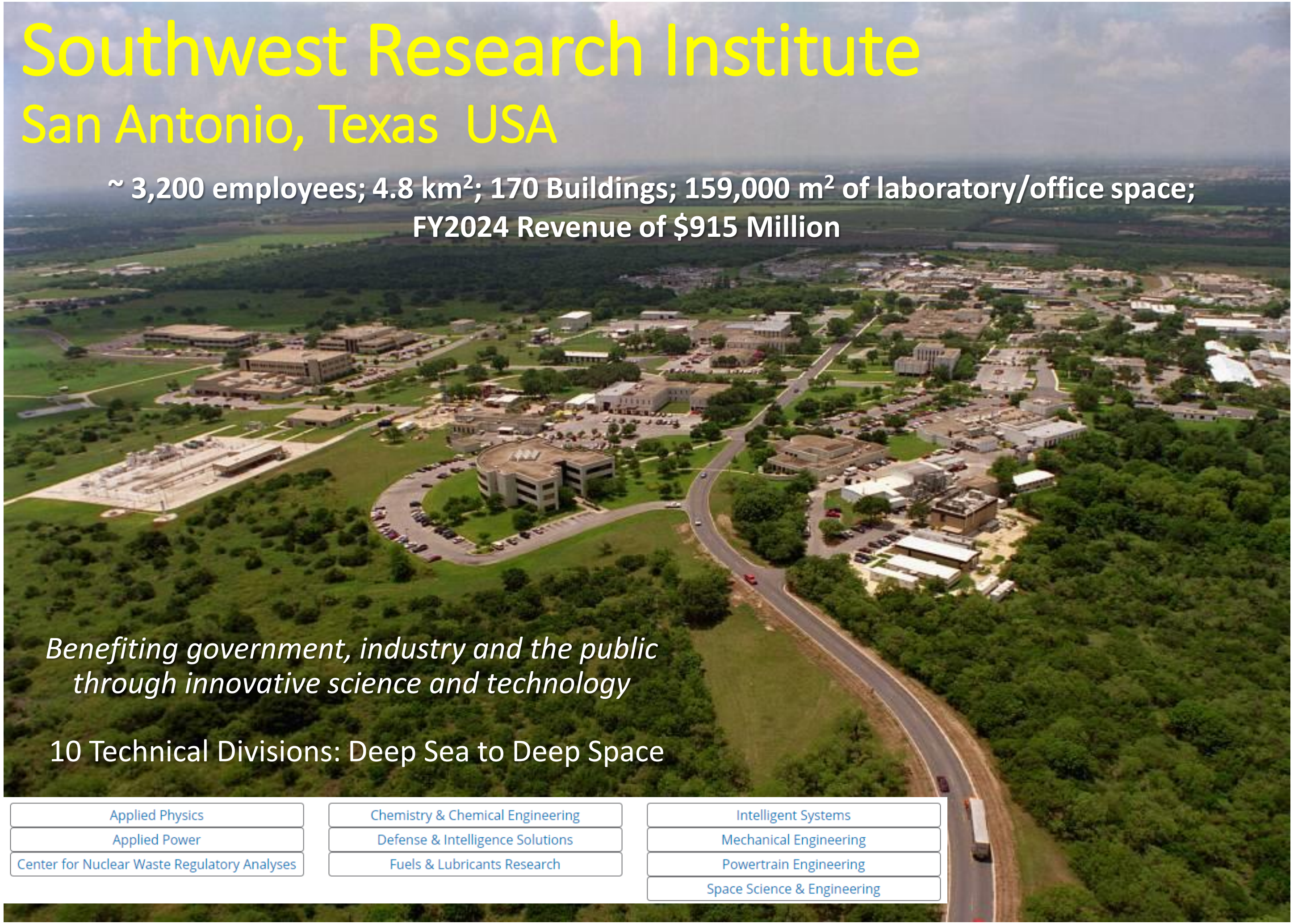
Imad.Khalek@swri.org

MDEC, October 6-9, 2025, Toronto, Ontario, Canada

Southwest Research Institute

San Antonio, Texas USA

~ 3,200 employees; 4.8 km^2; 170 Buildings; 159,000 m^2 of laboratory/office space;
FY2024 Revenue of $915 Million



Benefiting government, industry and the public through innovative science and technology

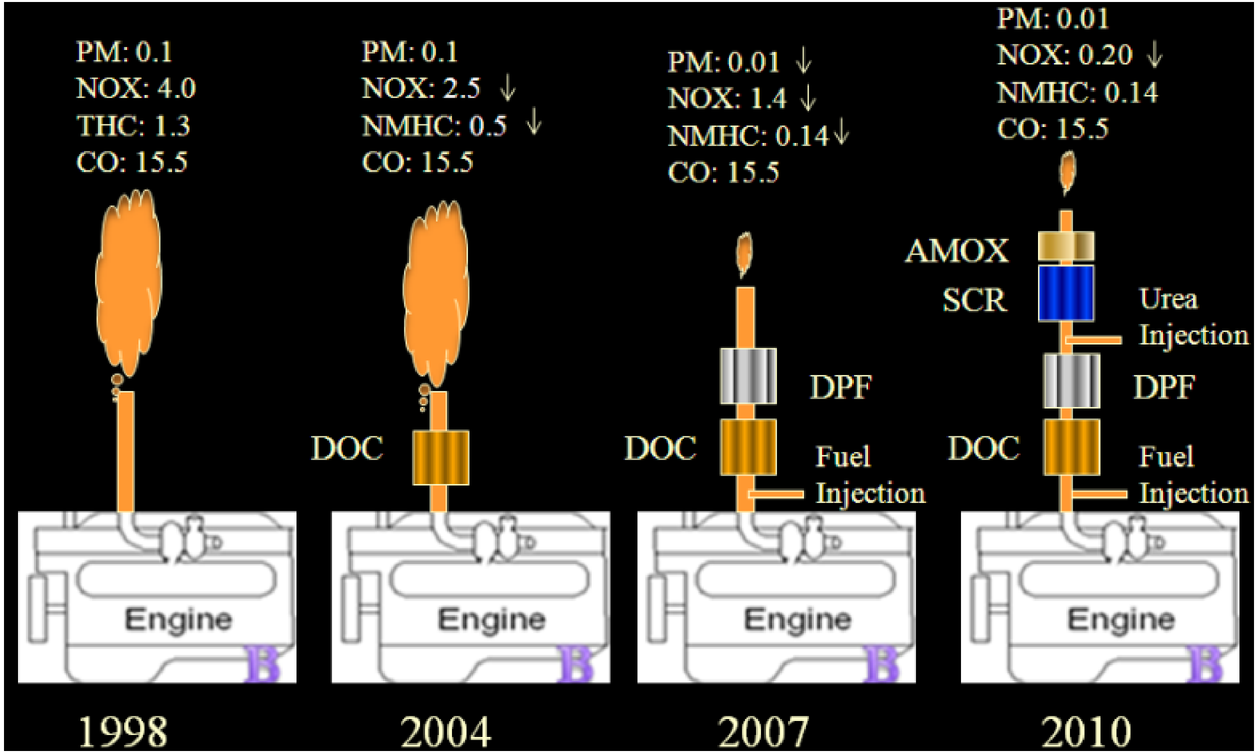
10 Technical Divisions: Deep Sea to Deep Space

