11th CRC MOBILE SOURCE AIR TOXICS WORKSHOP

Trends, Measurements, Modeling, and Impacts

California Air Resources Board
4001 Iowa Avenue, Riverside, California 92507
February 13-14, 2024

Co-Sponsored by:
American Petroleum Institute
California Air Resources Board
US EPA- Office of Transportation and Air Quality

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Introduction

The 11th Coordinating Research Council (CRC) Mobile Source Air Toxics (MSAT) Workshop was held February 13 and 14, 2024, at the California Air Resources Board's (CARB) new Southern California Headquarters and emissions testing laboratory in Riverside, CA. After the 10th workshop was postponed to February 2022, and held virtually because of the on-going COVID pandemic, the 11th workshop was a welcomed in-person event. The increased levels of discussion on the topics presented and heightened interactions between attendees affirmed the benefits from the in-person format.

The MSAT Workshop brings together researchers and policy makers concerned about air quality and health impacts from air toxics. The workshop format for the first ten workshops remained fairly constant, with sessions addressing tailpipe emissions, atmospheric measurements, atmospheric modeling, policy and accountability. Recognizing that the ongoing electrification of motor vehicles may dramatically alter the nature, sources and distribution of air toxics, the MSAT Organizing Committee modified the workshop agenda to include two new sessions. Session 1, "MSATs from battery electric, hydrogen and alternative fuel vehicles: Energy production and storage", was introduced to address the changing nature of potential MSAT sources as fossil fuels and their associated tailpipe emissions are phased out. Session 3, "Non-Road: Marine", was added to acknowledge the relatively larger fraction of MSATs originating from other sources besides motor vehicles as tailpipe emissions standards have become much more stringent over time. Other changes included combining policy and accountability into a single session, combining atmospheric measurements and modeling into a single session and broadening vehicle emissions MSATs to include non-exhaust emissions.

Judging from reactions by workshop attendees and participants, these changes were a success. The "MSATs from battery electric, hydrogen and alternative fuel vehicles" session helped broaden our perspectives of how MSAT sources may change over time, as well as on how electrification benefits air quality and environmental justice of local communities. The Non-Road: Marine session, albeit specific to the South Coast Air Basin, provided an instructive example of the impact of ship emissions on port communities and mitigation measures available to reduce this. Over half of the talks in the vehicle emissions session addressed brake and tire wear debris emissions and their impacts on the qualities of air and marine environments, demonstrating the growing interest in these topics as tailpipe emissions have significantly declined.

Workshop Overview

The 11th MSAT Workshop began with the keynote talk "Introduction to Mobile Source Air Toxic Emissions in an Electrified Economy" to introduce the new session on this topic. The talk characterized our current situation as a work in progress from a fossil fuel-based economy to an aspirational electrified economy. Progress varies across different sectors depending on the maturity of the underlying technology. As electrification increases in more mature sectors, fossil fuel use may be displaced to other activities, for example battery manufacturing, at least temporarily until elec trification spreads more broadly across the economy. The difficulty in predicting how this occurs, particularly in areas where electrification technology is nascent, leads to uncertainties in predicting emissions benefits during the transition from fossil fuels. The future electrification scenarios also relied heavily on "curtailment", which, when questioned, could not be determined if that was mandatory measures (i.e. - brownouts) or voluntary (i.e. Demand Side Management). DSM can also lead to higher emissions from behind the meter generation.

Session 1 continued on the theme of electrification, but also addressed the alternative fuel aspect of this session with a talk on interim benefits possible from plug-in hybrid vehicles (PHEVs) run with higher ethanol fuels. While electrification has certain air quality and health benefits depending on range and scope of the study, impacts on specific pollutants and communities are mixed. The transition from combustion engine to battery powered vehicles lowers NOx emissions steadily, but VOC and PM2.5 emissions remain flatter and show increases. NOx levels decline because they are closely linked to combustion, particularly by diesel engines; however, VOCs and PM2.5 arise from multiple sources, including solvents and road dust. Furthermore, vehicle electrification can exacerbate emissions; namely, the additional weight from the battery increases tire and road dust PM.

The environmental justice impact is similar. Vehicle electrification benefits disadvantaged communities overall owing to pollutant emissions decreases, but disparities remain since near-road communities are still disproportionally impacted by non-exhaust emissions from vehicle traffic. Air quality benefits need not wait for large scale adoption of battery vehicles, however, which still requires major electric power industry infrastructure changes, including a large increase in charging station availability. Interim use of PHEVs running on lower fossil carbon fuels, such as E30, can help accelerate air quality improvements.

Session 2 addressed policy, regulatory opportunities and accountability related to MSATs. It began with a presentation on CARB's LEV IV plans, which affect 2026 – 2035 model year (MY) vehicles. A major initiative is to phase out the inclusion of zero emitting vehicles (ZEV) when calculating fleet average emission rates by MY 2029. This will effectively tighten emissions from combustion engines and, thus, reduce emissions from new vehicles even while many standards, such as NMOG + NOx, will remain unchanged from LEV III. LEV IV will also reduce evaporative running losses to 0.01 g/mi. where possible, CARB plans to align with the US EPA's Tier 4 regulations. A number of other states have adopted California's emissions standards. A modeling investigation showed that this could provide significant emissions benefits extending to 2030 and 2050, more so for NOx and CO_2e than for PM2.5. The predicted benefits extend to specific MSATs as well.

AB 617 initiatives continue to have a positive impact on California communities by identifying pollutant sources and mitigation strategies. The program has introduced a number of tools to help identify and document air quality concerns. Lessons learned from earlier communities have helped new ones and are being used to track local scale improvements. The multiple air toxics exposure study (MATES) completed its fifth program showing continued improvement in lowering cancer risk in the South Coast Air Basin. MATES VI is in the planning stage. It will conduct a year of measurements at 10 locations. New goals include the addition of near-road sites and expansion to Coachella Valley. In addition, the emerging concern of ethylene oxide exposure will be addressed.

Modeling work to investigate policies that accelerate vehicle electrification found that they would benefit environmental justice communities. Encouraging earlier adoption would lower NOx exposures at near-road communities. The benefits to PM are smaller owing to its higher spatial uniformity in Southern California. On-board sensor-based measurements of vocational truck emissions revealed that they are often concentrated to specific locations. For example, emissions related to the transport of goods from port to warehouses tend to be located in those locations and less so on the roadways between them. Such data poses possible policy options to mitigate such "hot spots".

Session 3 started with a perspective on the crossroads between science, policy and community health. Examples, such as the impact from an offshore fuel terminal, illustrated how environmental policy decisions based on insightful scientific data can reduce exposures in affected communities. Subsequent talks focused more specifically on shipboard measurements that demonstrated how strategies, such as fuel sulfur reduction and changing to clear fuel when near ports lower emissions impacts on port communities. One study showed that using biofuels to power ship engines can lower both PM as well as fossil carbon emissions. Another demonstrated lower NOx, PM2.5 and CO_2 emissions upon switching from diesel to natural gas fuel. The session concluded with a look at a specific retrofit emissions reduction strategy, namely adding water to the fuel. Water addition cools the combustion mixture, which can significantly reduce NOx formation. A prototype retrofit on a container vessel provided a 12% reduction in NOx emissions, but CO_2 and PM emissions increased slightly.

The second day's keynote talk described how on-board sensor-based emissions measurements can provide deeper insights into truck emissions and their community-based impacts. Although less accurate than laboratory instruments, their small size and low cost allows unobtrusive installation on large numbers of trucks over long time periods. The lower accuracy is more than compensated for by the ability to record emissions during the trucks' everyday operations, which reveals what operating conditions cause emissions, as well as truck-to-truck and day-to-day variabilities. By coupling the emissions with GPS locations, one can map community-by-community emissions impacts.

Session 4 focused primarily on mobile monitoring and traffic related air quality modeling. It began with a talk on the development of a new compact, low power and cost, instrument for metals detection based on spark-induced breakdown spectroscopy. Preliminary ambient measurements exhibited good correlation with PM2.5, but somewhat weak correlation with X-ray fluorescence. The instruments ~1 minute time resolution permits time-of-day resolved metals measurements. A subsequent talk on hyperlocal mobile monitoring demonstrated the need for this kind of instrumentation in industrialized areas. Its investigation in East and Southeast Los Angeles showed elevated metals emissions primarily from the high number of metals processing facilities, traffic, and soil dust. Another mobile monitoring study examined locally elevated pollutant concentrations across communities with varying environmental justice scores in the Sacramento area. It found arterial roads to have the highest community impacts across multiple pollutants, including NOx, alkanes and aromatics. A third mobile monitoring study looked at pollutant sources in the Pittsburgh area via aerosol mass spectrometry. Signatures based on select PAH to black carbon ratios allowed apportioning emissions among diesel vehicles, cars, and coke emissions, revealing that traffic was an important source of PAHs.

Two modeling talks focused on combining traffic and emissions models to investigate the impact of various traffic scenarios on local pollutant levels. One talk compared centralized versus distributed on-demand passenger pickup scenarios. Although overall emissions increased slightly for the distributed pickup, PM2.5 levels decreased at the central bus facility leading to overall lower PM exposure. The second talk compared bus decarbonization scenario impacts on pollutant levels at the central bus station in Surrey, BC. It showed that prioritizing the replacement of diesel buses with electric versions is better for emissions reductions than replacing buses based on age. It also found that promoting renewable diesel fuel to reduce greenhouse gas emissions can increase pollutant exposures in high traffic areas. Both talks showed how including emissions is important in traffic planning policy.

Section 5 focused on non-exhaust emissions. The University of California at Irvine contributed three talks on light duty brake wear emissions, characterizing them under light versus heavier braking conditions. Both produce coarse mode particles, more so under the heavier conditions. Heavier braking also raised brake temperatures. One consequence was ultrafine particle nucleation as brake temperatures rose sufficiently high to cause pyrolysis or smoldering of resins in the brake pads. Brake wear emissions depend on pad type, with ceramic pads exhibiting higher mass emissions than semi-metallic pads. The metal content of brake wear is dominated by iron, even with ceramic pads. Braking also contributes VOC emissions, which increase sharply as the rotor temperature surpasses ~150 C. The constituents include BTEX and oxygenated semi-volatile VOCs, suggesting that these emissions will contribute to secondary organic aerosol formation. Under aqueous conditions brake wear particles were found to generate OH radicals which causes oxidative stress in biological systems. CARB researchers presented work related to heavy duty vehicle brake emissions. Results on drum brakes revealed brake wear with characteristics very similar to disc brakes. The emissions were bimodal, with a coarse mode of wear debris and a highly temperature dependent ultrafine mode related to brake binder materials. An examination of brake PM composition profiles showed relatively little variation between different vehicle types, truck size class or brake manufacturers. Composition did vary, however, between pad types, such as non-asbestos organic versus semi-metallic.

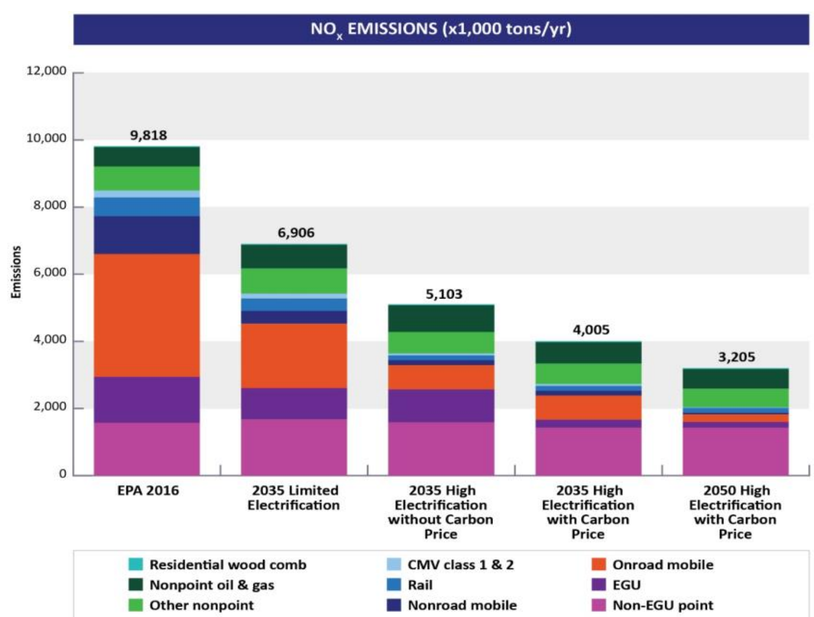
Tire wear PM measurements were also presented. Tire wear varies significantly with tire design and composition; for example, US tire wear rates per kilometer are roughly five times higher than in Europe. The size range extends to the hundreds of microns, with the PM10 and PM2.5 fractions considerably higher than current tailpipe PM emissions rates. The emissions are associated with a very large array of organic compounds. One is the antioxidant 6PPD added to slow rubber degradation. However, exposed to ozone it converts to 6PPD-quinone, which has been identified as harmful to fish once the compound enters the marine environment.

One talk related to tailpipe emissions examined measurement variability. In a study involving five identical model vehicles, the normalized tailpipe emissions ranges did not show any statistically significant differences between vehicles. Roadside HD truck NOx emissions comparisons were presented between winter and summer in Utah. Winter emissions were higher than in summer, with significant increases observed for vehicles in the 0 – 4-year age range. The newest trucks have emissions rates comparable to California, but by MY NOx emissions are higher in Utah. MOVES4 underestimates 2010 – 2016 and overestimates 2022 – 2024 truck NOx emissions. The workshop's concluding talk examined the effects of tampering on truck emissions in Edmonton, AB. Comparing measurements to MOVES predictions, the researchers found that tampering is equivalent to a substantial increase in effective fleet age.

