Summary of the CRC 32nd Real World Emissions Workshop

March 13 – 17, 2022 held at San Diego, California. [Link](#) to workshop page.

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Plenary talks

Plenary talk 1: Tim Seidel, Phillips66

Fossil fuels are not easy to displace: 75% of energy could be supported by fossil fuels in 2050

Renewables are growing rapidly in absolute figures: Annual growth - wind at 25 TWh, solar ~ 10 TWh. But that is a very small fraction of the overall consumption in the US (~ 4000 TWh) today.

Also, the global demand for fossil fuels is increasing. Renewables met ~ 10% of energy consumption in 2020 and this is projected to increase to ~ 15% in 2030 and ~20% by 2050. About 5% would be nuclear in 2050 and the rest (75%) would still be supported by fossil fuels.

Phillips targets for GHG reduction vs 2019:

30% & 50% from scope 1 & 2 operations, 15% by 2030 for scope 3 (products sold)

Coke production sufficient for 34M EVs by 2030

150,000 tons of renewable H_2 production

20% renewable power used in operations

1.5B gallons of renewable fuels per year

Plenary talk 2: CARB

Cleaning up along the Transition to Zero

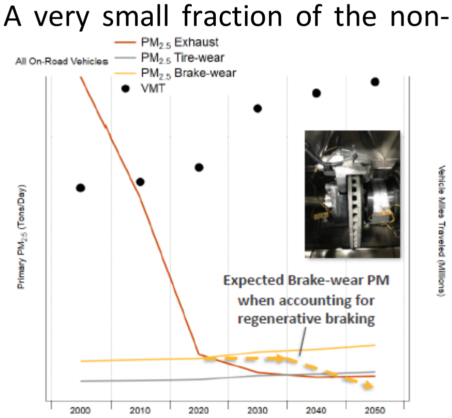
As of 2021, California had 6 of the 10 most polluted cities for particle pollution, and 7 out of 10 for ozone pollution. It is pursuing its ultimate goal of 100% ZEV sales for light-duty by 2035 and heavy-duty by 2045, and has earmarked $2.17B in funding for the transition.

Still, even in 2035, there will be close to 18 million vehicles with an ICE, so that upcoming ACC 2.0 regulations are needed to address tailpipe emissions.

Trucks make up 6% of the state fleet but emit 21% of transportation GHG and nearly half of transportation NOx, hence the focus on the Low NOx and Advanced Clean Trucks (ZEV) rule. A very small fraction of the non-compliant trucks lead to most of the in-use emissions, hence there is a growing focus on in-use testing and closing the gap with certification (e.g. low load cycle). Also enhanced are the on-board emission measurement (REAL), warranty and inspection & maintenance programs.

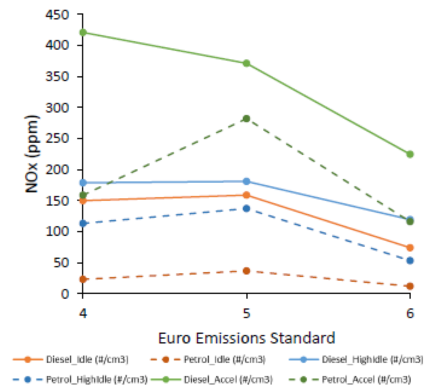
By the end of the decade, NOx emissions from federally regulated trucks operating in California will exceed emissions from CA regulated trucks – hence the push for stronger federal standards as well.

There is a recognition that non-tailpipe particulate emissions will exceed tailpipe by the end of this decade.



Light-duty vehicles

Advanced Inspection and Maintenance Methods To Identify High Emitters – D. Thomas, 3DATX Corp.



In Europe, there is consideration to adding NOx measurement to the periodic technical inspection (PTI) of vehicles. Existing PTI equipment is not suitable to meet these new requirements.

Over 450 vehicles have been tested, 50 – 50 diesel/gasoline and covering all emission standards (Euro 1 – 6)

A test protocol has been proposed which adds 5 mins to the PTI. Includes 2 mins for idling and PN emission measurements and high idle and accelerated driving segments for NOx measurements.

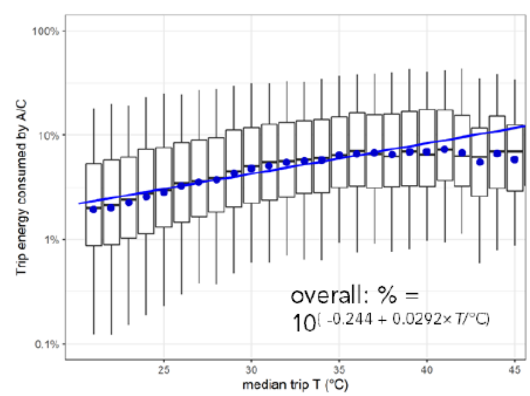
A newer version of the parSYNC iPEMS device was discussed. NOx concentration measurements were found to be effective for identifying high emitters on idling and acceleration tests.