Applied Physics	Chemistry & Chemical Engineering	Intelligent Systems
Applied Power	Defense & Intelligence Solutions	Mechanical Engineering
Center for Nuclear Waste Regulatory Analyses	Fuels & Lubricants Research	Powertrain Engineering
		Space Science & Engineering

Topical Coverage

- Heavy-Duty Diesel Engine Particle & NOx Emissions
- Gasoline Particle Emissions
- Brake & Tire Particle Emissions
  - New Euro 7 Regulations
- Li Ion Battery Fire
  - Fire Fighters and Public Concern
- Closing

Emissions Reduction & Modern Diesel Engine (Chemical Plant in Engine Exhaust)



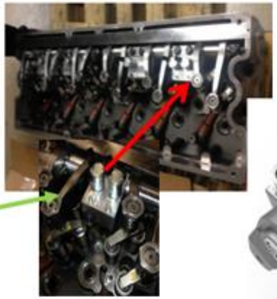
The MORE Modern Diesel Engine (MORE of a Chemical Plant in Engine Exhaust)

Additional ~90 % Reduction in NOx Emissions

2017 Cummins X15 Engine

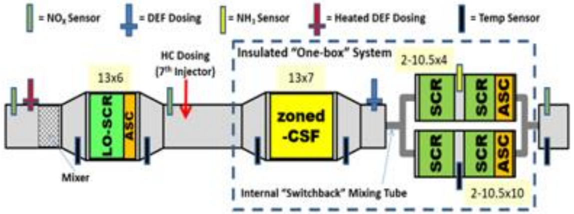
SAE Paper 2021-01-0589

Additional Engine Hardware (Cylinder Deactivation)



Eaton CDA Hardware

Advanced Low Aftertreatment (Dual SCR-Dual Dosing)

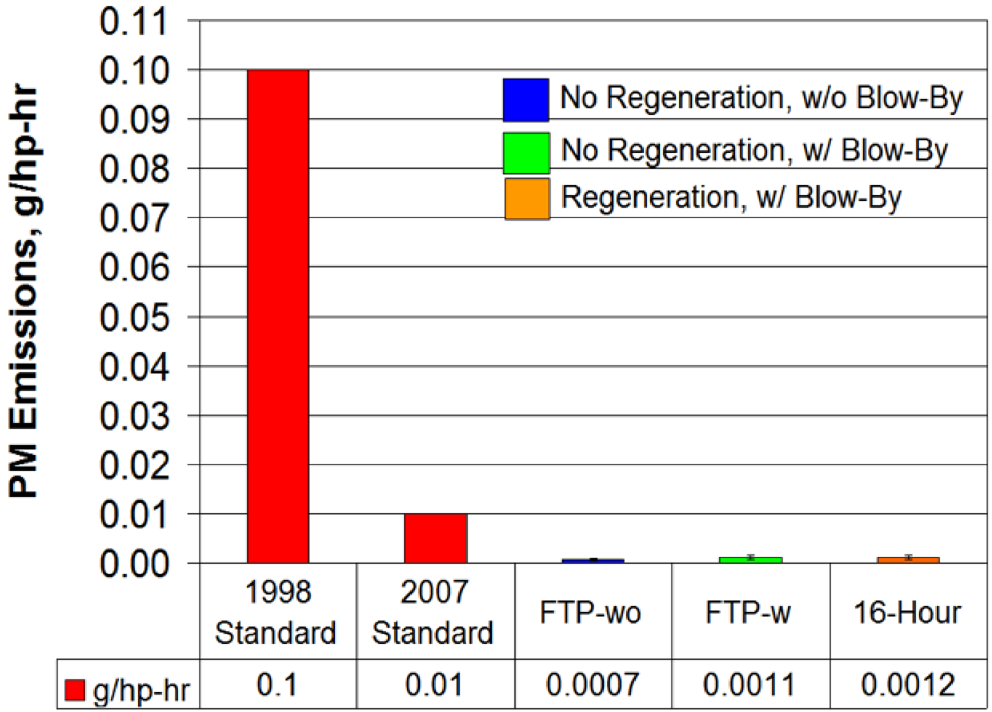


Targets:

- FTP/RMC NO_X 0.02 g/hp-hr
- Lowest feasible LLC and in-use NO_X
- No adverse GHG impact

2027 Regulations: 0.035 g/hp-hr, Lab Cert

Diesel Engine Impressive Particulate Matter (PM) Emissions Reduction



Future Standard of 0.005 g/hp-hr (2024-2027)

- 90 percent reduction in PM emissions was mandated by US EPA for 2007 heavy-duty diesel engines and beyond
- High efficiency catalyzed wall-flow DPF technology selected by the engine manufacturers achieved **more than 99 percent reduction in PM mass** emissions relative to 1998 engine technology
- The composition of the PM left is dominated by organic & inorganic semivolatile/volatile compounds

Diesel Engine is an Ambient Air Cleaner for Solid Particles Down to 10 nm

At 99.9% efficiency, solid exhaust particle concentration can be on the order of 500-5,000 particle/cm3 for diesel.

Particle size class	Particle size range	Particle number before filter	Particle number after filter	Penetration [%]	Filtration efficiency [%]
1	15.4	1.33E+05	0.00E+00	0.000%	100.000%
2	20.5	6.93E+05	1.96E+02	0.028%	99.972%
3	27.4	2.01E+06	2.39E+02	0.012%	99.988%
4	36.5	4.20E+06	6.62E+02	0.016%	99.984%
5	48.7	6.49E+06	6.60E+02	0.010%	99.990%
6	64.9	8.36E+06	5.69E+02	0.007%	99.993%
7	86.6	8.82E+06	5.23E+02	0.006%	99.994%
8	115.5	7.60E+06	2.86E+02	0.004%	99.996%
9	154	5.30E+06	2.19E+02	0.004%	99.996%
10	205.4	2.82E+06	1.89E+02	0.007%	99.993%
11	273.9	8.80E+05	2.45E+02	0.028%	99.972%
overall		4.63E+07	3.54E+03	0.008%	99.992%