Keynote Talks

Introduction to Mobile Source Air Toxic Emissions in an Electrified Economy, John Grant, Ramboll

The 11th CRC MSAT Workshop kicked off with John Grant's overview of MSATs in an electrified economy, which served as a nice introduction to this workshop's newly added session, "MSATs from battery electric, hydrogen and alternative fuel vehicles: Energy production and storage". John discussed the challenges of emissions assessments during the transition from a fossil fuel based to electrified economy. Electrification is a relatively mature technology in the light duty vehicle sector, with the projected stock of electric vehicles in 2050 ranging from 11% to 26%. There is ongoing development of electric busses, delivery vans, and drayage trucks, but extending this to long haul trucks, agricultural machinery and construction equipment presents more of a challenge. Electric power for trains is mature but requires high capital



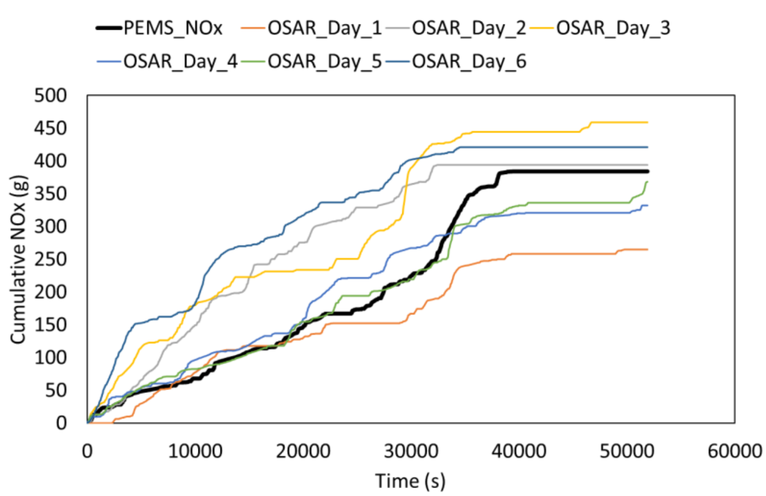
investments to expand significantly. Electrified technologies for marine vessels and aircraft represent longer term challenges. This suggests that the transition will continue for the foreseeable future.

Mobile sources across the US currently account for about 33% of MSAT emissions. Stationary sources account for ~21%, whereas petroleum extraction, refining, bulk terminal and refueling ~9% of MSAT emissions. As shown in the accompanying figure, these differ between various electrification scenarios, which project reductions from some sources, but also displacement to other sources (for example, non-point oil & gas and non-EGU point sources). Model projections estimate a 30% reduction in NOx emissions from 2016 to 2035 from limited electrification, increasing to a 67% reduction from 2016 to 2050 in a high electrification and carbon price controls scenario. In both cases the reductions occur largely from lower diesel engine use. VOC emissions, in contrast, are projected to increase slightly to 2035 and then decrease slowly to 2050 due to reductions from mobile sources being offset by increases in solvent use and commercial and residential combustion.

John concluded his talk with some emerging challenges. One is uncertainties in predicting the outcomes from long-term electrification, especially in sectors where the technology is nascent. Due to a combination of direct and indirect effects, such as refineries and crude oil production, both the magnitudes and time scales of emissions reductions will be uncertain. The second challenge concerns equity. Projected emissions trends exhibit significant geographic variability. Electrification may not uniformly benefit all communities evenly given, for example, the affordability of electric vehicles. Policy and incentive efforts targeted to achieve equity goals while reducing air toxic exposures may help ameliorate these challenges.

On Board Sensing for Community-Based Emissions Impact Analysis, Kent Johnson, UCR

Kent Johnson spoke on the workshop's second day about the benefits of sensor-based emissions measurements to assess the local impacts of mobile source emissions. Because of on-board diagnostics regulations, compact, low cost, sensors have been developed for NOx and PM detection. These admittedly provide lower accuracy than laboratory and portable emissions measurement systems (PEMS) instruments, roughly 10% compared to 2% and 5%, respectively. On the other hand, they have a number of benefits. Foremost are the much larger data quantity to cost and time ratios that can be achieved via sensors as compared to laboratory or PEMS measurements. Multiple trucks can be outfitted with sensors and tracked for months with data loggers for lower cost and less effort than laboratory or PEMS testing of a single truck. While sensor function needs to be confirmed by comparison with laboratory or PEMS instruments, sensors do not require calibration, which is done by the manufacturer. Also, sensors are much less intrusive to vehicle operators, which simplifies vehicle recruitment.



Laboratory and PEMS measurements provide limited snapshots of vehicle emissions. Example NOx data in the figure below show a vehicle's day-to-day emissions variability observed via sensor that are missed when looking at just a single day's PEMS data. Likewise, one can readily examine vehicle-to-vehicle variability by equipping multiple same-model vehicles with sensors. More importantly, using sensor-based devices enables emissions to be monitored over long time periods, which can reveal how real-world operating conditions impact emissions rates and pinpoint the locations where they occur. This permits examination of the geographical distribution of mobile source emissions, for example near docks versus in local neighborhoods or on roadways.

There are multiple means to bin emissions, such as by moving average window or by speed and percent load. However, by binning emissions according to vehicle physical activity, Kent and his team observed that NOx emissions tended to occur during cold start and then over re-starts throughout the day as the vehicles were loaded and unloaded across the Long Beach regional area. About 50% of the vehicles' total emissions occurred over 40 minutes of a 10-hour workday. The fact that they predominantly happened during starts and restarts means that the emissions impacted communities near the shipping docks and warehouses. Such data can inform policy decisions to help mitigate exposures to adversely affected communities; for example, hybrid powertrains could be employed to power vehicles electrically when near such communities and via combustion engine during transit from dock to warehouse.

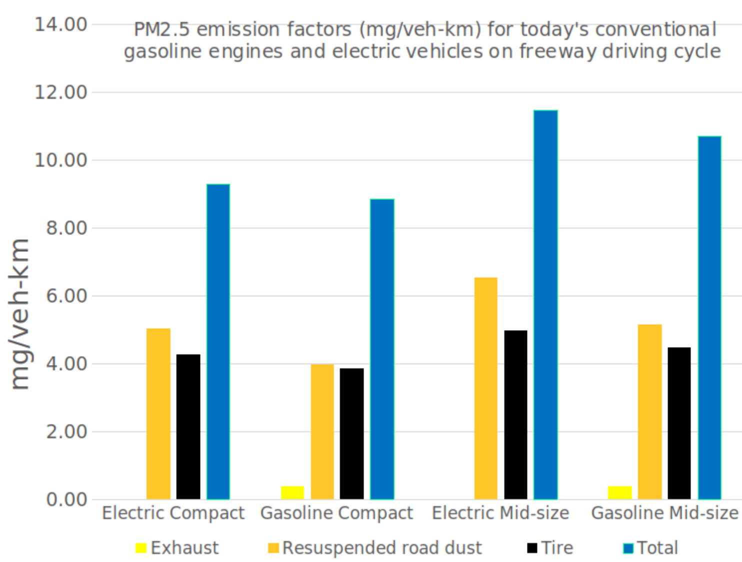
Session 1 – MSATs from Battery Electric, Hydrogen and Alternative Fuel Vehicles: Energy Production and Storage

Chairpersons: Greg Meyers (Marathon Petroleum) and Sandy Winkler (Ford)

Air Quality Impacts from Electric Vehicles, Darrin Trageser, ICF

David Trageser's talk addressed non-exhaust particulate matter (PM) emissions impacts from electric vehicles (EVs). PM2.5 levels remain high, with 97% of US cities not meeting the WHO 5 μg/m^3 target in 2021. Following increasingly stringent tailpipe standards, much of the PM2.5 emissions come from non-exhaust sources, including brakes, tires, and resuspended road dust. The exhaust contribution has shrunk to about 5% of the total PM emissions, which are dominated by tires and road dust, as illustrated in the figure. Tires incorporate the anti-degradation additive 6PPD, which via storm water runoff can adversely impact marine environments.

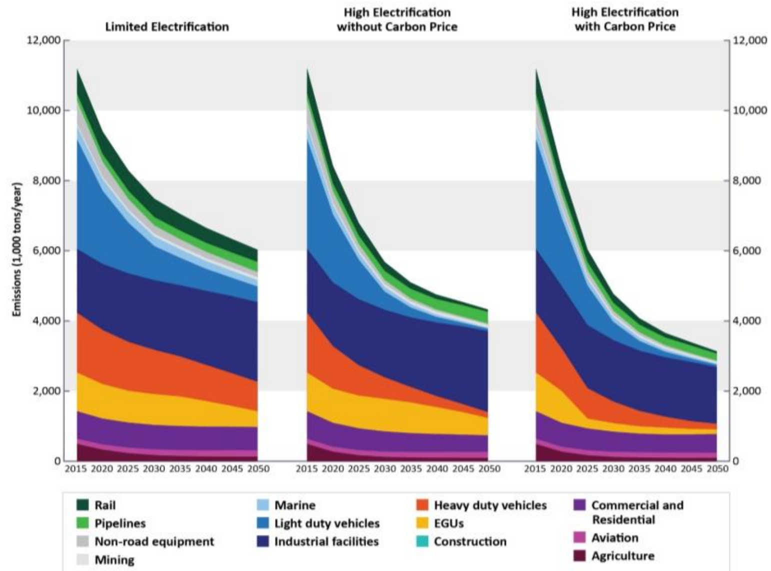
The shift to EVs can exacerbate PM levels, especially near roadways. Tire and brake wear scale with vehicle weight and to a lesser extent with engine torque. Both increase for EVs, with weight due to the battery and torque due to electric motor capability. EV versions of the same vehicle model are typically 30% heavier than their IC engine counterparts, leading to an ~20% increase in tire wear and road dust PM emissions and a 5 – 7% increase in total PM2.5. Autonomous and connected vehicle technologies can lead to further emissions increases by allowing for increases in vehicle miles traveled.



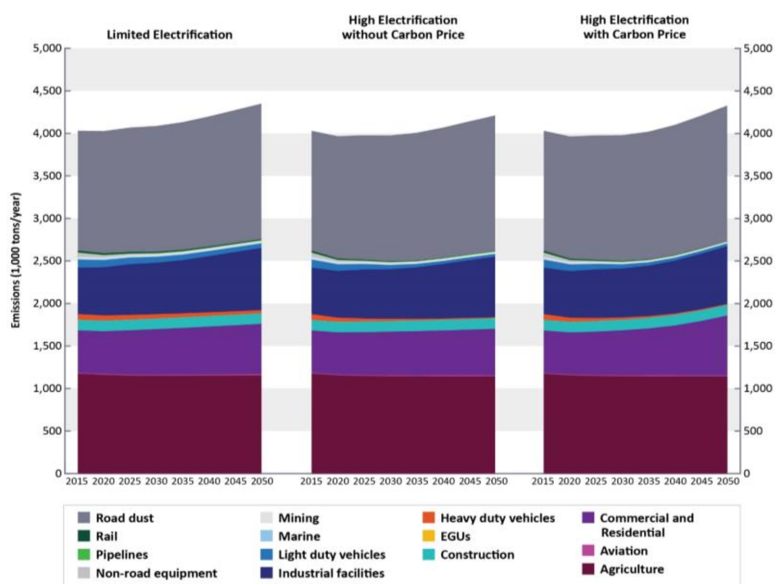
The primary mitigation measures are reductions in vehicle weight and vehicle miles traveled. Green infrastructure, such as roadside vegetation can help reduce the spread of non-exhaust PM into near roadway communities. Finally, technological improvements to brakes, tires, and the materials used in these components can reduce emissions and their environmental impact.

Air Quality Impacts of Us Economy-Wide Electrification and Climate Policy, John Grant, Ramboll

In his second talk, John Grant presented a modeling study of the impacts of electrification on criteria pollutant emissions. This work utilized the Electric Power Research Institute's US Regional Economy, Greenhouse Gas, and Energy model (REGEN), a combined energy – economy model. The study adopted a baseline using EPA's 2014 National Emissions Inventory and forecast economic activity, technology, and emissions controls for three scenarios: limited electrification, high electrification and high electrification with carbon price. The model forecast expanded natural gas and wind energy meeting the high electric scenarios and predicted an earlier phase-out of coal in the carbon price scenario.



Model results indicate strong decreases in NOx emissions over the 2015 – 2050 time frame led primarily by emissions reductions from mobile sources and EGUs even while industrial emissions increase, as exhibited in the figure above. All three scenarios exhibit NOx decreases, but they are sharpest in the high electrification with carbon price scenario. In contrast, VOC emissions predictions initially exhibit a slight decrease in time, but then increase to above baseline for the low and high electrification scenarios. The decrease comes from light duty vehicle reductions, but this is more than offset over time by industrial facility emissions. The industrial contribution is mitigated in the high electrification with carbon price scenario. Finally, PM2.5 emissions remain roughly flat, as depicted in the figure below, since these emissions are dominated by agricultural and road dust.