Examination of the data shows that Euro 6 vehicles are emitting lower NOx compared to previous regulatory stages, showing that post-dieselgate emission norms are working.

Characterization of Trip Starts, Including Initial Idle Time and Acceleration, for 82 Real-world Internal Combustion Engine Light-duty Vehicles – C. Ruehl, CARB

The FTP test cycle begins with a 20 sec idle time. This work tried to find whether this was representative of real-world driving. > 700 LD vehicles across CA were monitored to get data. > 50% of the trips were found to have idle times < 13 sec, while 25% were less than 5 sec. The reduced idle time is being considered by CARB as an additional test requirement for NOx emissions as part of ACC 2.0.

Impact of Regenerative Braking, Heating, and Air Conditioning on Energy Consumption of Light-Duty Plug-in Electric Vehicles – C. Ruehl, CARB



Data was collected on 246 plug-in electric vehicles, covering 294K trips and over 2.26M miles

Two conclusions from the study -

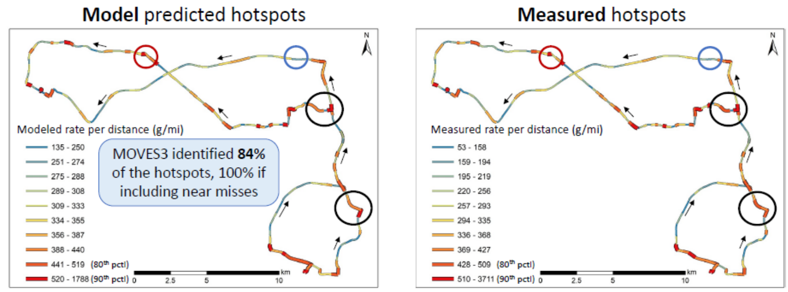
Regenerative braking helped recover almost 100% of the available braking energy when road grade is neglected.

PEVs were found to use 2 – 10% of total trip energy for AC from 20 - 45°C and up to 30% energy at 0°C for cabin heating.

Real-World Speciated Volatile Organic Compounds: Comparison Of Old And New Gasoline Cars – N. Molden, Emissions Analytics

2D gas chromatography with mass spectrometry was used to measured VOCs from 7 gasoline and 2 diesel vehicles - MY 2005 – 2021. Gasoline vehicles were found to emit larger amounts of VOCs.

Accuracy Of The Predictions Of Modeled Emission Hotspots Based On Real-World Measured Traffic Activity And Emissions – C. Quaassdorff, U. Politécnica de Madrid

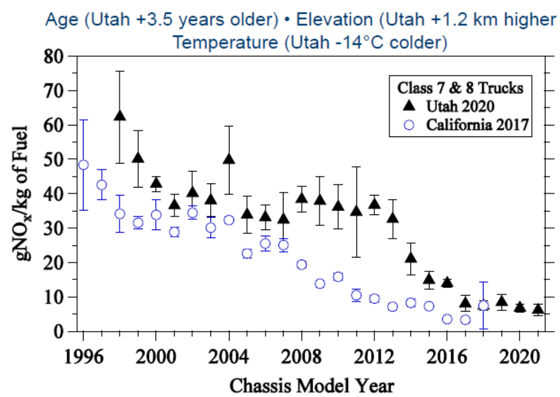


On-road PEMS measurements and MOVES3 was done to compare emissions from10 Tier 2 gasoline vehicles on 8 routes and see if the model can capture "hot-spots", defined as segments with top 10% emission rates. MOVES was found to be very accurate, it identified 86 - 97% of the hotspots for CO2, CO, HC and NOx.

Heavy-duty vehicles – In-use emissions

Wintertime Measurements of HDV Emissions at a Utah Port of Entry - M. Haugen, U. of Cambridge

Measurements done in Dec 2020 in Utah show higher emissions compared to those done in California due to an older fleet (+ 3.5 years), higher elevation (+ 1.2 km) and colder temperature (- 14 C colder). Temperature accounts for 25% increase in emissions. Newer models have low emissions even in low temps. → SCR deteriorates after ~ 8 years.