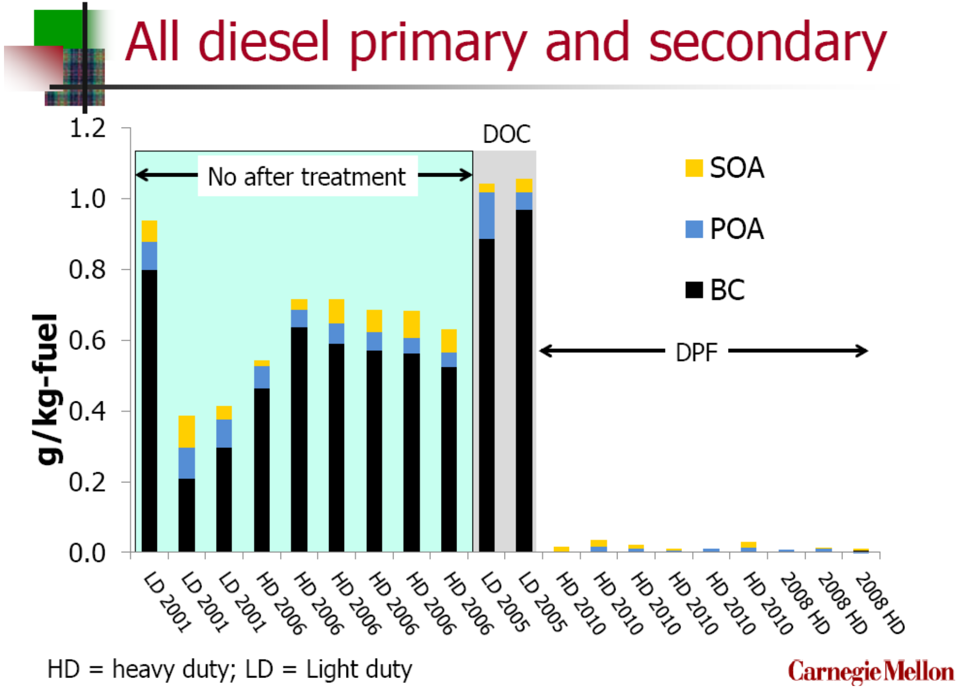
Significant Unregulated Emissions Benefit

Compounds	% Lower Than 2004 Engine Technology	
	16-Hour Cycle	CARBx-ICT
Single Ring Aromatics	82%	69%
PAH	79%	26%
Nitro-PAH	81%	49%
Alkanes	85%	84%
Polar	81%	12%
Hopanes/Steranes	99%	99%
Carbonyls	98%	78%
Inorganic Ions	38%	100%
Metals and Elements	98%	90%
Organic Carbon	96%	78%
Elemental Carbon	99%	100%
Dioxins/Furans[a]	99%	N/A

[a] Relative to 1998 Engine Technology

Due to the presence of exhaust SCR catalyst for NOX reduction in 2010 engines and later years, NO_X as well as NO_2 are at least 90% lower than 2004 technology engines

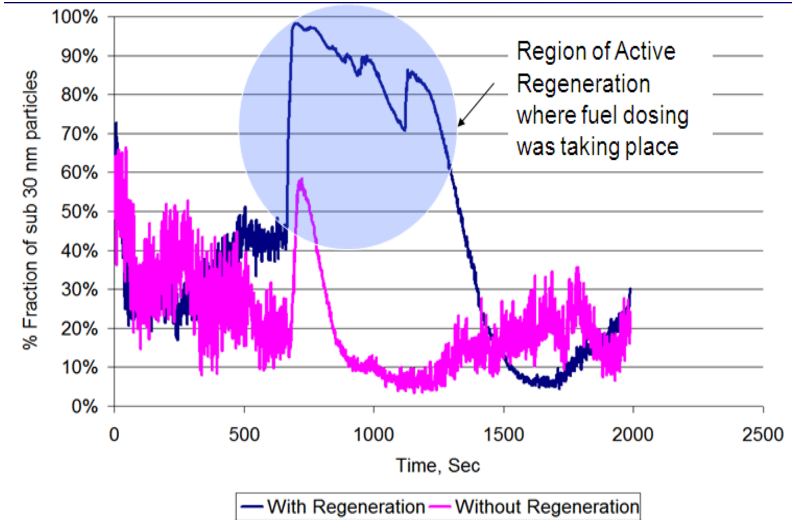
Reduction in Secondary Organic Aerosol Formation



Robinson et al., 22nd CRC Real World Emissions Workshop, San Diego, CA, March 25-28, 2012

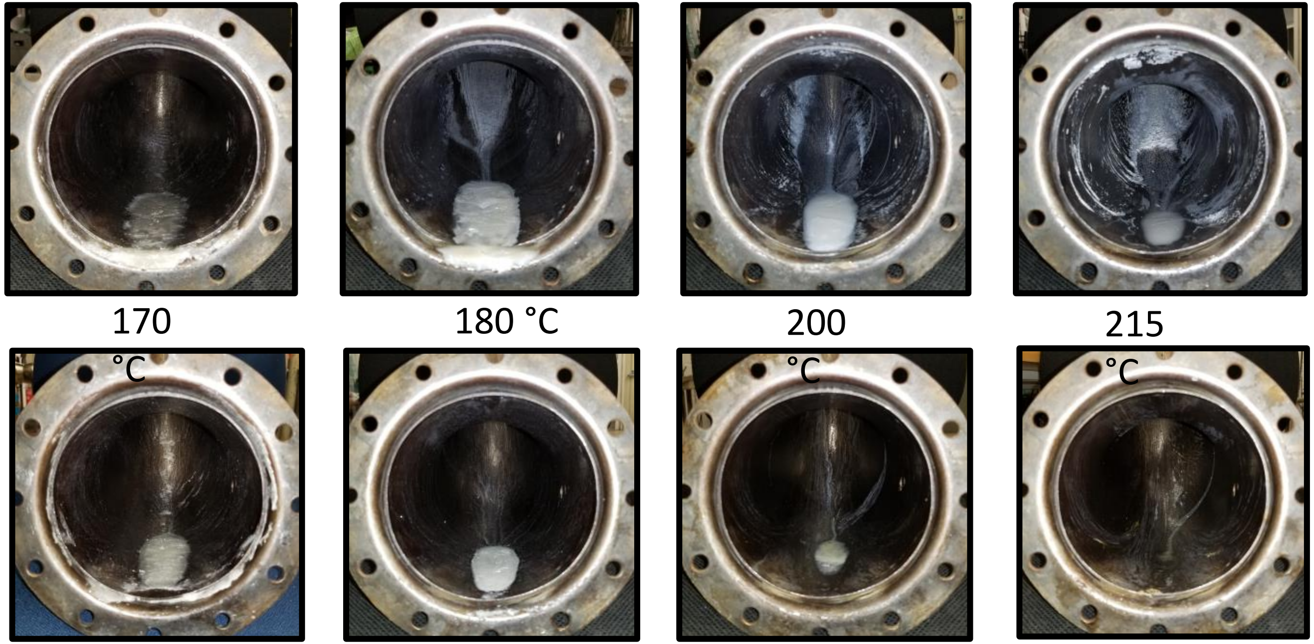
Three Problem Areas Arise from using Exhaust Filters

1. Volatile particle formation during regeneration
   1. Sulfuric acid is the trigger. **We need ZERO sulfur fuel**
2. Ash loading on the filter, raising backpressure & require infrequent manual cleaning
   1. Lube oil ash is culprit. **We need ASHLESS lube oil**
3. In-use failure (cracks, leaks, **tampering**, etc..)
   1. We need continuous emissions monitoring via sensors to tackle this issue
      1. **SwRI has been working on particle sensors for onboard monitoring through SwRI Particle Sensor Performance & Durability (PSPD) consortium since 2011**



SwRI

Urea Water Solution Deposit Formation and Cleaning Additives



- Deposit reduction was greater when ATO and Triton X-100 were combined in UWS, compared to ATO alone
- A significant deposit reduction was observed at all temperatures

Diesel Emissions Summary

- Drastic reduction in tailpipe NOx emissions is coming in 2027
- Diesel engines equipped with high-efficiency DPF can clean the air from solid particles
- Formation of sub 30 nm volatile particles that is high in number
- Ash in lube oil
- Tampering
    - ~2% of heavy-duty vehicles inspected in California were recently cited for tampering with the exhaust aftertreatment system
        - If exhaust filter is removed, each vehicle will emit as much as 1000 vehicles with filters
- New regulations will cut PM emissions by 50%. This should not impact heavy-duty on-highway engine, but it will force nonroad engines to use DPF

The Catch!