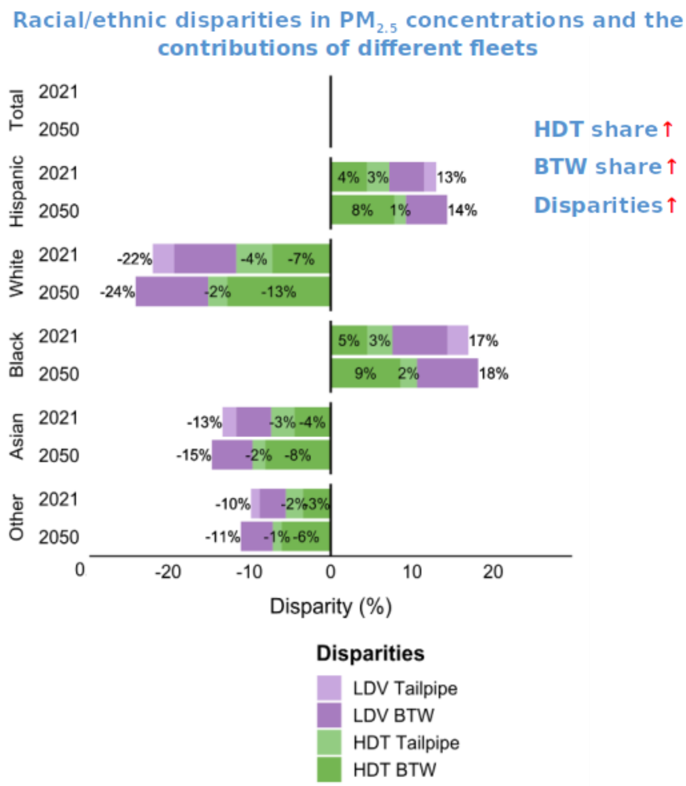
Combining the REGEN results with CAMx modeling leads to predictions of significant ozone decreases across the US over the 2016 to 2035 and 2016 to 2050 time frames, particularly in eastern US. These are driven primarily by the NOx reductions predicted by REGEN. Regional modeling over Georgia predicts PM2.5 reductions below the 12 μg/m^3 NAAQS value. Key takeaways from this study are that "on the books" strategies may be insufficient to meet NAAQs goals in some states and that high electrification can effectively extend ozone improvements PM2.5 improvements, however, stall as secondary PM2.5 precursor reductions (NOx and SO_2) are offset by growing primary PM2.5 emissions.

Persistent Environmental Injustice Due to Brake and Tire Wear Emissions and Heavy-Duty Trucks in Future California Zero-Emission Fleets, Yifang Zhu, UCLA

In her talk, Yifang Zhu examined the question of how future ZEV fleets might impact environmental justice in near-roadway communities. In particular, she looked at California county level and Los Angeles link-level changes in brake and tire wear PM2.5 emissions as a function of light duty vehicle and heavy-duty truck fleets. As opposed to previous top-down studies, she took a bottom-up approach that included travel demand and supply, agent-based travel patterns, and tract-specific ZEV ownership, with a 50-meter spatial and second based temporal resolution. Predicted emissions in 2050 were compared to a 2021 baseline.

The modeling shows the ZEV fleet percentage to grow from 1 – 2% in 2021 to >90% in 2050 for both arterial and freeway traffic in Los Angeles County. While total PM2.5 levels decrease over this time period, both brake and tire wear PM and heavy-duty truck PM increase. The principal drivers are vehicle miles traveled, which increases PM2.5 concentrations in 2050, and tailpipe emissions controls, light duty adoption of ZEVs and zero emission truck adoption, all of which lower PM2.5 concentrations.

While disadvantaged communities derive a larger share of environmental benefits from ZEV adoption, disparities remain, as depicted in the figure to the right. Hispanic and black communities remain with higher population weighted PM2.5 concentrations as compared to white and Asian communities. The heavy-duty truck and brake & tire wear contributions become larger shares in these disparities in 2050.

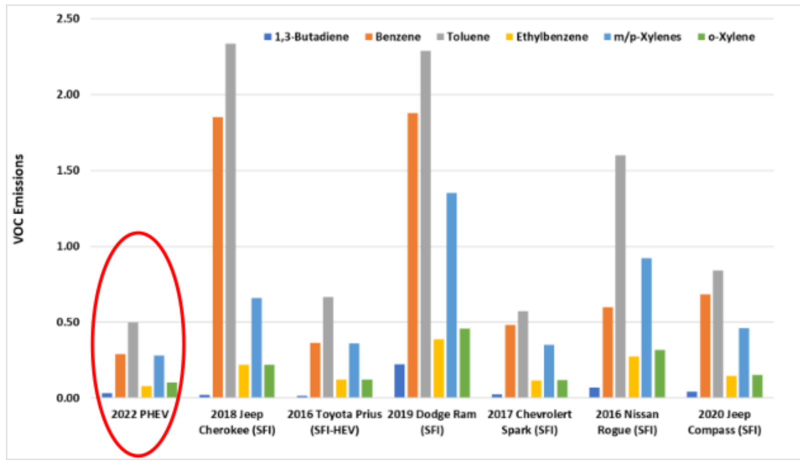


The key findings from this work are that targeting heavy duty trucks in ZEV policies can lead to a higher impact on environmental justice than focusing solely on light duty vehicles. Near roadway PM2.5 disparities persist due to higher truck traffic and brake & tire wear, which will require fleet specific policies to overcome.

Mobile Source Air Toxics, Ultrafine Particles and Particulate Matter Toxicity from a PHEV Fueled with E10, E30, and E83 Blends, Georgios Karavalakis, UCR

Georgios Karavalakis spoke on the combination of hybrid technology and low carbon fuels as means to help advance the decarbonization of transportation. Specifically, he examined tailpipe emissions from a 2022 model year plug-in hybrid vehicle (PHEV) run on E10, E30 and E83 ethanol / gasoline blend fuels. The E10 fuel was a blend of fuels from three refineries, and the E30 and E83 fuels were produced by splash blending with ethanol. After preconditioning the vehicle with multiple fuel drain and fills and prep drive cycles, emissions were recorded over the Federal Test Procedure drive cycle (FTP) and the high speed US06 extension. Emissions were measured on a chassis dynamometer using both real time measurement instruments (e.g., particle number and black carbon) and off-line analysis of sampled exhaust (e.g., PM mass and BTEX).

NOx emissions exhibited a statistically significant decrease with higher ethanol content over the FTP average and US06 cycles, likely from ethanol's cooling influence on the in-cylinder air-fuel mixture. Total VOC emissions did not vary much between ethanol blends. However, BTEX and 1,3 butadiene emissions increased with higher ethanol, more from E10 to E30 than from E30 to E83. As expected, formaldehyde and acetaldehyde increase substantially, particularly for E83. Overall, though, these emissions were generally lower than from other LEV III vehicles, as demonstrated in the accompanying figure for the case of BTEX. PM mass emissions were below the California 1 mg/mile standard. FTP PM emissions were similar for E10 and E30, but US06 PM emissions decreased. For E83 there were strong decreases in both PM and black carbon emissions. Similar trends were found for solid particle number. Toxicological analysis showed mixed results; oxidative stress was lower for E30 and E83 fuels, but cytotoxicity increased for E83. Overall, these results show that higher ethanol blends can provide environmental benefits of lower NOx, PM and ultrafine particles, while at the same time lowering GHG emissions. The main disadvantage is the increase in carbonyl emissions.

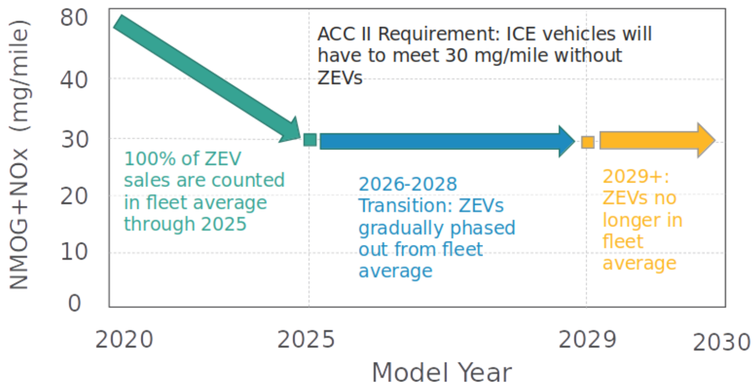


Session 2 – Policy, Regulatory Opportunities and Accountability

Chairpersons: Georgios Karavalakis (UCR) and Seungju Yoon (CARB)

Advanced Clean Cars II – LEV IV Criteria Emission Regulations and Amendments, Kevin Sothy, CARB

Kevin Sothy provided a progress update on developing CARB's LEV IV emissions regulations. These regulations will impact 2026 – 2035 model year light duty (LD) and medium duty (MD) vehicles in the areas of air pollutant emissions, greenhouse gas (GHG) emissions, ZEV assurance measures, and ZEV sales requirements. The new regulations are looking to align with EPA where appropriate with respect to air pollutant and GHG emissions. CARB is examining new GHG standards beyond 2025 to support climate goals and considering new measures to further support the ZEV market. The kick-off workshop took place in November 2023. EPA is expected to finalize its rules in Spring 2024 and CARB expects to release its staff report Spring – Summer 2025 for a Board decision Summer – Fall 2025.



The main changes in LEV IV will require manufacturers: to meet pollutant and GHG fleet average requirements without including ZEVs, to reduce tailpipe emissions during cold starts and aggressive driving, to meet more stringent evaporative emissions and to fulfill more robust in-use emissions controls for MD vehicles. More specifically, the light duty NMOG + NOx fleet average standard will remain at 30 mg/mi, but a phaseout of including ZEVs in the fleet average will begin with model year (MY) 2026 and conclude by MY 2029. The PM emissions standard will remain at 1 mg/mi for the FTP cycle but be reduced to 3 mg/mi for the US06. There is the possibility that this will be amended to align with EPA's Tier 4 proposal of 0.5 mg/mi for both the FTP and US06 cycles. LEV IV is looking at partial soak standards to control the impact of cool-downs on emissions, and early drive-away standards that more closely follow how drivers behave in the real world. It will reduce the LD vehicle evaporative running loss standard from 0.05 to 0.01 g/mi and will design requirements to minimize "puff" emissions during refueling. The evaporative emissions standards may change depending on alignment with EPA's Tier 4 proposal.

The MD NMOG+NOx standard will be lowered from 175 to 150 mg/mi for class 2b and from 250 to 175 mg/mi for class 3 fleet averages. As with the LD fleet, ZEVs will also be phased out of the MD fleet average beginning with 2026 MY. The PM emissions standard remains unchanged for the FTP cycle but will fall to 8 mg/mi US06 cycle for class 2b a to 6 mg/mi over the LA92 cycle for class 3 vehicles, again with a phase-out of ZEVs. Vehicles with heavy tow capability (>14k lbs) will need to meet HD in-use PEMS standards. These standards and requirements can potentially change depending on EPA's final Tier 4 regulations and the extent of CARB's alignment with them.

Benefits from Adoption of California Light- and Medium/Heavy Duty Regulations in Other U.S. States, Jeff Houk, Sonoma Technology

Jeff Houk presented modeling investigations of how the adoption of CA Advanced Clean Truck (ACT) and Advanced Clean Car (ACC) initiatives can benefit other states. A key driver for the study was the 2020 multi state ZEV action plan, which included 17 states, Washington D.C., and Quebec. The modeling combined MOVES and Argonne National Lab's GREET. MOVES calculations for NOx, PM2.5 and CO_2e were performed on a county scale for 2017, 2030, and 2050 for MD and HD trucks and at the default scale to generate interpolation factors for intervening years. The MOVES results were adjusted based on CARB projections of EV market penetration. EV energy consumption was used in the GREET model to estimate emissions attributable to electricity generation. At the same time, the reduction in fuel consumption was used to decrease refinery related emissions.

California's ACT initiative requires 55% ZEV class 2b-3 sales, 75% ZEV class 4-8 truck sales and 40% ZEV truck tractor sales by 2035. Its low NOx regulation will require a 90% reduction by 2027. Adopting these regulations in 18 other states, which together with CA account for 42% of MD and HD trucks and 47% of the US population would on average reduce NOx by 27%, PM2.5 by 13% and well-to-wheels CO_2e by 28% between 2025 and 2050.

Advanced Clean Car II mandates 35% ZEVs in new LD vehicle sales starting model year 2026, increasing to 100% by MY 2035. Adopting this mandate in 16 other states, which combine with CA for 37% of the 2022 LD vehicle market and include 38% of the US population, is predicted to avoid cumulative emissions of 135,700 US tons of NOx, 9,200 US tons of PM2.5 and 1.1 billion metric tons of well-to-wheels CO2e over the 2025 – 2040 period.

For the 11th CRC MSAT workshop Sonoma Technology carried out additional analyses on the projected benefits regarding benzene and diesel PM emissions in NJ and NY. As evident in the figure to the right, adoption of the ACC II rule would benefit MSAT emissions similarly as for NOx and PM2.5. The modeling results presented by Jeff show the overall benefits possible by the California initiatives, but as discussed during Q&A, do not provide spatial resolution needed for community level impacts.