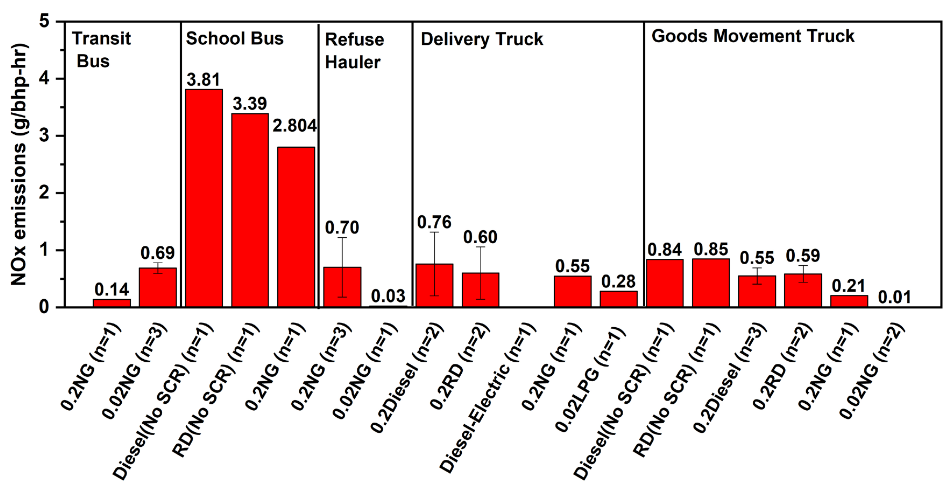
In-Use Emissions Testing And Fuel Usage Profile Of On-Road Heavy-Duty Vehicles – 200 Vehicle Study Chassis - H. Zhu, UC Riverside

MY 2009 – 2018 vocational vehicles (diesels & CNG) tested.

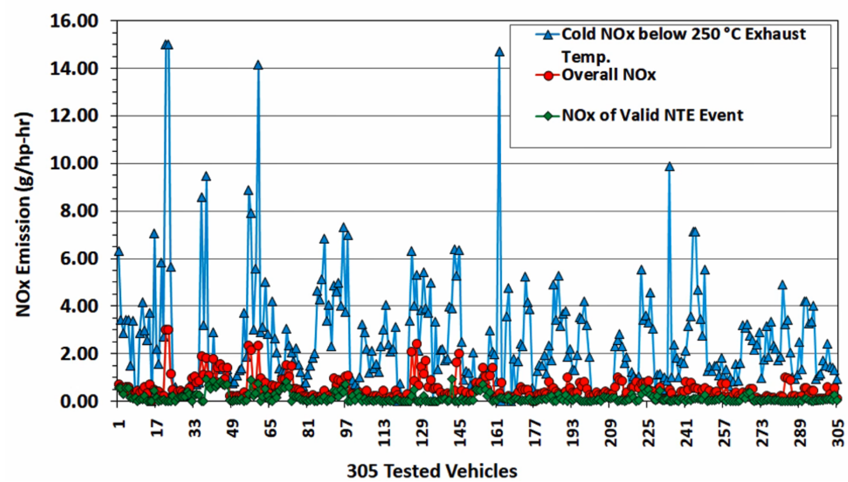
<u>NOx emissions</u>: Diesel No SCR > 0.2 Diesel > Diesel Hybrid > 0.2 NG / LPG > 0.02 NG (0.2 or 0.02 refers to the regulated limit in g/bhp-h). Higher NOx partly due to Idling and low temperatures.

<u>PM emissions</u>: Overall very low < 5 mg/bhp-hr. CNG > diesel.

<u>GHG emissions</u>: 0.02 CNG > 0.2 CNG > 0.2 diesel > others. For NG, CH_4 slip and N_2O formed on TWC are partly the cause of higher GHGs



Analysis and Summary of Manufacturers In-Use Testing Data Collected from Heavy-Duty Diesel Engines for 2012-2019 Test Orders Using PEMS Systems – A. Duncan, US EPA



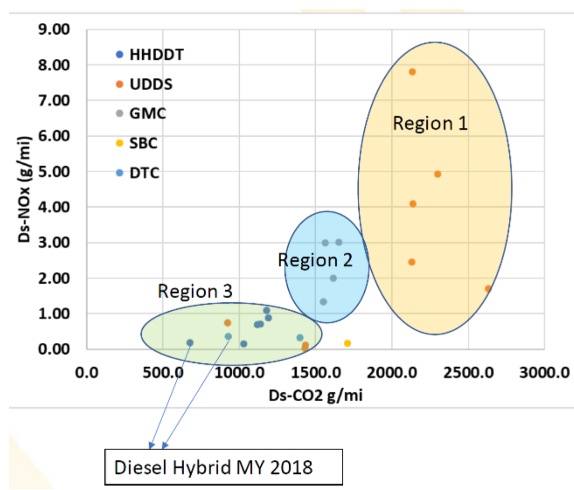
This was a summary of in-use testing of 305 vehicles, and analysis of emissions for total, not-to-exceed (NTE) and cold-temperature (< 250 °C, which are excluded in NTE methodology)

Average NOx for valid NTE was 0.15 g/bhp-hr (note this meets the current limit of 0.2 g/bhp-hr)

Average overall NOx was 0.52 g/bhp-hr (> 3X NTE)

Average cold NOx was 2.54 g/bhp-hr (~ 17X NTE !)