- After significant improvements in criteria pollutant emissions and efficiency,
  - diesel engines are under pressure to achieve zero GHG tailpipe emissions, meaning no fossil fuels or even clean fuels are allowed!
    - This signifies the end of diesel.

Should We Get Rid of Heavy-Duty Diesel Engines?

- What alternatives do we have?
  - EV, FC, H_2-ICE, NH_3-ICE
    - Going to take time
- What other ways we can achieve significant reduction in GHG?
  - Sustainable liquid drop-in fuel
  - Less carbon intensity fuel
  - More incentives to produce with regulatory certainty

There are hundreds of millions of heavy-duty diesel trucks worldwide that can have an immediate impact on GHG emissions reduction

- Do we need zero GHG emissions at the tailpipe
  - No, but we need to agree on life-cycle analysis

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%)*	■■■	–	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	■■	■	■
Long-Haul Heavy Trucks (~7%)	■	■■■	■■
Off-road (10%)	■■	■	■
Rail (2%)	■■	■■	■■
Maritime (3%)	■	■■†	■■■
Aviation (11%)	■	■	■■■
Pipelines (4%)	■■	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

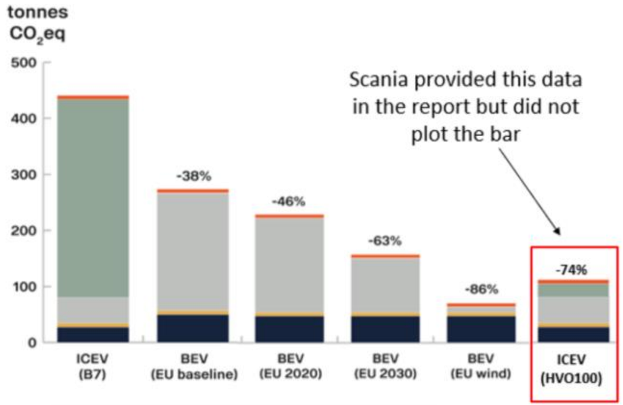
https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf

https://www.statista.com/topics/3582/trucks-and-commercial-vehicles/#editorsPicks

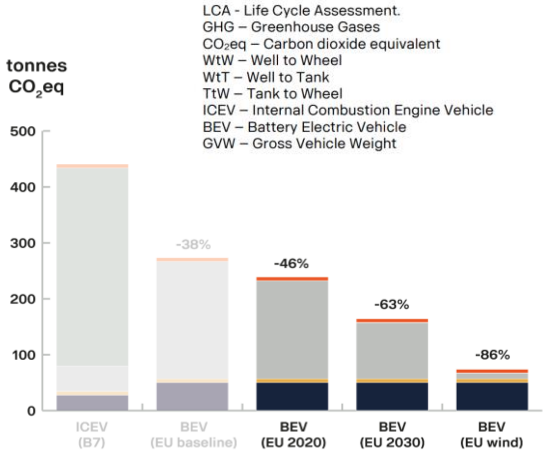
SwRI

Example of EV Real CO_2 Emissions-Energy Sources are Key

- Jury still out on GHG emissions benefit of EV
  - Depending on electric power source used
  - Advancement in alternative fuel
  - This is an interesting example from Scania:



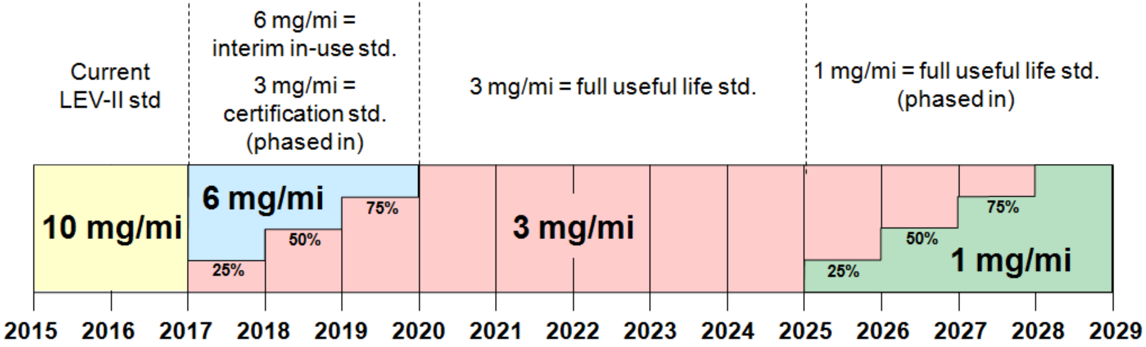
https://www.scania.com/content/dam/group/press-and-media/press-releases/documents/Scania-Life-cycle-assessment-of-distribution-vehicles.pdf



Vehicle	Production	Maintenance	Use WtT	Use TtW	Recovery
ICEV (B7)	27,5	2,4	44,9	354,3	2,1
BEV (EU baseline)	53,6	2,4	209,5	0,0	2,1
BEV (EU 2020)	53,6	2,4	175,0	0,0	2,1
BEV (EU 2030)	53,6	2,4	100,2	0,0	2,1
BEV (EU wind)	53,6	2,4	4,7	0,0	2,1

Light-Duty Gasoline Vehicles-Current Regulations

- CARB LEV III and US Tier 3 Regulations (Particle Mass Only)
  - No Gasoline Particle Filter (GPF) required



CARB LEVI III only

- Euro 6 (Solid Number and Mass)
  - 4.5 mg/km
  - 6×10^{12} part/km (2014-2016)
  - 6×10^{11} part/km in **2017** for Particle > 23 nm **(~50% below 2025 CARB LEV III)**
  - GPF required for Euro 6 starting 2017