NJ and NY MSAT Benefits: ACC II Rule*

New Jersey	Vehicle Only		Well-to-Wheel	
	Benzene, TPY	DPM, TPY	Benzene, TPY	DPM, TPY
2030	6.44	0.09	6.42	0.09
2040	28.11	0.21	28.02	0.21
Cumulative, 2025-2040	200.86	2.10	**200.32**	**2.11**

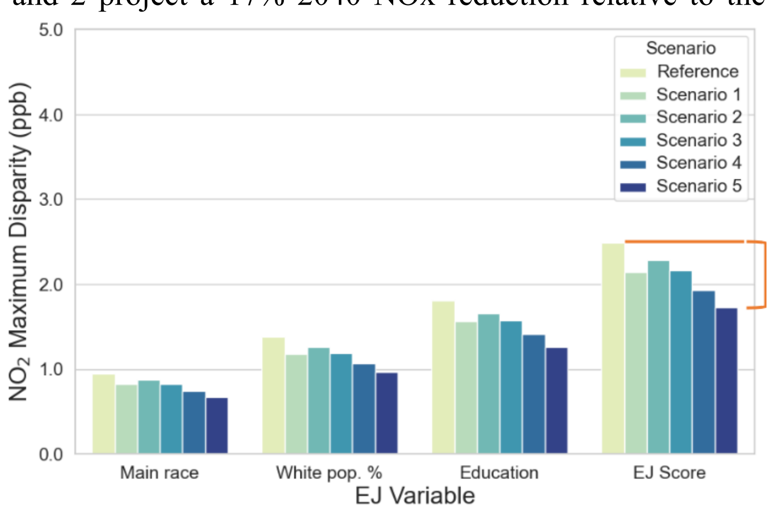
New York	Vehicle Only		Well-to-Wheel**	
	Benzene, TPY	DPM, TPY	**Benzene**, TPY	**DPM**, TPY
2030	12.50	0.18	12.45	0.18
2040	57.70	0.41	57.26	0.41
Cumulative, 2025-2040	408.03	4.19	**405.37**	**4.19**

Accelerating Electric Vehicle Penetration: Air Quality Benefits and Environmental Justice Implications, Jeff Houk, Sonoma Technology

In a second talk, Jeff Houk presented the paper "Electric vehicle fleet penetration helps address inequalities in air quality and improves environmental justice" by Shih Ying Chang (Sonoma Technology) et al., published in Communications Earth and Environment, Vol. 4, 2023. This study examines how electrification of MD/HD and LD vehicle fleets may impact environmental justice (EJ) communities. The study is set in the I-710 corridor of southern California where trucks account for up to 16% of annual average daily traffic and which includes communities with and without (EJ) concerns. It compares five electrification scenarios to a reference case with respect to projected 2040 NOx and PM2.5 emissions and their community scale impacts in terms of various EJ-defining parameters.

Three of the five scenarios correspond to policy cases, whereas the other two represent idealized cases. Scenario 1 includes a mix of truck and LD vehicle actions corresponding to the advance clean truck and car initiatives, with a 2040 projected 18% EV fleet as compared to 9% in the reference scenario. Scenarios 2 and 3 include mostly truck and entirely truck actions resulting in 11% total EV penetration in the on-road fleet by 2040. Scenarios 4 and 5 correspond to 100% EV sales by 2035 and 2023, respectively, with 2040 penetrations of 59% and 85%.

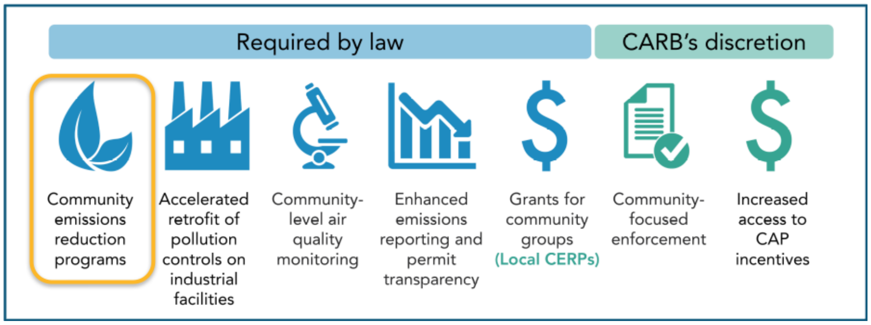
In the reference scenario trucks dominate 2040 NOx emissions, roughly 80%, whereas LD vehicles are the major PM2.5 contributor. Scenarios 1 and 2 project a 17% 2040 NOx reduction relative to the reference scenario primarily from truck electrification and a 32% reduction from electrification of both trucks and LD vehicles. Scenario 4, 100% EV sales by 2035, shows much larger reductions, 44% NOx and 29% PM2.5. In all scenarios, the NOx reductions are higher near major roads, whereas the PM2.5 reductions are more spatially uniform. Owing to the tendency of EJ communities to be near major roads, the NOx reductions from electrification tend to benefit these communities leading to reductions across various EJ variables as seen in the figure.



The higher spatial uniformity in PM2.5 concentrations leads to a lower impact of electrification on PM2.5 disparities.

An AB 617 Perspective to Address Air Toxics in California Communities, Cynthia Wong, CARB

Cynthia Wong provided an update on AB 617, a community air protection program focused on air toxics and criteria pollutants. This program was first established in 2017, with the updated Program Blueprint 2.0 adopted in 2023. Thus far it has had about $2 billion allocated for implementation, Air Grants and incentives.



The main elements of the program are displayed in the accompanying figure. Many are required by law, but CARB has discretion over community focused enforcement and access to CAP incentives. The strategies and actions available include rules and regulations, air quality permitting, facility-specific risk reduction, land use and transportation and exposure mitigation coupled with incentives and enforcement. Example actions to reduce air toxics include incentives to promote the use of cleaner equipment and use of zero emissions technologies, strategies for truck routing and creation of buffer zones, enforcement of truck idling rules and investigations based on community air monitoring. Just over half of the funding for community air protection incentives has gone to on- and off-road equipment, including agricultural use. Almost one quarter has gone towards community identified projects.

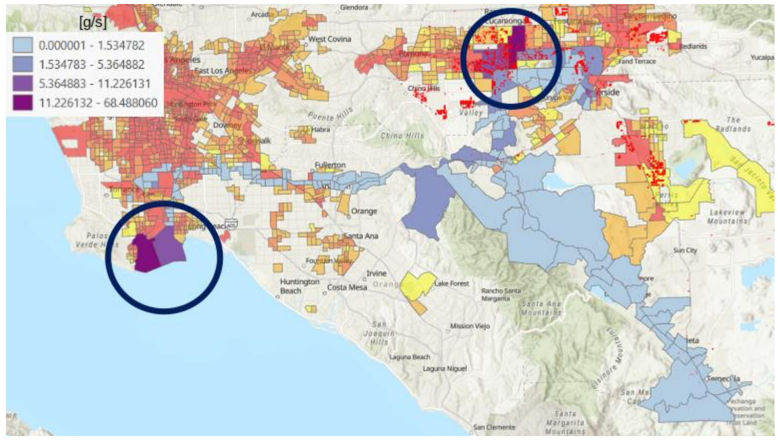
To address questions such as “What is the air quality in my community?”, “How can emissions be reduced?” and others, the program provides numerous tools available to communities including: CommunityHub2.0, a platform offering comprehensive insight into the program; California Air Toxics Assessment (CATA); Community Emission Inventory, which provides emissions data for selected AB 617 communities; the AB 617 Technology Clearinghouse to assist in identifying emissions reduction strategies; the AQview Community Air Quality Viewer; and the website Funding for Cleaner Air: Your Orientation to Community Air Protection Incentives.

Key takeaways are: The community air protection program is helping reduce emissions and exposure to air toxics, lessons from earlier communities should be consistently applied to newly nominated communities and there is a need to track the improvements at a local scale.

Air Quality Impacts and NOx Emissions Exposures in Disadvantaged Communities from Heavy-Duty Vocational Vehicles, Troy Hurren, UCR

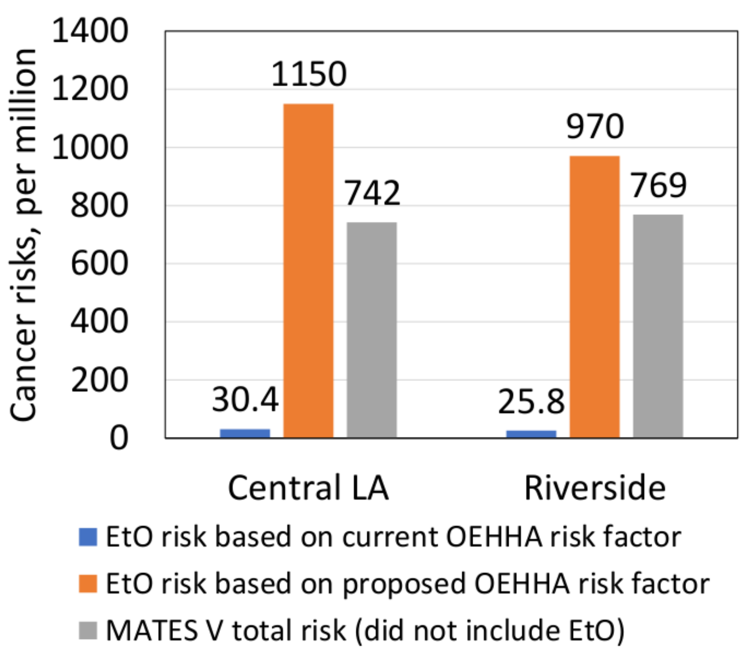
Troy Hurren spoke on the air quality impacts of heavy-duty vocational vehicle emissions on disadvantaged communities. Southern California communities near ports, highways and warehouses generally fall into the lowest quartile of CalEnvironScreen 4.0 scores and are considered disadvantaged communities. To develop a better understanding of these emissions, Troy and coworkers outfitted over 50 heavy duty diesel and natural gas vehicles with portable emissions measurement systems (PEMS) and analyzed their NOx emissions while they operated under business-as-usual. The objective was to compare these to local point-source emissions and determine engine technologies and fuels that can best benefit disadvantaged communities.

The test vehicles ranged from school and transit buses to goods transport and delivery vehicles and refuse haulers. Test routes were selected to represent densely populated areas, warehouses, logistic facilities and ports in the South Coast Air Basin. The highest NOx emissions occurred in the port of Long Beach and warehouses, as shown by the accompanying Figure. Much of these emissions came from low load engine operation. These areas have high scores with respect to poverty and low education level and have ~75% Hispanic populations. Such "hot spot" areas pose challenges to future policy decisions aimed at alleviating emissions exposures in disproportionately impacted communities.



Quantifying the Health Risks from Air Toxics Over Time in Southern California with the Multiple Air Toxics Exposure Study, Scott Epstein, SCAQMD

Scott Epstein provided a summary of results from the MATES V program and a preview of MATES VI. The Multiple Air Toxics Exposure Study (MATES) goals are to provide public information about air toxics and their risks, evaluate progress in their reduction and provide direction to future toxics control programs. The first MATES program began in 1986 and subsequent programs have occurred at eight-year intervals on average. Whereas MATES I focused on benzene and Cr(VI) impacts, subsequent programs have expanded to look at diesel PM, ultrafine particles, and black carbon. The MATES V report was released in 2021. It detailed a 50% reduction in cancer risk since 2012 in the South Coast Air Basin from 997 per million in MATES IV to 455 per million in MATES V. However, the risk remains higher than other regions; for example, Coachella Valley saw a reduction from 357 to 250 per million cancer risk. Highest cancer risks occur around the ports. Diesel PM is the highest contributor, but its fraction is decreasing. Environmental justice communities also saw lower risks, but still higher than basin averages. Advanced air monitoring methods were evaluated at and near refineries. And chronic non-cancer health impacts were estimated for the first time.



MATES VI will include comprehensive modeling of air toxics cancer risk with an updated emissions inventory, a one-year air monitoring campaign at 10 locations, measured data for cancer and chronic non-cancer health risks, analysis of concentration and health risk over past MATES studies, and an online interactive data display for risk and concentration visualization. New goals include near-road measurements at two sites, expansion of measurements to Coachella Valley, air toxics source apportionment, evaluation of brake and tire wear contributions to PM, and ethylene oxide (EtO) measurement and risk analysis. As shown in the accompanying figure, a preliminary assessment indicates an EtO cancer risk in the South Coast to be higher than the total MATES V risk, which did not include EtO.

MATES provides a comprehensive view of air toxics and their health risk in Southern California and shows that the risk has declined over time. Results from this program are useful to evaluate air toxic control programs, prioritize policy making decisions, help interpret data from monitoring studies and community monitoring programs and address public inquiries on air toxics.