Comparison of NOx and Greenhouse Gas Emissions between Diesel and Natural Gas Heavy-Duty Vehicles During Real-World Operation – A. Thiruvengadam, WV Univ.



50 vehicles were PEMS tested and 20 chassis tested over vocational cycles

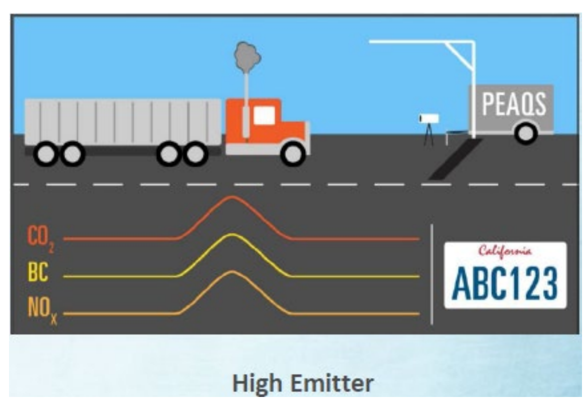
Low NOx NG vehicles emitted 93% lower NOx than diesels w/ SCR

For diesels the NOx – CO2 plot shows that there is NOT a trade-off, in fact NOx is lower when CO2 is lower → when temperatures are > 200 C, then SCR is active and there is no need for thermal management which carries a fuel penalty (region 1 for example)

Interestingly, comparing a 0.2 NG and a 0.02 NG vehicle showed that the latter also emitted significantly lower methane.

N2O formation in diesels was found to be dependent on dosing strategy. At T of 200 – 250 C, it is formed on DOC and ASC, while at temperatures > 300 C it is formed on SCR.

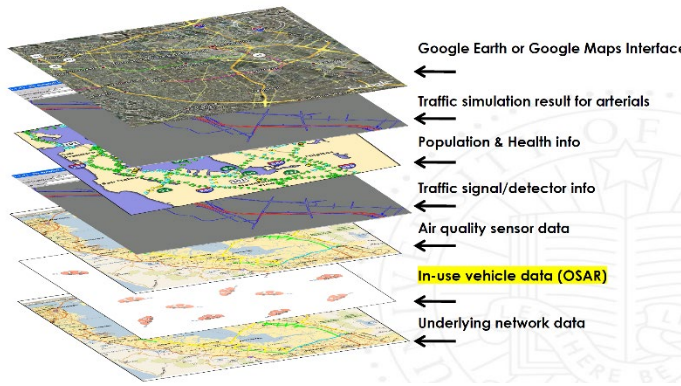
Identifying High Emitting Heavy Duty Diesel Vehicles Using Portable Emission Acquisition Systems (PEAQS)To Support Roadside Enforcement In California – I. Lino, CARB



By the end of the decade, CARB expects 3% of malfunctioning HD trucks to emit 65% of PM2.5

PEAQS is a plume-capture vehicle emissions screening system. Both mobile and stationary versions of the system have been deployed at key locations in CA as part of the HD I&M program. The citation to inspection ratio has increased from ~ 16% to 41% before and after PEAQS implementation.

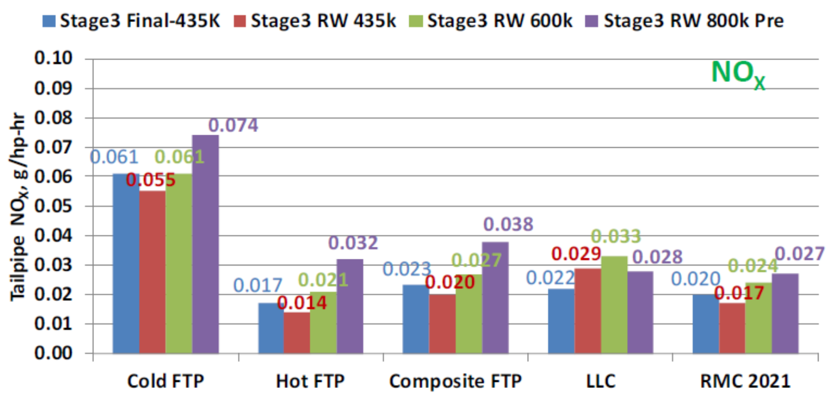
Development, Application, And Demonstration Of A Sensor-Based Onboard Sensing, Analysis, And Reporting (OSAR) For Emission And Activity Data Collection – K. Johnson, UC Riverside



On-board low-cost sensors are being developed with the aim to provide continuous emissions data. The data may not be as accurate as full PEMS but will help understand events over longer durations (e.g. catalyst deterioration) or as a function of multiple trips showing route dependency of NOx emissions. The data can then be integrated with other data sets to help make decisions for ultimately improving air quality. An example shown was designing a low exposure route, which increased driving time by only half a minute, but reduced inhaled PM by 73% (it included considerations for sensitive populations).