Light-Duty-New Particle Regulations

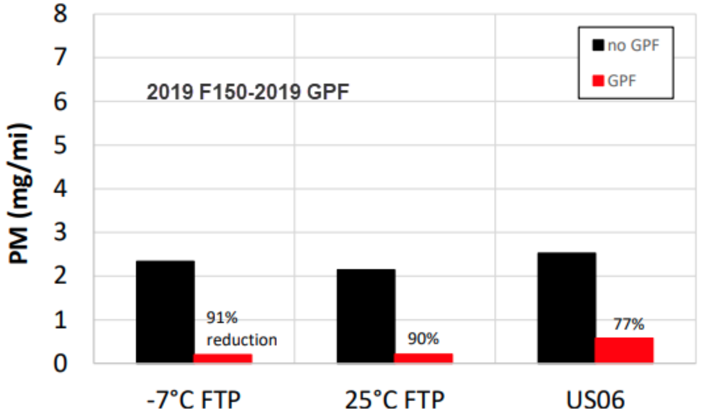
- US EPA Tier 4……2032+
  - PM mass at 0.5 mg/mi (~ equivalent to EU in 2017)
  - Vehicles **likely to require a GPF** because the regulation applies at -7 °C
- Euro 7……2030-2032+
  - Solid Particle Number Emission is at $6x10^{11}$ part./km for particles **> 10 nm**. This applies to all vehicle types.
  - More stringent than Euro 6

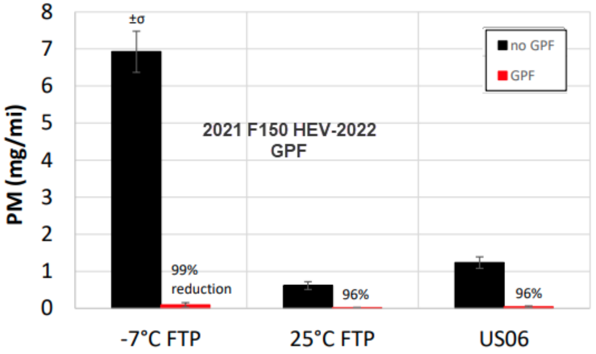
US Direct injection gasoline engines emit much high PM compared to EU between 2017-2032

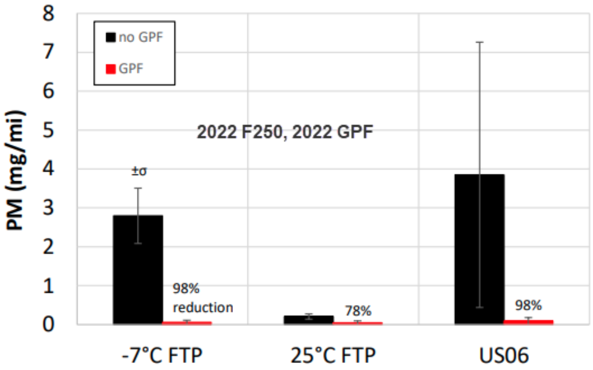
Model Year	US EPA				CARB			
	FTP, -7°C	FTP, 25°C	US06, 25°C	Phase In	FTP, -7°C	FTP, 25°C	US06, 25°C	Phase In
2024	N/A	3	6	Tier 3	N/A	3	6	Tier 3
2025	N/A	3	6	Tier 3	N/A	1	6[b]	25%
2026	N/A	3	6	Tier 3	N/A	1	6[b]	50%
2027	N/A	3	6	Tier 3	N/A	1	6[b]	75%
2028	N/A	3	6	Tier 3	N/A	1	6[b]	100%
2029	N/A	3	6	Tier 3	N/A	1	6[b]	100%
2030	N/A	3	6	Tier 3	N/A	1	6[b]	100%
2031	N/A	3	6	Tier 3	N/A	1	6[b]	100%
2032	0.5[a]	0.5[a]	0.5[a]	Tier 4	0.5[a]	0.5[a]	0.5[a]	Tier 4

[a] Emissions Cap, [b] No Phase in

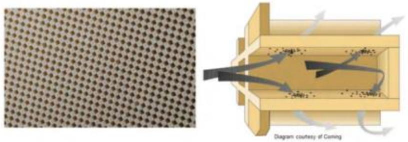
Approaches to Meeting US Tier 4 PM Standards : Gasoline Particle Filter (GPF)







- EPA demonstrated meeting the standard in the Draft Regulatory Impact Analysis (DRIA) using GPFs
- PM emissions reported well below 0.5 mg/mi with new technology GPFs
- GPF was shown to decrease PAHs and off-cycle emissions



Other Possible Approaches to Reduce PM/PN, E-Fuel

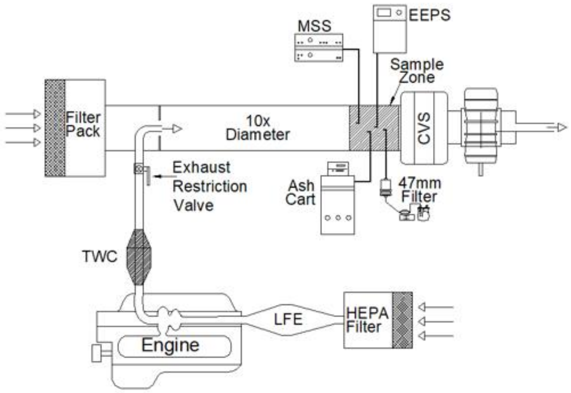
- One can get significant reduction in all particle metrics using E-Fuel with ultra low PM Index (PMI)

$$PM\ Index = \sum_{i=1}^{n}\left(\frac{DBE_i + 1}{V.P(443K)_i} \times Wt_i\right)$$

	EPA Tier 3 Cert Fuel, PMI 2.4						
Test Name	Soot Mass	SPN23	SPN10	Ash	PM	EEPS	SPN10-SPN23
F1, mg/#/kW-hr	55.71	6.9E+13	1.1E+14	9.9E+12	79.7	2.3E+14	3.9E+13
Stdev, mg/#/kW-hr	4.38	5.9E+12	1.4E+13	7.7E+11	5.3	3.1E+13	
COV, %	0.08	8.6E-02	1.2E-01	7.8E-02	0.1	1.3E-01	
	% Change Relative to EPA Fuel						
	CARB LEV III Cert Fuel, PMI 1.23						
F2	-42.6%	-51.1%	-16.4%	-38.2%	-34.4%	25.1%	44.2%
	E-Fuel with Ultra Low PMI of 0.27						
F3	-95.3%	-86.0%	-84.3%	-87.3%	-91.2%	-74.0%	-81.2%

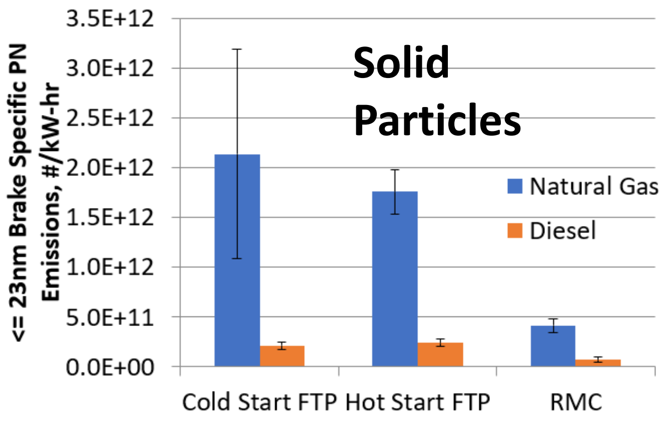
Drop-in E-Fuel with Ultra Low PMI can benefit existing fleet by reducing PM/PN emissions and greenhouse gas