Session 3 – Non-Road: Marine

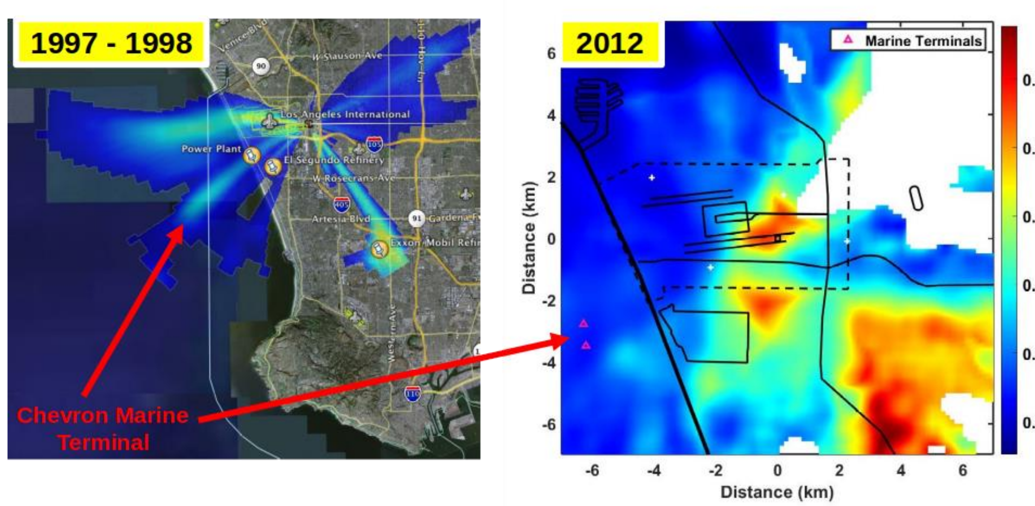
Chairperson: Wayne Miller (UCR)

Experiences at the Crossroads of Science, Policy and Community Health: Efforts to Measure and Reduce Non-Road Air Pollution in the South Coast Air Basin, Joe Lyou, Coalition of Clean Air

Joe Lyou shared his experiences on the interplay between science, policy and community health via a series of examples related to non-road pollution issues that have arisen in the South Coast Air Basin. Through these, he strove to convey the lessons: that admitting a lack of knowledge is essential to learning, that seeking new things is required to discover something new and that changing the way one looks at things is key to bringing about change.

The first example was from a 2013 LAX air quality source apportionment study. SO_2 measurements conducted in 1997 and 1998, shown below, revealed several plumes consistently stretching from the ocean towards the airport, one of which coincided with the location of a marine fuel terminal. Following CARB regulations on fuel sulfur and other operational requirements for ocean-going vessels in 2008, this plume disappeared in subsequent 2012 SO_2 measurements. This demonstrates the success that regulations can have in mitigating pollution, which in turn benefits the surrounding communities.

Comparison of SO_2 Measurements in LAX Area, 1997-98 vs. 2012



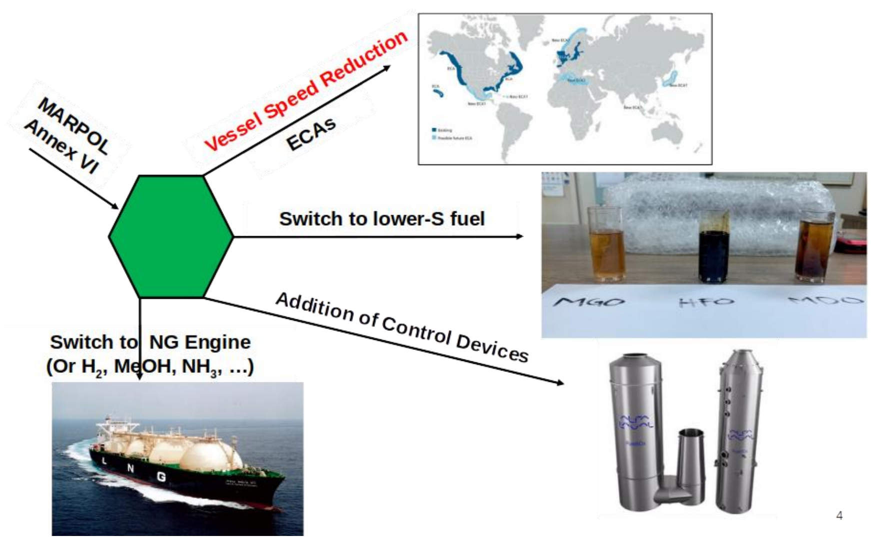
The second example was the South Coast AQMD's MATES studies, which began measuring select air toxics in 1987. One finding from MATES II was elevated styrene concentrations in Anaheim. These were traced to three local facilities close to the monitoring site and provided early evidence of the existence of "hot spots". Similarly MATES III identified elevated levels of Cr(VI) in Rubidoux. After addressing these and other such emissions, MATES IV and V showed decreases in other air toxics, for example vanadium.

The final example concerned costal odor complaints in the Huntington Beach, Seal Beach, Long Beach area. Nearly 1400 complaints were logged since January 2016 regarding a petroleum / sulfur type odor. These were investigated using a toxic vapor analyzer and optical gas imaging camera, which revealed elevated methane and ethane levels downwind of an oil tanker. Thus, requiring ships to remain farther from shore can alleviate exposure from their emissions.

These examples help illustrate how air quality monitoring can inform policy and regulatory effectiveness. Since the focus of the Clean Air Act is on criteria pollutants, regulators need information from other sources to address air toxics emissions; thus, a more effective approach to these emissions is overdue.

The Impact of Control Measure Advances and Implementation on the Emissions of Hazardous Air Pollutants from Ocean-Going Vessels, Ryan Drover, UCR

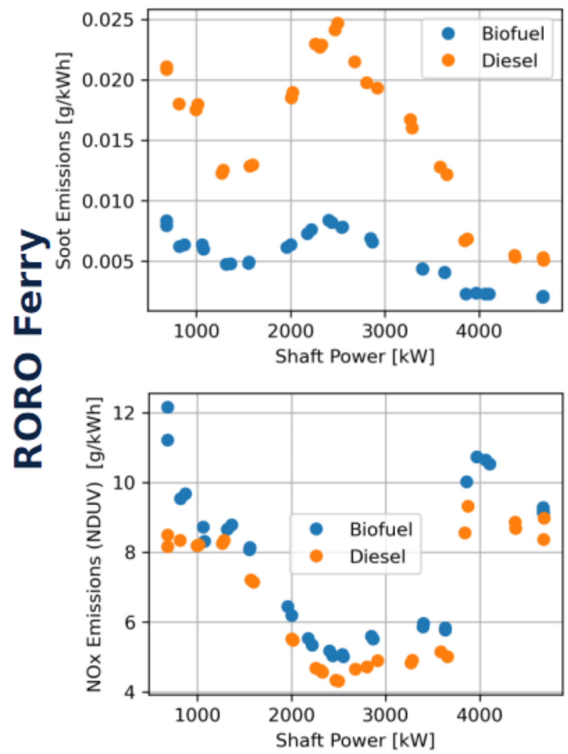
Ryan Drover discussed advances in addressing emissions of hazardous air pollutants from ocean-going vessels. Ships account for 80 – 90% of the global trade volume. However, they also emit large amounts of NOx, SOx, and PM. About 70% of these emissions occur within 400 km of land. Various control strategies exist to reduce ship emissions. One is to reduce speed when operating near land. Another is to switch to low sulfur fuel. Control devices can be added to the engine exhaust stack. And ships can switch to natural gas fuel, or other clean fuel, when operating near ports.



Ryan described some detailed ship emissions measurements. The main engine produces about an order of magnitude more PM than the auxiliary engine ~2 g/kwhr as compared to 0.15 g/kwhr. The main engine's PM is dominated by hydrated sulfate, whereas the largest component of auxiliary engine PM is organic carbon. Reducing the fuel sulfur content leads to a roughly proportional decrease in total PM emissions; however, the total carbon fraction remains approximately constant. Aldehyde and ketone emissions are dominated by formaldehyde, up to 40 mg/kwhr at light load from the main engine but decreasing steeply with increased load. The main engine emits roughly four times the amount of these compounds as the auxiliary engine. PAH emissions from the main engine are relatively flat with load and include a wide range of PAHs similar to heavy duty trucks burning conventional diesel fuel.

While detailed maritime emissions measurements remain limited, this work identifies ship emissions as a major risk area with respect the air toxics. Emissions reductions efforts, such as low sulfur fuel and the use of natural gas, have been shown to be effective. But "real world" operation needs more attention; for example, some pollutants, such as formaldehyde and acetaldehyde increase at low load operation.

PM and NOx Emissions from Marine and Freight Vehicles using Bio and Renewable Diesel, Patrick Kirchen, UBC



Patrick Kirchen reported on the impacts of bio versus renewable diesel fuel on PM and NOx emissions from two marine vessels and a locomotive. The first two were relatively modern, a 2020 roll-on roll-off (RORO) ferry and 2015 harbor tug with 4-stroke engines and Tier III/II and Tier II certifications, respectively. The locomotive dated from 1957 with a 2-stroke diesel engine and pre-tier 0 certification. The ferry and locomotive were tested with 100% soybean methyl ester fuel, whereas the harbor tug was tested with 100% hydrogenation-derived renewable diesel fuel. Compared to a conventional diesel heating value of 45.4 Mj/kg, the soy methyl ester fuel and renewable diesel had values of 38.9 and 46.9 Mj/kg, respectively. No modifications to engine or vessel were made when operated using the renewable fuels.

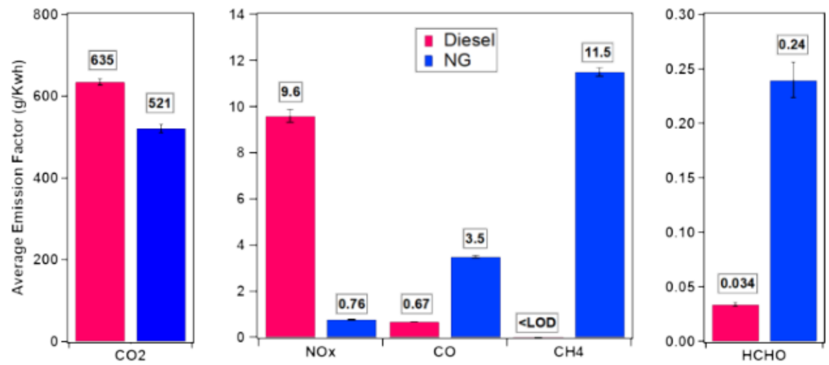
Emissions were sampled from the exhaust stacks and measured via a suite of on-vehicle instruments including Fourier transform infrared (FTIR) analysis of CO_2, NOx, and CO; AVL Microsoot sensor, Dustrak, and gravimetric filter for PM; and scanning mobility particle sizer (SMPS) and electrical low pressure impactor (ELPI+) for particle number and size. Operation of the RORO ferry with soy methyl ester resulted in significant PM emissions reductions as well as slight decreases in NOx, as illustrated in the figure above. Similar significant PM and slight NOx reductions were observed when the locomotive was operated on soy fuel. In contrast, operation of the harbor tugboat on hydrogenation derived renewable diesel fuel resulted in no PM reductions but did lower NOx emissions somewhat at low – medium engine speed.

These results demonstrate that the use of biofuel in marine vessels can lower both fossil carbon and PM emissions. In contrast PM emissions using hydrogenation-derived renewable diesel are comparable to conventional diesel, whereas there may be a small NOx benefit. More detailed analyses are underway to better characterize the emissions and other fuels are contemplated for future studies.

Air Toxics and Health Risk Impacts of Switching a Marine Vessel from Diesel Fuel to Natural Gas, Ryan Drover, UCR

Ryan Drover's talk continued the theme of fuel impacts on marine vessel pollutant emissions. Marine vessels are potent emissions sources, which can significantly impact communities near ports. One means for emissions control is to switch to cleaner fuel, at least for operation near land if not the entire voyage. Switching from diesel fuel to natural gas is one such option.

Ryan and collaborators compared air toxic, criteria and greenhouse gas emissions from ultra-low sulfur diesel versus natural gas (>92% CH_4) for a dual fuel commercial ferry in Vancouver, Canada. As the figure illustrates, they observed substantial reductions in CO2 (20%), NOx (92%), PM2.5 (93%), and black carbon (97%) emissions when using natural gas as opposed to diesel fuel. Interestingly, the PM was dominated by organic carbon in either case. In contrast, CO emissions increased by a factor of 4, formaldehyde by a factor of 6 and methane by 11.5 g/kWh when the ferry operated on natural gas. Emissions factors were generally highest under idle operation and decreased with increasing engine load. Cancer and chronic health risks were reduced for the natural gas fuel largely due to its lower PM emissions. However, short term health risks rose due to the higher formaldehyde emissions.

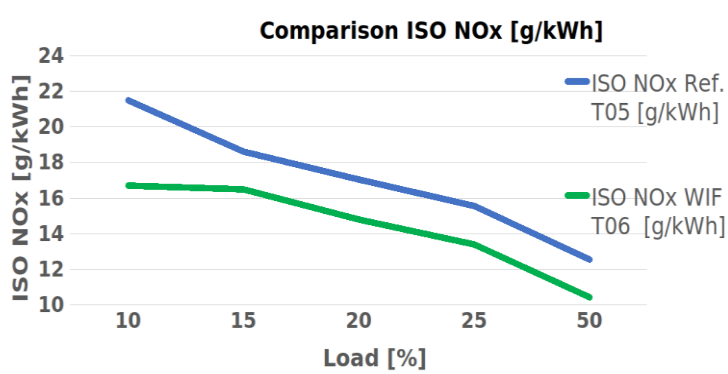


Aside from fuel choice, other mitigation strategies can benefit health and climate impacts from marine vessels. Plugging in to shore power can offset the need to run engines while in port. Cylinder deactivation can reduce CO, CH_4 and HCHO emissions (by 60% with 3 cylinders off). And oxidation catalysts can be applied to reduce HCHO by 95%. The potential secondary pollutant impacts from marine vessels require further study.

NOx and PM Emissions from an Ocean-Going Vessel with Water-in-Fuel Retrofit, Mei Wang, SCAQMD

To conclude the Non- Road: Marine session, Mei Wang presented results from a study of NOx and PM emissions reductions provided from a water-in-fuel retrofit of an ocean-going vessel. The work was motivated by the need for ~70% NOx reductions to achieve the ozone standard in the South Coast Air Basin. A large fraction of the emissions originates from ocean-going vessels. Since upgrading these vessels is costly, mitigation measures via retrofit technologies offer a good opportunity to help achieve South Coast NOx goals.