Progress towards Heavy-duty Low NOx

An Update on Continuing Progress at SwRI Towards 2027 Heavy Duty Low NOX Targets – C. Sharp, SWRI



Details were presented on the Stage 3 rework system for demonstrating technology pathway for meeting CARB (and now EPA) ultra-low NOx regulations. New data was presented showing the results at 800,000 miles aging. As expected, NOx emissions increased with aging, but are well within the limits at that mileage, both for FTP/RMC and the low load (LLC) cycles. The results shown were before ash cleaning, so that some more improvement is expected post ash cleaning. NOx conversion at 800K miles is 99.5% on FTP, 99.8% on RMC and 99.4% on LLC. N2O emissions also increased and were recorded at 0.093 g/bhp-hr, but still are below the 0.1 g/bhp-hr limit. Particulate mass (PM) emissions were at 1.5 mg/bhp-hr on FTP at 800K miles, well below the 5 mg/bhp-hr limit. Vehicle level CO2 analysis was done using GEM on Cruise and ARB transient cycles and shows CO_2 reduction by 1% – 5% over baseline engine even at these low NOx levels, due to use of CDA.

Low CO_2, Ultralow NOx Heavy Duty Diesel Engine – F. Redon, Achates Power

The 10.6L opposed piston (OP) engine is now running on a 2019 Peterbilt 579 truck for the past few months. Fuel economy advantage of > 10% is being measured compared to a reference vehicle. On one of the test days, fuel economy of 10.8 mi/gal was recorded (!)

The first-generation engine was shown to emit 0.016 g/bhp-hr NOx on the FTP using a conventional DOC + SCRoF + SCR/ASC after-treatment (development aged parts). This is 20% below the CARB 2027 limit. On-road PEMS measurements coupled with 3-Bin MAW analysis showed emissions meeting the 2031 proposed limit with a 50+% margin.

A 2nd generation engine testing is underway. This engine has improved air handling using a SuperTurbo and EGR pump. It delivered 49.2% BTE vs 47.1% for the 1st gen. resulting in 5% lower CO2 on SET. Also, 30% higher exhaust heat was measured in catalyst light-off mode. The after-treatment is a DOC + DPF + 2xSCR + ASC. Based on preliminary engine results, modeling shows the potential for meeting 2027 CARB standards with a significant margin. Note that the after-treatment is conventional in that there is no light-off SCR.

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

Fuels

Aiming At The Increase Of California's Ethanol 'Blend Wall': Gaseous And Particulate Emissions Evaluation From A Fleet Of GDI And PFI Vehicles Operated On E10 And E15 Fuels – T. Tang, UC Riverside

CARB is considering increasing the ethanol blend limit from 10% to 15% in California (EPA already allows E15). Several MY 2016 – 2021 vehicles were tested on FTP cycle: 11 GDI, 6 PFI, 2 PFI + GDI and 1 PFI PHEV, using E10 and E15 fuels. The E15 fuel had ~ 1% lower aromatics content.

Here are the key observations for various tailpipe emissions when using E15 vs E10:

NOx and CO_2: No significant difference

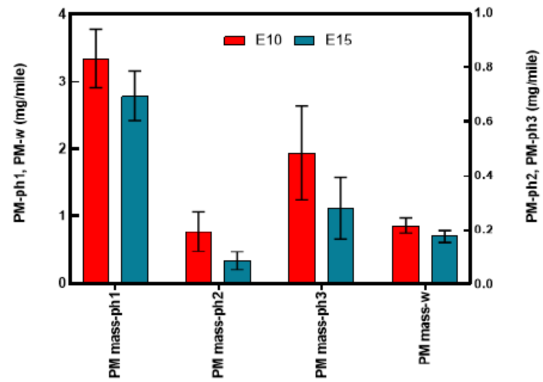
CO and NMHC: 17% and 8% lower, respectively for E15

Air toxics (ethylbenzene, xylenes): ~ 10% reduction with E15

Ethanol and acetaldehyde: 77% and 32% increase, respectively

PM: Reduced by 18% for cold-start and 43% for hot start, for E15

PN: Emissions reduced by 12%.