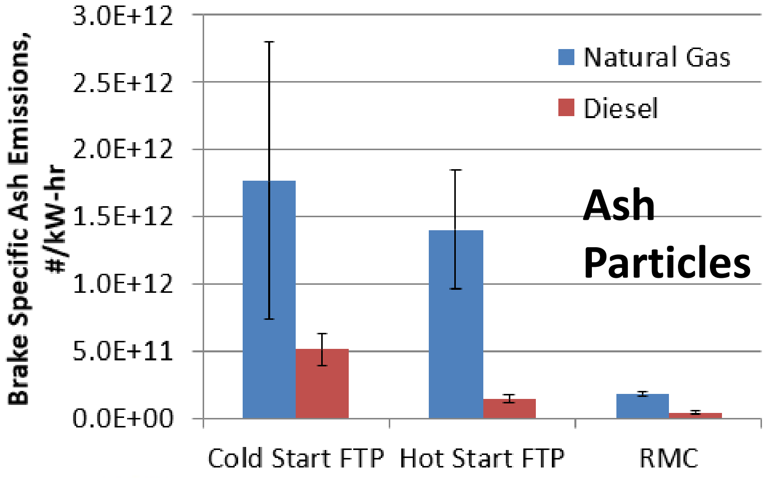
- 2018 Ford Ecoboost, turbocharger, direct injection engine
- 2.3 L, 310 hp/350 ft.lb torque at 3,000 rpm
- Used in MY 2018 Ford Mustang



Other Combustion Sources-High on Number, Low on Mass

- Natural Gas ICE
  - Large number of solid particles below 23 nm in diameter-Lube Oil Ash
- H_2 ICE
  - Similar findings in H2 ICE and other soot-free or low soot emitting engines
- Jet Engines
  - Large number to mass ratio, compared with diesel and gasoline (two orders of magnitude higher)





Gasoline Exhaust Summary

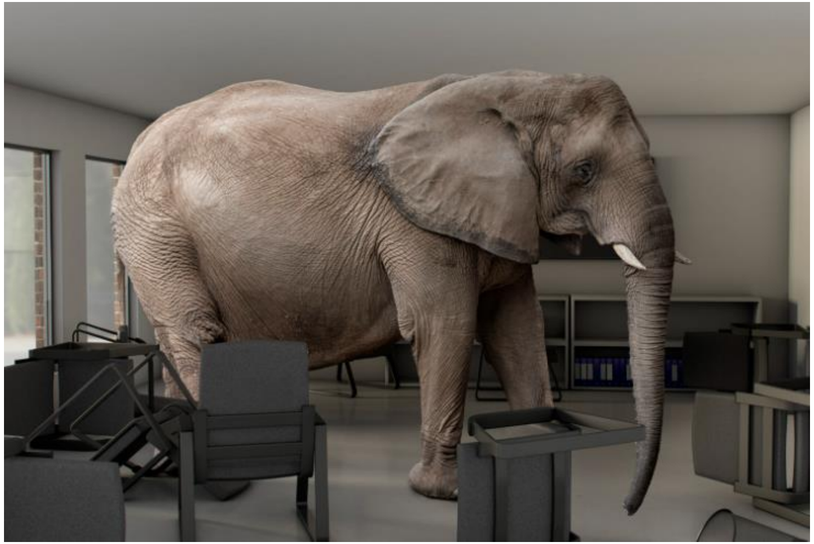
- Gasoline engine particle emissions are much more stringent in the EU than the USA
- US EPA does not regulate on particle number (PN) and continue to focus on PM mass
  - US EPA regulates PN only for aircraft engines
- Particle number metric is different than the mass metric
  - We could see cases of very low PM mass but high particle number
    - PFI Gasoline, natural gas, H_2-ICE & others

Should the US regulate particle emissions using the number and mass metrics. The number metric is already used for aircraft, why not for automotive?

Other Outstanding Elephant in the Room **New** Particle Emissions Issues

- Brake Particle Emissions
- Tire Abrasion

- Euro 7 includes brake emissions and tire abrasion
  - Brake emissions cycle has been developed and completed
  - Tire abrasion method has been finalized
- No US regulations in the horizon on brake and tire emissions
  - Interest is there



Brake and Tire Wear Expected to Dominate PM Emissions from Mobile Sources

- Diesel and Gasoline Exhaust Particulate Filters (DPF & GPF) have SIGNIFICANTLY reduced exhaust PM. Tire & Brake PM become DOMINANT emitters
- EV may be Worse than ICEV

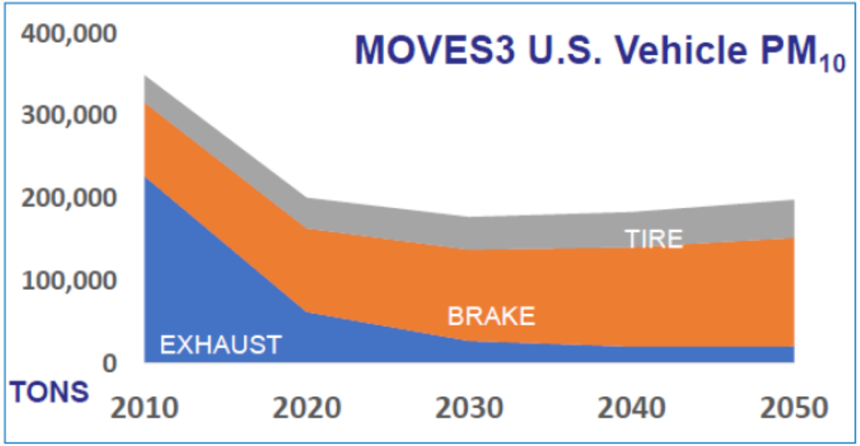
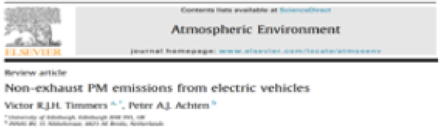


FIGURE 8. EXHAUST, BRAKE AND TIRE PM_{10} AS PROJECTED BY MOVES IN USA

[17] Koupal et al., "New Research on Brake Wear Particulate Matter Emissions from Several Heavy-Duty Truck Vocations in California," 32nd CRC Workshop, March 13-16, 2022.

Comparison between expected $PM_{2.5}$ emissions of EVs, gasoline and diesel ICEVs.