Possible retrofit technologies include: selective catalytic reduction (SCR), exhaust gas recirculation (EGR), water-in-fuel, alternative fuels, and battery and fuel cell. This project investigated the water-in-fuel option on a 9,000 TEU container vessel with a 2-stroke 47,430 kW main engine and four auxiliary engines built in 2015. The tests compared a base marine diesel oil with 0.1% sulfur to the base fuel mixed with water and emulsifier. They included three sea trials conducted: London – Hamburg, Antwerp – London and Antwerp – Sines.



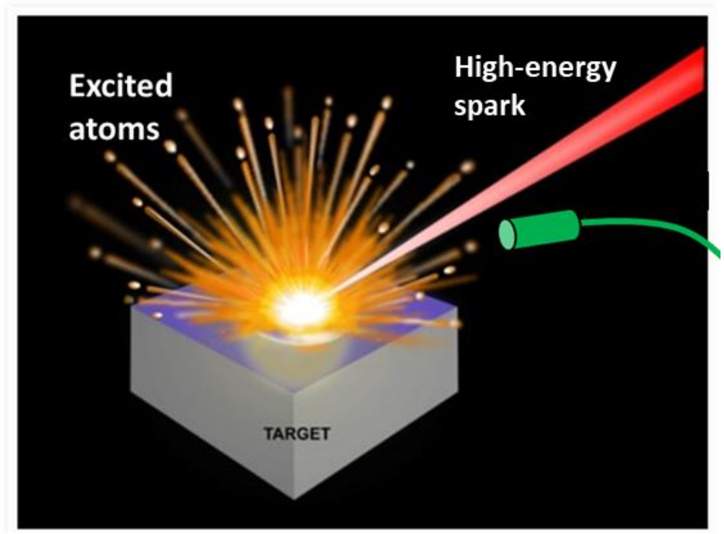
The water-in-fuel (WIF) retrofit led to roughly 12% NOx emissions reductions from 15 – 50% load and ~20% reduction at 10% load as seen from the figure above. CO_2 emissions increased slightly under most loads but decreased at 10% load. PM emissions increased by ~10%. The study concluded that the water-in-fuel retrofit can save significant NOx emissions, 1543 lb/port call and that commercialization of this technology can benefit the South Coast Air Basin.

Session 4 – Air Quality Exposure Measurements & Modeling of MSATs

Chairpersons: Richard Baldauf (US EPA) and Abhilash Vijayan (Sonoma Technology)

Measurement of Traffic-Related Particulate Metals using TARTA, Hanyang Li, San Diego SU

Hanyang Li led off the exposure and modeling session with a talk on traffic related metal particles. These particles include iron, copper and chromium from engine wear; zinc, lead, nickel, and cadmium from fuel and lube additives; chromium, nickel, and copper from brake wear; zinc, lead, and cadmium from tire wear; and potassium, iron, and aluminum from road dust. Two traditional methods for metals analysis are X-ray fluorescence and inductively coupled plasma mass spectrometry, both of which are large, expensive, laboratory-based instruments.



Hanyang and coworkers developed a compact, inexpensive, instrument using spark induced breakdown spectroscopy (illustrated above), the Toxic-metal Aerosol Real Time Analyzer (TARTA). This instrument can detect and quantify multiple metals (Cr, Cu, Mn, Ni, Fe, Zn, Co, Al, K, Be, Hg, Cd, Pb, V, Mg, Na, and Ca) with detection limits as low as 17 ng/m^3, depending on sampling conditions. The instrument is inexpensive (~$3000) to build, consumes less than 30 W, and is capable of unattended operation via remote control, but does require roughly monthly electrode replacement. The operating principle is based on the formation of excited metal atoms and ions by a high energy electrical spark. Light emitted by these excited species is collected and spectrally analyzed to identify and quantify individual metal species.

Measurements in downtown Sacramento and Pico Rivera demonstrate good correlation between aerosol metals recorded by TARTA (for example Fe, Cu, Zn, Mn, and Cr) and PM 2.5 concentrations, indicating that these metals are relatively well mixed. A comparison of simultaneous TARTA and Xact (based on X-ray fluorescence) measurements reveals a correlation in Fe detection with $R^2 = 0.37$. The low correlation may be due to differences in the particle standards used for calibration, differences in the sizes of particles detected, and possibly other reasons. TARTA has been employed in traffic monitoring at the Caldecott tunnel (2021) and in mobile monitoring in North Sacramento and Imperial Valley (2023). The tunnel results reveal strong correlations among heavy metals, whereas rural measurements show correlations among crustal elements. The instrument's time resolution of 30 – 60 seconds is sufficient to examine trends in metals emissions as traffic volumes change, for example, but not fast enough to follow an individual vehicle's emissions over time.

Community-Scale Air Toxics Monitoring in Sacramento, CA using an integrated mobile platform, Aurelie Marcotte, Entanglement Technologies, Inc.

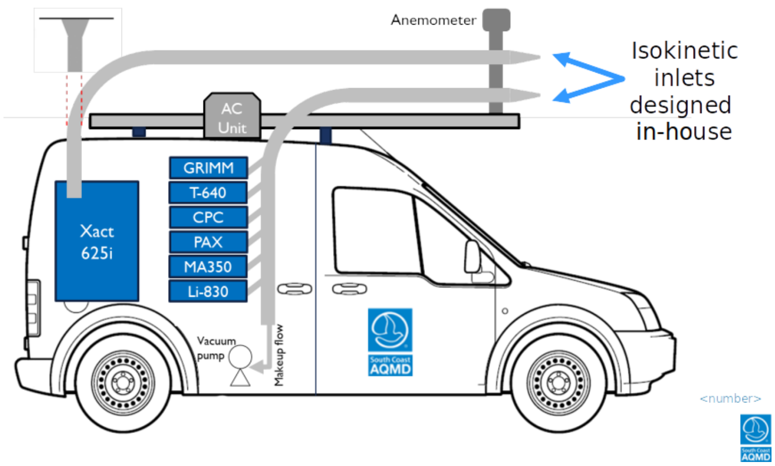
Aurelie Marcotte gave an overview of detailed mobile monitoring of criteria pollutants, climate forcing compounds and air toxics in the Sacramento area. The study's objectives were to assess spatial and temporal patterns in air pollutant concentrations, identify local hot spots, evaluate pollution levels in disadvantaged communities and provide air quality data needed for informed policy decisions. Measurements were conducted in conjunction with the District's AB 617 efforts and with community collaboration. Sampling near arterial and local roads, as well as schools was prioritized. Two sets of communities were examined: one in North and the other in South Sacramento, with EJ indexes ranging from below 50 to above 95. Measurement timing was chosen to minimize day-to-day variability and time of day effects, and to maximize the ability to make inter-community comparisons.

The measurements were made with a mobile laboratory that contains a suite of instruments to measure a wide range of greenhouse gases and gaseous and particulate air pollutants, including a cavity ring-down analyzer to record speciated air toxics. The measurement campaign logged over 100 hours across 193 miles of roadway and 94 hours of stationary measurements at 10 community sites. Data analysis included calculations to determine the extents of local pollutant enhancement over backgrounds. These data were then binned to 30, 60, or 90 meter grid cells, which were statistically analyzed to identify hot spots, or pollution focus zones (PFZ).

Arterial roads tended to have the highest impact across multiple pollutants in communities. Black carbon was enhanced by 1.5 – 3 μg/m^3. NO_2 concentrations increased during morning and afternoon rush hours along with some VOCs, such as aromatics and alkanes. There were small differences between communities in both the pollutant mean levels and their variability over time. There are a number of takeaways from this study. Mobile monitoring can provide an effective means to determine locally elevated pollution levels. Spatial analysis of such data can help identify potential pollution sources and their community impact.

Hyperlocal Mobile Monitoring of Particle-Bound Metals in Two Environmental Justice (EJ) Communities in the South Coast Air Basin, Julia Montoya-Aguilera, SCAQMD

Julia Montoya-Aguilera presented a mobile monitoring study of particle-bound metals in East and Southeast Los Angeles environmental justice (EJ) communities that are part of the AB 617 program. South Coast AQMD and community representatives worked together to identify potential high emissions sources from the > 150 metal processing facilities in these communities and to determine if any follow-up actions were needed. The study combined fixed-site and mobile monitoring to identify spatial and temporal patterns of metals emissions and identify sources with elevated community impact. The fixed sites consisted of the Huntington Park and Resurrection Church air monitoring stations. Mobile measurements were conducted with the multi-metal mobile platform, which is equipped with a suite of aerosol instruments as well as an Xact 625i x-ray fluorescence-based metals monitor.

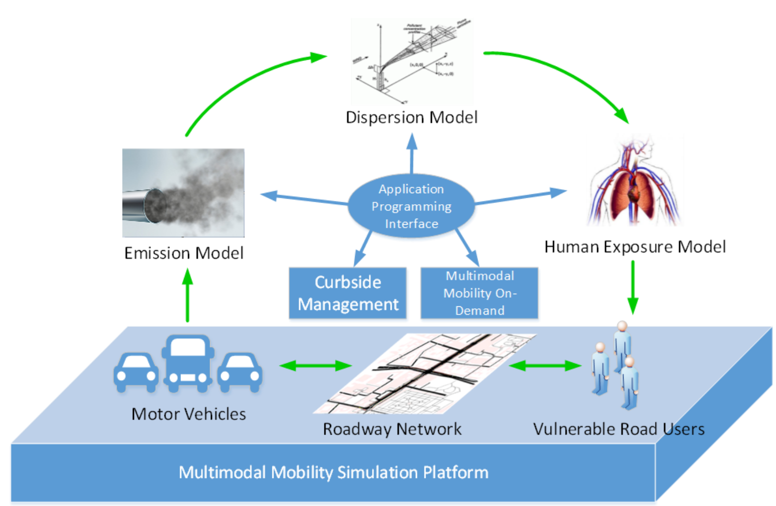


The monitoring study was performed over 52 days from June 2022 through September 2023, with ~300 hours of measurements within the communities. The various measured species (e.g., K, Si, Ca, Ti, Mn, Fe, Cr, Ni, Cu, V, and many others) were attributed to various sources: industry, traffic and soil dust. Various facilities were then prioritized for follow-up detailed source characterization based on concentrations of at least two metals lying above the 80th percentile.

Preliminary analysis identified three main metal source factors: metal processing facilities, traffic and soil dust. These data are being used to inform compliance efforts and better prioritize facility inspections. The next steps in this program are to perform follow-up measurements in areas with elevated metal levels, conduct needed compliance and enforcement actions, ascertain the effectiveness in emissions reduction activities and perform a comprehensive source apportionment study.

Integrated Simulation Platform for Quantifying the Traffic-Induced Environmental and Health Impacts, Guoyuan Wu, UCR

Guoyuan Wu described an integrated platform to model traffic impacts on health and the environment. The idea is to couple existing traffic models with emissions, dispersion and exposure models. A microscopic traffic simulator tracks traffic demand, captures the relevant roadway network and includes a traffic control interface to support route selection for on-demand mobility providers, pedestrians and background traffic. Emissions of CO, HCs, NOx, PM2.5, PM10 and CO_2 as well as energy



use are modeled by MOVES based on vehicle type, speed and road grade. A grid-based dispersion model is used to calculate pollutant concentrations based on wind speed and direction. Field experiments were used to calibrate the model. A human exposure model took the concentration and pedestrian data to determine long-term cancer risk.

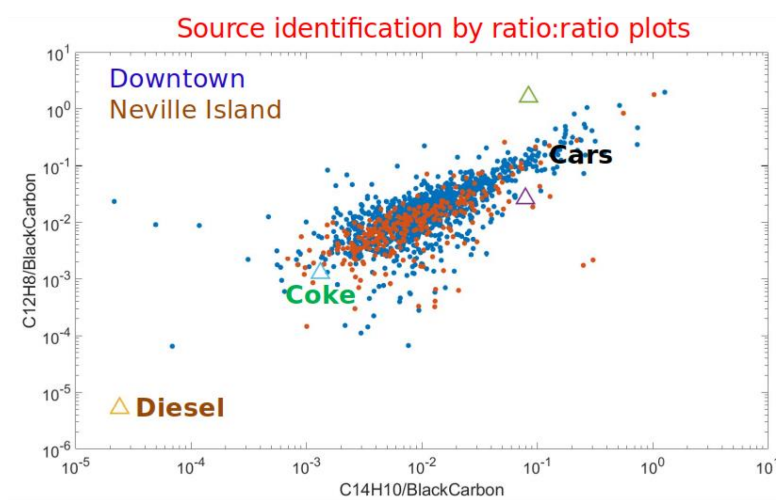
A preliminary application of this integrated platform was to compare centralized versus decentralized on-demand pickup service within a community. The modeling used a 353x185 grid array of 5x5 m cells. It included 120 on-demand mobility providers, 240 pedestrians and a background traffic of 2280 vehicles. The modeling revealed 6.3% higher velocity and 4.9% higher emissions by the on-demand mobility vehicles in the distributed pickup scenario. NOx concentrations modeled at the centralized bus station were comparable for the two scenarios, but PM2.5 levels were significantly lower for the distributed pick-up case, which translated to a predicted 33% decrease in cancer risk.