Quantifying Ethanol Carbon Intensity in Gasoline Blends – Nigel Clark, Transport Energy Strategies

Ethanol lowers carbon intensity of gasoline in 3 ways: (1) Lower CI vs. gasoline, (2) reducing aromatics content and (3) improved energy efficiency of the engine

Pathways (1) and (2) were used to assign a "blending" carbon intensity for ethanol, which is ~ 17% lower than the chemical CI.

For (2), which is the highest contributor, it was shown that 10% addition of ethanol helps displace ~ 9% aromatics content in gasoline (at same octane requirement)

The well-to-wheel CI of ethanol is 38 – 44% lower than gasoline based on GREET and other analyses → and this CI is expected to further reduce with improving efficiency of agriculture for corn production.

Tailpipe CO2 emissions are reduced by 2.2% for 15% ethanol vs. E0

Exhaust Emissions From A Heavy-Duty Engine Running On DME Fuel – G. Hardy & I. Tate, FPT

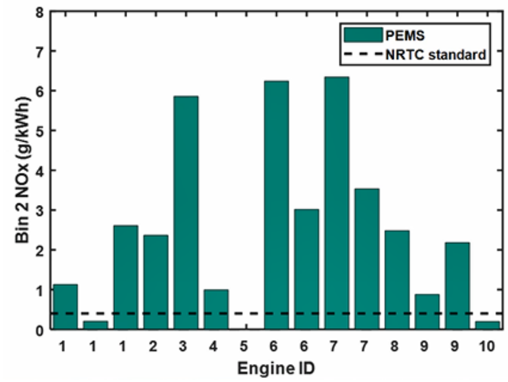
The key advantage of Dimethyl ether (DME) is the near zero CO2 emissions from a WtW perspective when produced using biomass or synthetic route (green H2 + CO2 capture)

DME has a very high H/C ratio, which is favorable for efficient combustion: 1 liter of DME @ 6bar/20 °C contains 23.5% more H_2 by weight than liquid H_2 at -240 °C and 2X more H_2 than compressed H_2 @ 350 bar/20 °C

An 11L HD Diesel engine was modified to run on DME. Modifications included optimized bowl shape and higher CR, optimized turbo, DME resistant sealings, injector nozzles with increased flow, high-P EGR system, dedicated DME engine oil, HP fuel pump.
Steady state measurements were done which show ~ 11% reduction in CO_2 with DME vs diesel.
There was so soot measured, which breaks the soot-NOx trade-off and allows for less EGR, as an example.
Brake thermal efficiency of > 40% with brake-specific NOx of 1 g/kWh is achievable.

Off-road Engines

Application of the 3-Bin Moving Average Window Method for Off-Road Diesel Engines – Y. Tan, CARB



Tier 5 regulations are being discussed for off-road engines. Currently, > 50% if Tier 4 final engines are certified without a DPF, and do not show good emission reduction during low load operation.
Emission measurements were done on NRTC using 10 construction equipment and 15 PEMS tests, over simulated real-world equipment operations.
Real world activity was collected on 35 construction equipment covering Tier 3 – Tier 4, 2008 – 2018 model years, 72 – 416 kW.
Average load of NRTC was ~ 37% while that of real-world data was ~ 19%. A work-based moving averaged window method was used to calculate emissions over 3 bins: < 6%, 6 – 20% and > 20% of rated power. As previously found for on-road engines, the analysis shows that low load emissions are not well controlled for off-road engines as well and are much higher than the NRTC limit.

Characterizing PM2.5 and NOx Emissions for Off-Road Construction Equipment with DPF and SCR Using an Engine Power Binning Method – Q. Yao, CARB
Emission and activity data was collected on 12 pieces of Tier-4 construction equipment – backhoes, crawler dozers, excavators and wheel loaders – undergoing vocational activities. A new engine power binning method was developed to characterize the emissions. Emissions during low power (< 20% engine power) operations contribute inordinately to the overall emissions: 38% - 60% NOx and 11% - 51% of PM emissions were associated with low power.

Tailpipe Particulate Emissions

Influence of Combustion Strategies and Ethanol Content on Effective Density and Mass-mobility Exponent of solid PM and PN from Lean and Stoichiometric GDI Engine – D. Kittelson, U. Minnesota
The density of non-volatile soot particles was measured using a 2L GDI engine operated at a fixed point, on three fuels - E10, E30 and E50, under various stoichiometric and lean operating modes. The effective density is a function of the particle mobility diameter (decreasing with increasing dia.) and the average was found to be 0.46 g/cm^3 at 100 nm. The impact of ethanol was found to be dependent on combustion conditions, decreasing the PM and PN for stoichiometric and lean-stratified modes while increasing for lean homogenous mode.