Vehicle technology	Exhaust	Tyre wear	Brake wear	Road wear	Resuspension	Total
EV	0 mg/vkm	3.7 mg/vkm	0 mg/vkm	3.8 mg/vkm	14.9 mg/vkm	**22.4 mg/vkm**
Gasoline ICEV	3.0 mg/vkm	2.9 mg/vkm	2.2 mg/vkm	3.1 mg/vkm	12.0 mg/km	**23.2 mg/vkm**
Diesel ICEV	2.4 mg/vkm	2.9 mg/vkm	2.2 mg/vkm	3.1 mg/vkm	12.0 mg/vkm	**22.6 mg/vkm**

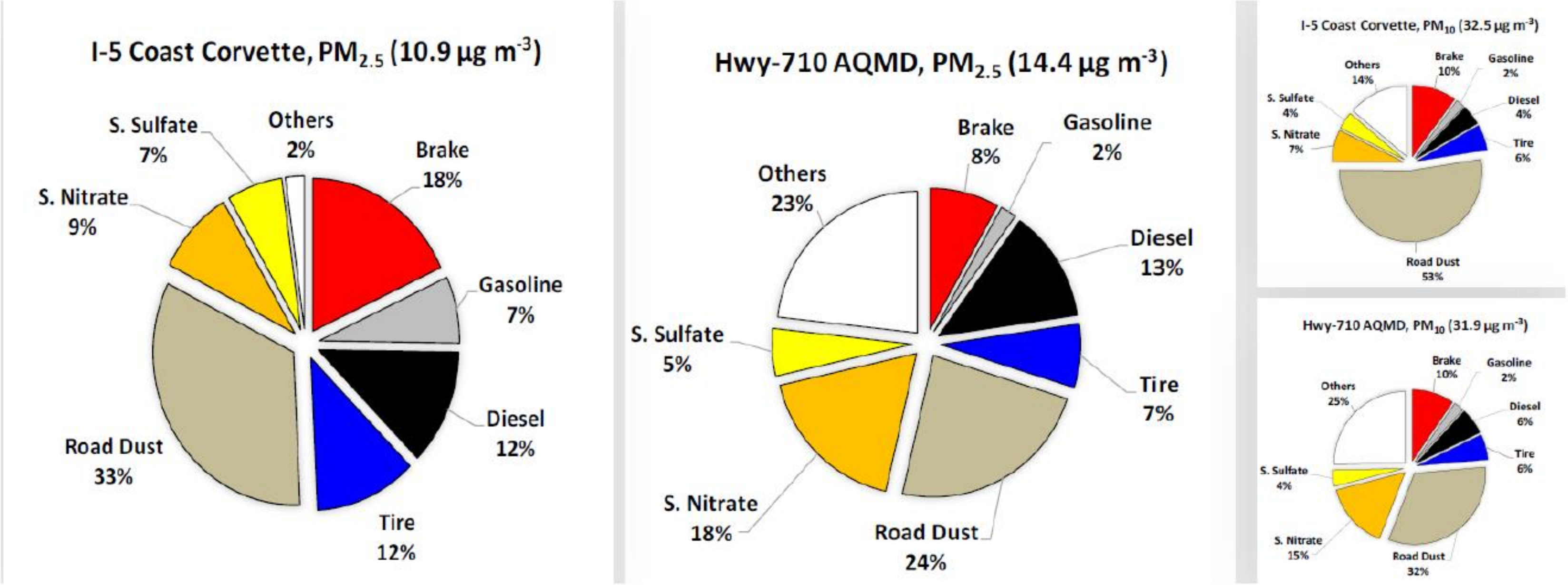

Atmospheric Environment

Review article

Non-exhaust PM emissions from electric vehicles

Victor R.J.H. Timmers, Peter A.J. Achten

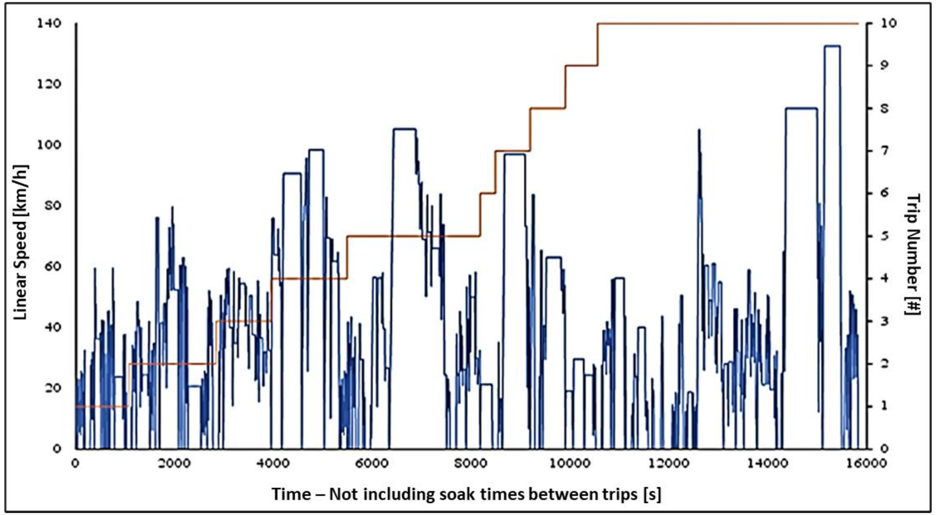
Near Roadway PM Composition in California

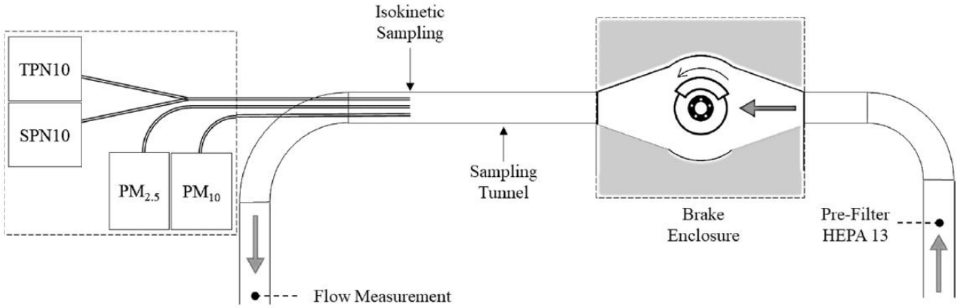


Lopez et al., "Elemental Content of Brake and Tire Wear PM2.5 and PM10 at Near-Road Environments" CRC Real World Emissions Workshop, 2023

Euro 7 Light-Duty Brake Particle Emissions

- Brake emissions limit at 7 mg/km for ICE starting in ~2027
- 3 mg/km for EVs starting in ~2027
- 3 mg/km for all powertrains starting in 2035