This work suggests that modeling of emissions exposure and health effects may usefully be added mobility and safety when designing and managing transportation systems. Future work will look at improving model accuracy by calibration against field experiments and investigate health impacts of various roadway designs.

Detection, Spatial Analysis, and Source Apportionment of PAHs using Mobile Sampling, Albert Presto, Carnegie Mellon University

Albert Presto spoke on the source apportionment of polycyclic aromatic hydrocarbons (PAHs) in Pittsburgh using mobile aerosol mass spectrometry. Mobile sampling was used to investigate city and neighborhood scale spatial concentration PAH profiles and record plumes from individual sources. The aerosol mass spectrometer (AMS) readily distinguishes sulfate, nitrate, ammonia and organic aerosol constituents. The spectra of organic species are typically very complex owing to fragmentation during the ionization process. However, PAHs are resistant to fragmentation and, thus, can be distinguished from other organics, matched to reference spectra and quantified.

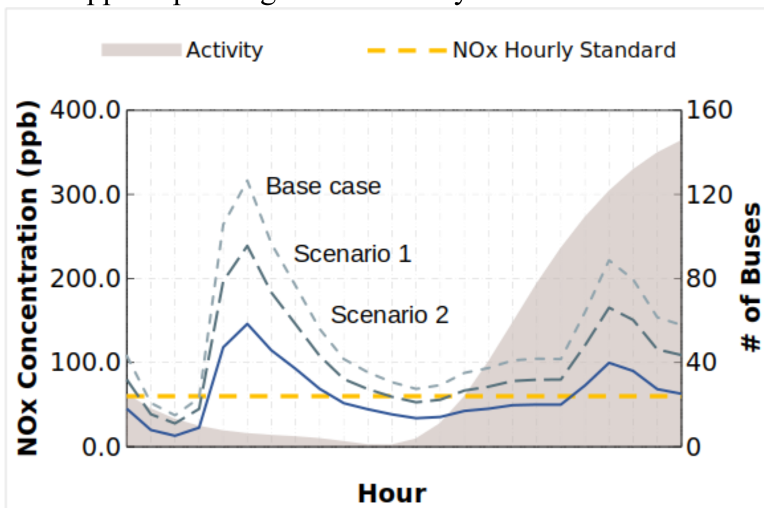
Mobile AMS sampling was used to investigate PAHs in the Shadyside, Oakland and downtown neighborhoods in Pittsburgh, as well as at Neville Island. PAH concentrations were mapped along various routes in these neighborhoods and the road to Neville Island. Shadyside and Oakland are primarily residential, whereas Neville Island is industrial. PAH levels were somewhat higher there and downtown as compared to the residential neighborhoods, whereas black carbon levels were more comparable across the four locations.



Emissions sources were identified by comparison of their $C_{12}H_8$/BC and $C_{14}H_{10}$/BC ratios, which distinguishes diesel versus car versus coke emissions, as illustrated in the figure to the right. Plotting the mobile sampling data on this graph reveals that the PAHs in downtown and Neville Island originate from a combination of coke (industrial) and light duty vehicle traffic, with little contribution from diesel sources. The PAHs also show moderate correlation with other AMS traffic markers; thus, traffic appears to be an important PAH contributor in the Pittsburgh area.

Analyzing the Impact of Decarbonization Plans on NOx Emissions and Air Quality of a Bus Station in BC, Canada, Maha Shehadeh, Simon Fraser University

Maha Shehadeh presented results from a study aimed at ascertaining how decarbonization of public transportation would impact air quality at a bus station in Surrey, British Columbia. Surrey saw a large increase in bus ridership, 50% between 2015 and 2019, while the population grew by 7%. The central district includes multiple university buildings, a large shopping mall, a major public transit hub and multiple high-rise residential buildings. Background NOx levels are about 10 ppb or below, whereas near-road concentrations vary between 10 and 75 ppb depending on time of day.



A base case and two bus decarbonization scenarios were investigated. In both scenarios, 35% of the fleet is replaced by EVs, but in the "age scenario" the oldest vehicles are replaced, whereas in the "fuel scenario" diesel buses are replaced, and not the CNG buses. Emissions for these three cases were determined using MOVES4. Bus activity data was collected and separated according to entry, idling and exit operation. The results showed roughly 20% lower NOx emissions in the "age" scenario and 50% lower for the "fuel" scenario. PM2.5 emissions declined about 15% and 30%, respectively. The AERMOD dispersion modeling package was used to predict hourly and average NOx and PM concentrations in the bus station vicinity. Time series plots, such as displayed in the figure above, show NOx decreases in both decarbonization scenarios relative to the base case, with a larger decrease of about 50% in the "fuel" scenario that replaced diesel buses with EVs.

The results of this work raise the concern that promoting public transportation without reducing bus emissions may elevate exposure risks to NOx and PM. If electrification occurs slowly over time, then prioritizing the replacement of diesel buses can more effectively reduce pollutant exposures at bus stations than replacing the oldest buses first.

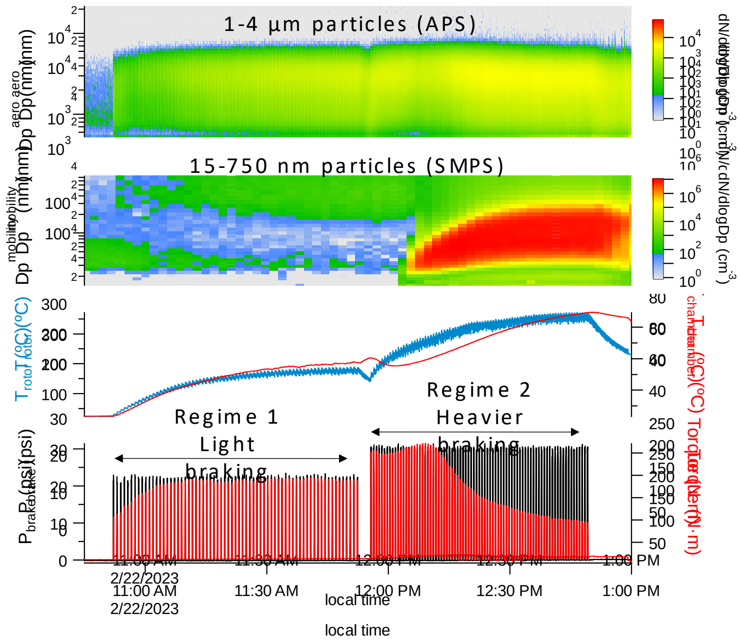
Session 5 – Measurements and Modeling of Vehicle Emissions MSATs

Chairpersons: Kent Johnson (UCR) and Chris Rabideau (Chevron)

Measurements of Size and Composition of Brake Wear Particles using a Custom Dynamometer, Lisa Wingen, UC Irvine

Lisa Wingen's talk compared brake wear PM emissions from ceramic versus semi-metallic brake pads. Emissions were measured under two regimes, light and heavier braking, using a custom brake dynamometer. The brake rotor spun at 173 rpm, corresponding to ~20 mph. The light braking regime was defined by applying brakes with a pressure of 20 psi for 8 s at 53 s intervals, whereas the high regime had brakes applied at 30 psi for 10 s at 40 s intervals. Owing to the higher brake pressure and shorter time interval, brake temperature rose to ~350 C in the heavy regime as opposed to ~200 C under the light regime.

The airborne wear debris was analyzed both for size and chemical composition. Under light braking the semi-metallic pad wear debris metal content was primarily Fe (~80%), whereas for the ceramic pads it was about half Fe and half other metals. Particle size ranged from 15 nm to > 4 µm. The larger size mode showed a similar size distribution over both braking modes; however, the lower mode revealed a sudden nucleation of sub-micron particles about 10 minutes into the series of heavy braking events, as the rotor temperature rose above ~200 C (as seen in the figure). Semi-metallic pads generally had higher brake temperatures than the ceramic pads, but the latter generated higher mass emissions.

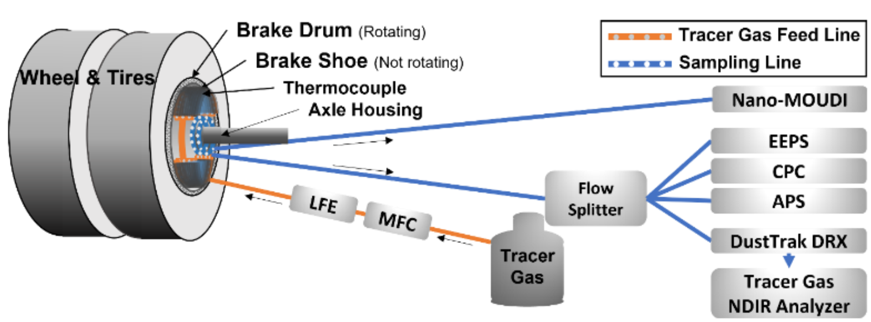


Aerosol mass spectrometry revealed a wide range of O:C ratio in the organic PM content from both pad types indicating a high degree of oxidation. Ultrafine particles that nucleate under the heavier braking regime tended to be somewhat less oxidized. Passing the brake wear particles through an electrostatic precipitator prior to counting them revealed a large fraction to be electrically charged. From tandem differential mobility analysis, the average particle had 20 – 30 charges, with particles from ceramic pads exhibiting higher charges.

Brake Wear Particle Emissions from Heavy-Duty Vehicles, Eon Lee, CARB

Eon Lee spoke on a less investigated source of brake wear debris, namely from drum brakes, which are often used on heavy duty vehicles. These brakes typically employ low metallic rather than non-asbestos organic friction materials owing to their higher friction coefficient, but the resulting PM mass emissions can be 3 – 4 times higher.

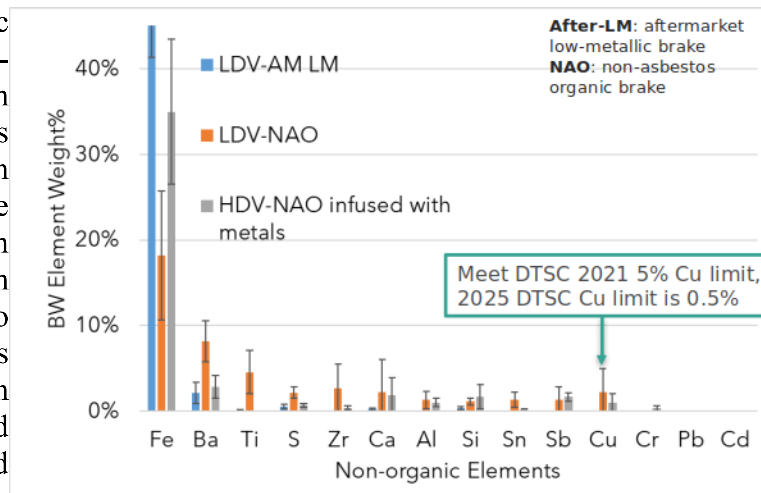
Brake wear emissions for three class 6 and one class 8 truck were measured on a brake dynamometer. Wear debris was sampled into a suite of particle instruments and quantified based on a tracer gas that was flowed through the brake housing. The PM2.5 mass emissions ranged from 0.7 – 1.5 mg/km/brake for the class 6 trucks and about 5 mg/km/brake for the class 8 truck when tested over a parcel delivery test cycle. The emissions rates increased with deceleration but were also present during acceleration due to resuspension from brake surfaces, which accounted for 8 – 31% of the total PM2.5. Mass weighted particle size distributions peaked at about 2 µm and appeared the same for particles recorded under deceleration and acceleration.



Particle number emissions were observed at about 10 nm and also from 30 – 80 nm. These emissions were attributed to thermal decomposition of brake binder materials and nucleation. As in other studies, these emissions were highly sensitive to brake temperature. Sharp increases in particle number emissions were observed beginning at a brake temperature of ~130 C for 11 nm and 52 nm particles. In contrast, emissions at 294 nm were relatively insensitive to temperature. Follow-up work to this pilot study is in progress.

Brake-Wear PM Composition Profiles: A Comparison Between Heavy-Duty Vehicles and Light-Duty Vehicles, Qi Yao, CARB

Qi Yao examined the non-organic composition of brake wear from representative light versus heavy-duty vehicles in California to learn how various factors, such as brake pad material and supplier, affect composition profiles. Brake wear debris was collected from 24 conventional passenger cars, 10 light duty trucks, 6 EVs, 13 T7-Class 8 trucks, 8 T6 trucks and 2 urban buses. These vehicles were run over various vocational cycles: the California Brake Dynamometer cycle for the LDVs and Cement, Drayage, local moving, and urban bus cycles for the HDVs. Brake wear composition was measured by X-ray fluorescence.

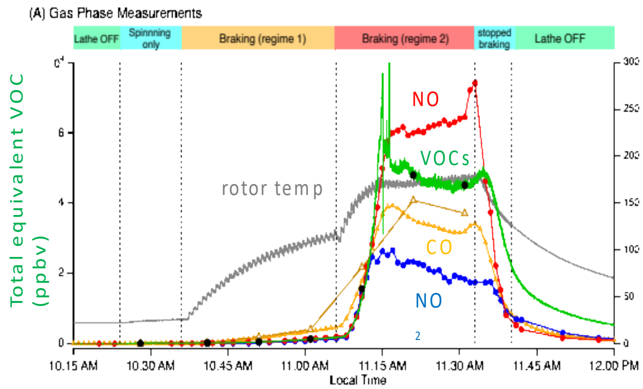


LDV brake wear from non-asbestos organic (NAO) pads was approximately 40% non-organic, with ~18% Fe as the main contributor followed by ~8% Ba. This composition profile varied little between vehicle make or pad supplier. The composition does change, however, with pad type. Low metallic pads have a much higher Fe content, ~45%, as compared to NAO and lower Ba, ~2%. Measurements from HDVs show that the composition profile is the same for both PM10 and PM2.5 size classes and for the T6, T7, and urban bus vehicle classes. However, the composition does shift from disc to drum brakes; for example, Fe content decreases from 48% to ~30%. As with LDVs, composition profile does not vary with brake supplier. The amount of brake debris generated may vary with vocational test cycle, but the composition does not.