Evaluation of Tailpipe Solid PN Measurement Methodologies for Euro VII – Y. Khan, Cummins

PN emissions were measured from 3 natural gas and 3 diesel engines using two different methodologies, one using a pre-diluter and another using a 0.5m heated line at 150 °C and compared with reference PMP measurement configurations. On one of the NG engines, using the pre-diluter led to ~ 40% lower PN compared to reference PMP measurement at ~ 10^{11} #/kWh, while it led to ~ 10% higher PN for another NG engine at PN of ~ 10^{12} #/kWh. The use of a heated line gave poor results on the NG engine due to the higher exhaust temperature and related thermophoretic losses. On a diesel engine the heated line provided a good correlation vs PMP system (but with 11% lower PN).

Evaluation of Finnish vehicle fleet exhaust solid particle number emissions with respect to upcoming European periodic testing legislation – E. Lamminen, Dekati

Data using an electrical PN counter was shown in the context of upcoming new periodic technical inspection (PTI) regulations in Europe to identify malfunctioning DPFs. A total of 259 vehicles certified to various regulatory levels were tested using the 60 sec idle PN counting method. The fleet also included gasoline and 25 heavy-duty vehicles. One of the 35 diesels with DPFs was found to emit > 250,000 #/cm3, the threshold for detecting bad DPFs. Interestingly, 6 of the 14 gasoline vehicles without a filter were found to emit greater than the PN threshold.

Evaluation of a New TSI Engine Exhaust Particle Sizer with Two-stage Dilution and Catalytic Stripper for Solid Particle Number Measurements – Y. Khan, Cummins

An EEPMS (Engine Exhaust Particle Measurement System) was used to measure solid particulate emissions from 4 diesel engines with engine out at ~ 10^{13} #/kWh level. The repeatability and reproducibility was found at 2.1% and 4.8%, respectively. Compared to PMP compliant systems, EEPMS measurements gave errors < 10% for both 10nm and 23 nm particles. DPFs were shown to operate at 99% efficiency and reduce solid PN by 2 orders of magnitude at end of life on FTP and RMC-SET cycles.

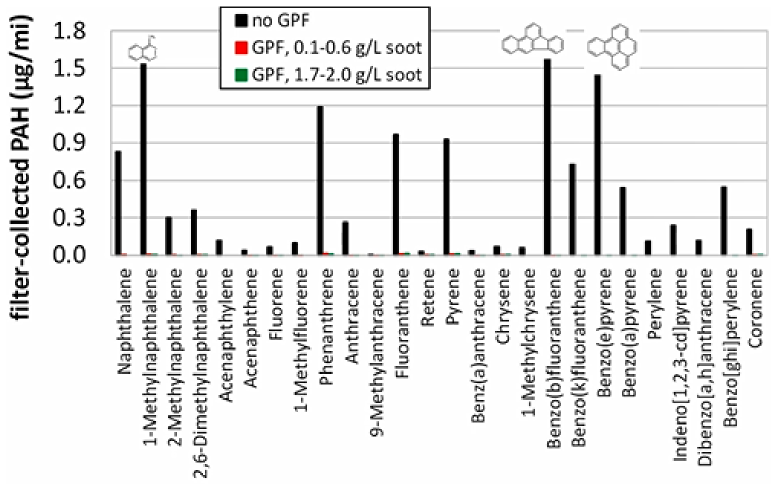
In-Use Vehicle Emissions of Black Carbon (BC) and Brown Carbon (BrC) from roadside field campaigns using a Portable Emissions Acquisition System (PEAQS) – M. Olson, CARB

While there is typically a lot of discussion on black carbon, the constituent of soot which leads to global warming, brown carbon (BrC) is not mentioned as often. BrC can be a significant contributor to near-UV light absorption. In this work, BrC emissions from a fleet of HD vehicles was measured at two locations in/near California. 370nm absorption was used to quantify the black and brown carbon emission contributions. Gasoline vehicles were found to emit lower BC but higher BrC compared to diesels.

PAH Emissions from a GPF-Equipped Light Duty Truck during Soot Accumulation and Regeneration – S. Bohac, U.S. EPA

Vehicle tests were performed on a MY2011 F150 3.5L Ecoboost GDI, and a commercialized 300/12 catalyzed GPF was added in the underfloor position. A composite cycle comprising of 60 mph cruise control, FTP, HWFET and US06 was used for soot accumulation and partial regeneration, while a sawtooth cycle with temperature varying between ~ 500 – 650 °C was used to study regeneration. Testing was done at various levels of soot load (none to ~2 g/L).