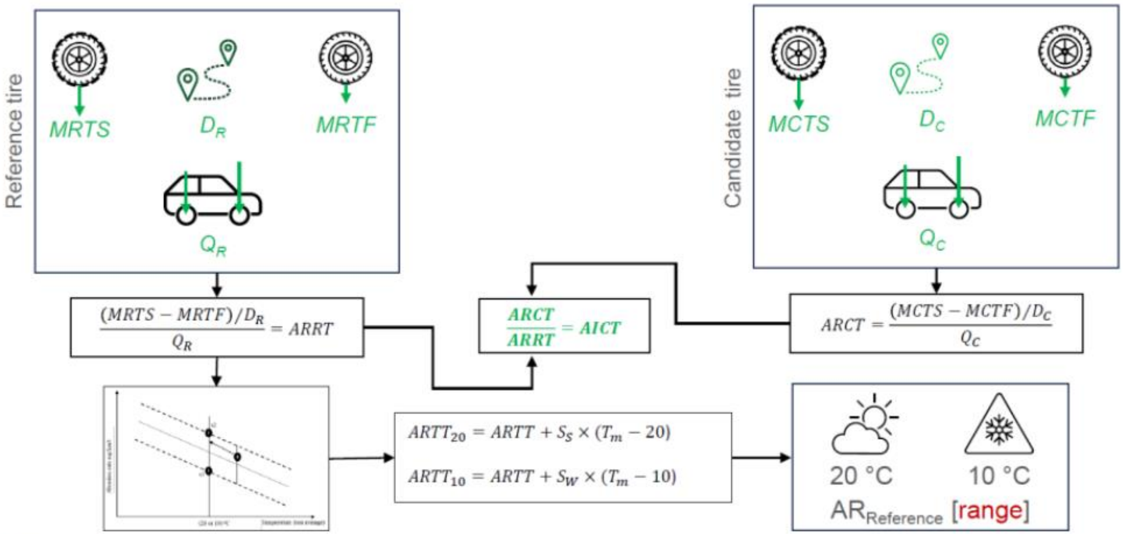


Euro 7 Tire Emissions (Abrasion)

- Conduct a review on tire abrasion before 2025 and define a limit by **mid-2026** through the UN WP.29
  - Objective is to reduce microplastics by 30% by 2030

Flowchart for abrasion rates and abrasion index

calculations include mass loss, test distance, tire loads, and validation with reference tire wear



SAE International®
2023 Brake Colloquium & Exhibition

Euro 7 Tutorial

Brake and Tire Particle Emissions Summary

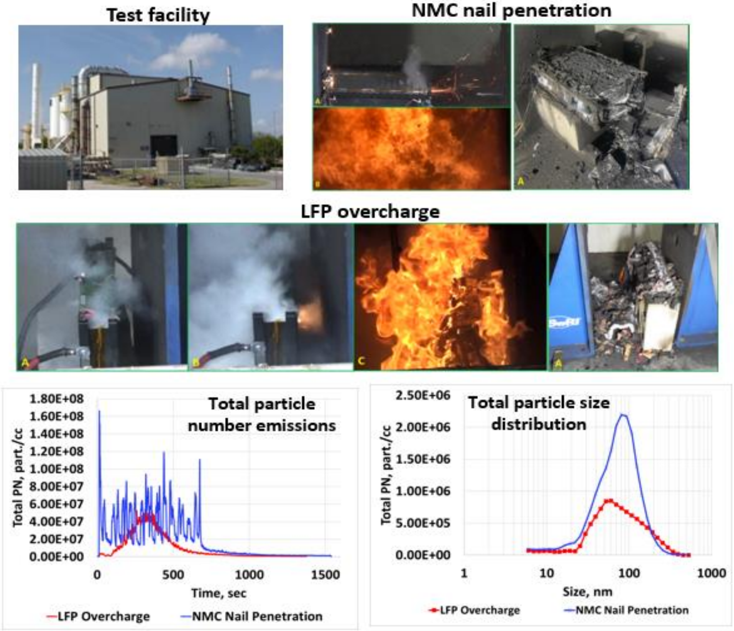
- Brake and Tire Particle Emissions will dominate going forward
- The EU has developed a standard for Brake emissions and work in progress on tire abrasion
- No regulations on the horizon in the USA yet

Other Brake/Tire Concerns-Aircraft Take-Off & Landing/Locomotive Braking/Rail Grinding

20 Tires for ~500 cycles or less

Other Non-Exhaust Safety Concern- EV BATTERY RUNAWAY FIRE

- Lithium-ion (Li-ion) batteries are widely used due to their high energy density and specific energy capacity – which makes them a safety concern
- There have been several battery fire incidents in the last few months
- Critically important to understand emissions to equip first responders with appropriate PPE, understand human and environmental impact
  - Especially with rapid electrification in the mobility sector
- Significant release of particulate and gaseous emissions were observed during thermal runaway
  - Particles were in the respirable size range with peak levels in the ultrafine size scale (sub 100 nm)



Background PM filter

PM Filter for Test 4

Vinay Premnath, Yanyu Wang, Nolan Wright, Imad Khalek & Steven Uribe (2022) Detailed characterization of particle emissions from battery fires, Aerosol Science and Technology, 56:4, 337-354, DOI: 10.1080/02786826.2021.2018399

Single small battery fire event can emit **4 orders of magnitude** higher particle number than a heavy-duty truck engine or equivalent to **one million miles of truck operation!**

EV Battery Thermal Runway Emissions

- Dominated by toxic gaseous and metallic compounds
  - This is work we have done recently with TEEX

Figure 7 (Left): *Battery Test #3, where internal pressure from Li battery thermal runaway forced the blast chamber door to open.*

Figure 8 (Right): *Remains of Li-ion battery in blast chamber post-thermal runaway.*

Mass by FTIR	Formula	Test 1 (g)	Test 2 (g)	Test 3 (g)
Carbon Dioxide	CO_2	71.724	770.790	574.400
Carbon Monoxide	CO	16.634	98.990	34.693
Nitric Oxide	NO	0.010	0.462	0.393
Nitrogen Dioxide	NO_2	<0.001	<0.001	0.009
Hydrogen Fluoride	HF	0.003	0.014	0.018
Hydrogen Chloride	HCl	<0.001	<0.001	0.108
Hydrogen Cyanide	HCN	<0.001	0.046	0.018
Formaldehyde	CH_2O	0.568	2.241	0.683
Methane	CH_4	0.977	5.704	1.703

Table 1: *Semi-Volatile Organic Compounds*

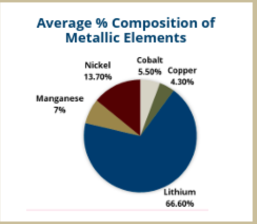


Figure 9: *Composition of Metallic Elements*

Elements	Test 1 (mg/m³)	Test 2 (mg/m³)	Test 3 (mg/m³)
Cobalt	0.9	1.3	1.8
Copper	0.7	1.2	1.6
Lithium	19.5	14.9	15.2
Manganese	1.4	1.6	2.3
Nickel	2.3	3.1	4.8
Sum of Metals	24.8	22.1	25.7
$PM_{2.5}$	159.5	111.1	111.9
% of $PM_{2.5}$	16%	20%	23%

Table 2: *Summary of Metals Identified During Tests One Through Three.*

[LITHIUM-ION BATTERY FIRES AND EMISSIONS CHARACTERIZATION REPORT]

SwRI

Li Battery Runaway Fire

- Topic is an important health concern due to the highly concentrated exposure in a short period of time

Questions

Imad A. Khalek

Southwest Research Institute

Imad.Khalek@swri.org