PM emissions were reduced from ~ 6 mg/mi to < 0.5 mg/mi with 94 – 98% filtration efficiency. During regeneration, PM emissions are slightly elevated, but these were still reduced by more than 83% relative to engine out.

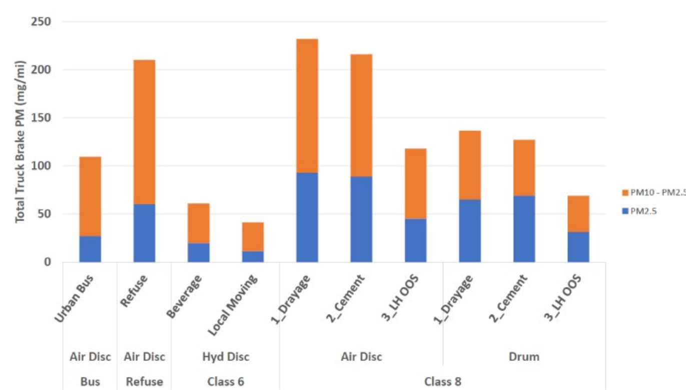


26 PAHs were quantified. GPFs were found to reduce filter collected (particle bound) PAHs by > 99% and gas phase PAHs by > 55%. The filter collected PAHs span from 2-ring to 7-ring species and several of these are carcinogenic. The GPF was found to reduce the cancer potency weighted toxicity of the PAH emissions by 99.8%. The corresponding figure for gas phase PAHs was 51%. These findings will be incorporated in the EPA MOVES inventory model.

Non-tailpipe Emissions

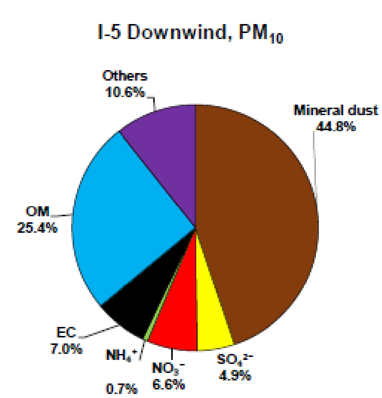
New Research On Brake Wear Particulate Matter Emissions From Several Heavy Truck Vocations In California – J. Koupal, ERG

Braking activity, duty cycle and loading are factors which influence brake temperature for HD applications. The brake temperature was evaluated on various HD vehicles with different brake types and across vocational cycles. Brake temperatures were in the 100 – 350 °C range. A "brake wear index" was developed as surrogate for brake activity and intensity, expressed as product of market share, wearable mass and wear rate for various axle and brake types. Total truck PM10 brake emissions were measured for a nurban bus, a refuse truck, Class 6 and Class 8 trucks, and these range from ~ 50 – 250 mg/mi, with up to half of the emissions being PM2.5.



Concentration and Chemical Characteristics of PM2.5and PM10near California Highways with a Focus on Non-Tailpipe Emissions – X. Wang, Desert Research Institute

The study measured concentrations and chemical composition of particulates near the I-5 and I-710 highways, with an aim to develop markers for non-tailpipe emissions. PM10 concentrations (~ 30 ug/m3) were 2 – 3 times that of PM2.5.
The major components of particulates were mineral dust (>40% of PM10), organic matter (30 – 40% for PM2.5, 25% for PM10), and elemental carbon (~ 10-15% for PM2.5). Some of the elements measured had high correlations pointing to a common source and were related to brake wear (Ba, Cu and Zr) and road dust (Al, Si, K and Ca). Tires from two manufacturers were compared and were found to be different in terms of the elemental and rubber compositions.



INSTRUMENTATION AND METHODS FOR QUANTIFYING BRAKE EMISSIONS – A. Tiwari, TSI

A PMP protocol has been developed for measuring brake emissions, with a regulation anticipated by 2024. There is a WLTP-Brake Cycle in place as part of GRPE-81-12. Details were provided on the test setup, brake temperature measurements, etc. The talk covered various factors which must be accounted for when measuring these particles (such as particle losses, sampling options, thermal treatment for solid particles, etc.)

Chemical fingerprinting tires to understand tire wear emissions – N. Molden, EmissionsAnalytics

Tires from 8 different brands were installed and tested on the same Mercedes C-Class vehicle. Overall tire mass loss was measured at ~ 40 – 90 mg/km, with about a third coming from the front tires. The wear increased by ~ 21% with 500 kg payload. The chemical composition of 10 tires was analyzed and found to contain a mix of C10 to C22 species. The tires were found to contain hundreds of compounds, classified into alkanes, cycloalkanes, terpenes, aromatics and N-containing carcinogens. Aromatics, PAH and nitro-containing groups were found to make up ~ 2/3rd of the compounds.