Measurements of Volatile (Organic) Compounds from Brakes Using a Custom Dynamometer, Veronique Perraud, UC Irvine

In a complement to the first talk of this session, Veronique Perraud addressed the organic component of brake wear emissions. As in the first talk, she compared emissions under two braking regimes: Regime 1 with about 20 psi of brake pressure and 86 – 177 C rotor temperature and regime 2 with ~31 psi pressure and 164 – 358 temperature range. Measurements were made using both off-line and on-line methods. The former included sampling into canisters and SVOC collection into sorbent tubes. On-line instruments included proton transfer time of flight mass spectrometry and chemi-ionization mass spectrometry for NO_3.

As illustrated by the accompanying figure, there was a steep increase in gaseous emissions when the brake temperature reached above ~150 C. This temperature profile coincides with the nucleation of ultrafine particles, whereas coarse mode particle levels remain relatively constant with brake temperature. Both CO and CO_2 concentrations increased, but CO predominates. The primary VOC constituents were alkanes, alkenes, and aromatics (including BTEX), with alkanes predominating for semi-metallic pads and aromatics for ceramic pads.

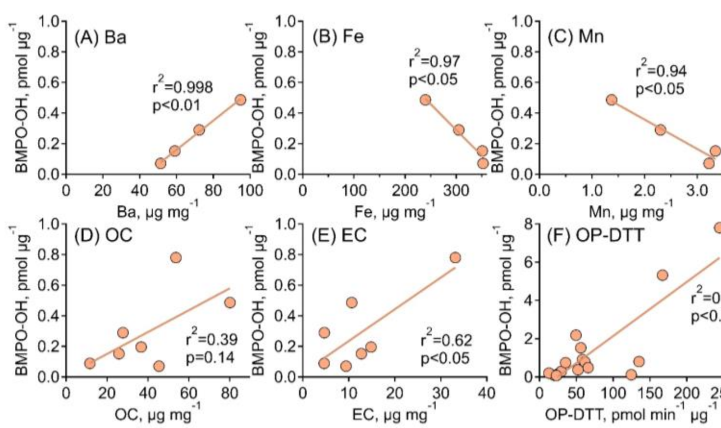


Overall, the emitted VOCs show high OC reactivity, suggesting they will contribute to secondary organic aerosol formation. The BTEX profile differs from tailpipe exhaust suggesting that it may serve as a tracer. Semi-volatile VOCs were dominated by oxygenated compounds, 52% for ceramic and 31% for semi-metallic pads. Oxygenated organics were similarly the major fraction of ultrafine brake wear particles, but in this case the composition profiles showed little difference between semi-metallic and ceramic pads. Mass spectrometric analysis also revealed significant emissions of phenolic and nitrogen containing organics. These originate from the binders employed in brake pads and the compounds used in their synthesis. The presence of these emissions and the correlation of VOC emissions with higher brake temperatures implicates binder pyrolysis as a likely source of the emissions.

Aqueous Production of Reactive Oxygen Species by Brake Wear Particles, Manabu Shiraiwa, UC Irvine

Manabu Shiraiwa addressed the biological implications of brake wear particles by examining the reactive oxygen species they help create in aqueous conditions. This work examined brake wear from semi-metallic and ceramic brake pads using the UC Irvine disc brake system and Regime 1 gentle braking and Regime 2 harsh braking described in the first talk of Session 5. Environmentally persistent free radicals (EPFR) and reactive oxygen species (ROS) produced from brake wear were detected by electron paramagnetic resonance, and the oxidative potential was measured using dithiothreitol (DTT) assay.

The brake wear was found to exclusively generate OH radicals. The yield increased from gentle to harsh braking. In the figure to the right, the observed OH production correlates positively with brake wear organic and elemental carbon contents. It also correlates positively with Ba concentration, but barium salts do not generate OH. The correlations with Fe and Mn are negative, suggesting that Fenton-like reactions are unlikely the OH source. Harsh braking led to ultrafine particle nucleation. These particles include phenolic resins from the pad binders, which degrade to organic hydroperoxides and, thus, provide a source of OH.

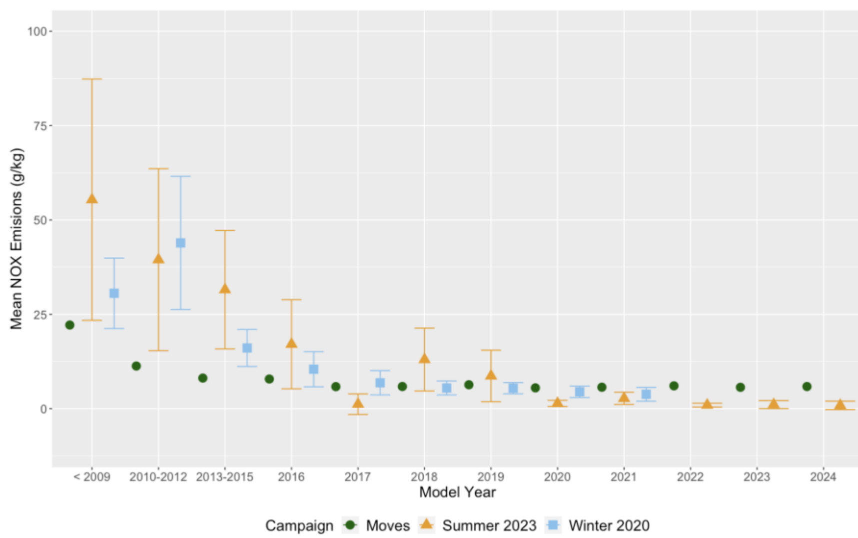


Manabu also presented results from ambient samples collected from urban, highway, and wildfire sites for comparison. Oxidative potential via DTT assay of highway and urban PM correlates with ROS, but not for wildfire PM. Wildfire PM generates various radicals, such as OH, O_2^- and organic, whereas highway and urban PM generates primarily OH, likely from brake wear particles. Tailpipe and wood burning in Fairbanks, Alaska, lead to the formation of EPFRs, which can be stabilized by complexing with Fe, and are known to be redox active to generate ROS.

Real-World Heavy Duty Diesel Vehicle Emissions in Utah During the Summer, Amber Allen, Brigham Young University

Amber Allen presented roadside measurements of heavy duty (HD) vehicle NOx emissions made in Utah during Summer 2023. The study objectives were to compare these to earlier Winter 2020 data recorded by Bishop et al. (2021) and to summertime emissions in California. She used the Fuel Efficiency Automobile Test (FEAT) methodology developed by Stedman and Bishop, which records pollutant emissions in terms of kilograms fuel used. HD trucks are configured with either high or low engine exhaust pipes. The present study recorded emissions only from trucks with the low exhaust configuration. It included 1073 valid observations.

For both the Summer 2023 and Winter 2020 campaigns, most of the trucks were less than 10 years old, 45% were less than 3 years old. The mean NOx emissions, for MY 2011 – 2024 trucks, was 5.0 g NOx per kg fuel in Summer 2023 as compared to 8.7 g NOx per kg fuel in Winter 2020. As shown at right, the emissions showed a steady decline by model year for both summer and winter. In both campaigns, real-world measurements exceeded MOVES4 model estimates for pre model year 2019 vehicles but were lower than the estimates for 2019 MY and newer vehicles.



The main conclusions were that Summer 2023 NOx emissions were significantly lower than Winter 2020 values owing both to vehicle age distribution and ambient temperature. Comparison to California data reveals that the newest trucks have similar emissions levels in both states, but that by model year, older trucks in Utah have significantly higher emissions, presumably from deterioration. The study also suggests that HD NOx emissions are affected by temperature, which is not reflected in MOVES4 estimates.

Variability in Engine-Out and Tailpipe Emissions from Production Gasoline Vehicles, Svitlana Kroll, SwRI

Svitlana Kroll examined data collected at SwRI during five non-related fuel evaluation studies conducted over a three-year period with the objective to better understand variability in light duty gasoline vehicle emissions. While these programs did not all use the same test vehicle, they did employ the same vehicle model, one 2019, three 2022, and one 2023 model year, All were new (<100 miles), with a 4-cylinder

2.5 L engine rated at 203 HP @ 6600 rpm, that underwent 4000 mi of mileage accumulation prior to testing. The fuel evaluation programs all included Tier 2 certification gasoline (no ethanol content) as a common fuel. And they all recorded both engine-out and tailpipe emissions measurements. Three days of testing were performed over the 4-phase cold-start FTP cycle for tailpipe emissions. The catalyst was then removed, and three more days of engine-out tests were performed. Measurements included criteria pollutants, speciated hydrocarbons, and aldehydes and ketones.

All criteria pollutant tailpipe emissions rates fell below their respective vehicle certification standards and ranged from 90% to 99% below engine out rates, depending on pollutant. A statistical analysis (Kruskall-Wallis test) was designed to test the hypothesis that for a specific emission, test phase, and tailpipe / engine-out configuration there is no difference in emissions rates between the five vehicles. This analysis did not find any emission that had sufficient statistical significance to demonstrate a vehicle-to-vehicle difference based on a corrected p-value of 0.05. The Tukey test was used to investigate if there were pairs of cars that had consistently different emissions rates. For both criteria emissions and select speciated emissions, one car was common to the five pairs that exhibited the largest number of emissions differences.

Test repeatability was examined via the normalized emissions range ((max - min)/avg) for each car, emissions species, test phase, and tailpipe / engine-out configuration. A one-sided t-test was used to test the hypothesis that each normalized range is within 20%. All of the gaseous criteria emissions had normalized ranges of <20%. However, this value was exceeded for PM and a number of speciated emissions such as formaldehyde and m & p-xylene, when measuring tailpipe emissions. Interestingly, car-to-car differences in some normalized ranges were noted for some criteria and speciated engine-out emissions, but not tailpipe emissions.

Tyre Emissions and Their Multiple Effects on Air Quality, Nick Molden, Emissions Analytics

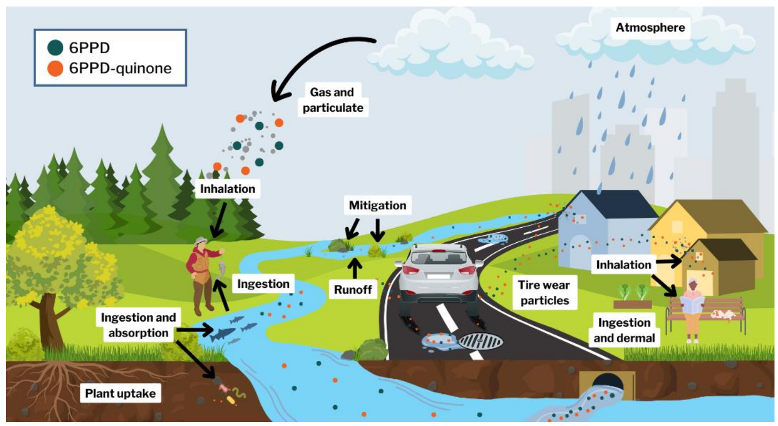
Session 5 returned to the topic of non-exhaust emissions with Nick Molden's talk on tire wear emissions. Tire wear rates depend a lot on their design and construction. Tires in the US representative of a typical midsize SUV exhibit a wear rate of up to 390 mg/km as compared to 74 mg/km in Europe. These rates are substantially higher than modern tailpipe emissions rates but include gases as well as particles ranging from sub-micron to hundreds of microns in size. Chemical fingerprinting via two-dimensional chromatographic / mass spectrometric analysis reveals a wide array of emitted chemical classes. These include alkanes, cycloalkanes, terpenes, aromatics and organo-nitrogen compounds; however, the chemical profiles vary between tires.

Tire emissions are estimated to be about 1 – 4 kg per year from a single car. Ultrafine and fine particles become airborne whereas coarse particles tend to settle onto the road and get washed into the water drainage system. A small fraction of particles falls into the PM10 range, and about 11% of these falls into PM2.5. In general, the particles are an internal mix of tire and road wear as opposed to solely tire material. Gaseous VOC emissions arise from off-gassing, as well as wear, and can contribute to ozone and secondary aerosol formation. There are perhaps ~2000 chemical compounds contained in tire wear debris. It is possible that subsets of these could yield fingerprints to serve as tracers for tire wear debris. A number of these compounds are of

human health concern, including benzene, xylenes, and related compounds. While identifying and quantifying tire emissions remains a daunting task, the wide range of chemicals emitted makes them important for future policy decisions.

Impacts of 6PPD and 6PPD-Quinone from Tire Wear, Richard Baldauf, US EPA

Rich Baldauf talked about the importance of tire and brake wear emissions to near-road exposures. In addition to potential air toxics, tire emissions include materials of emerging environmental and health concerns, such as microplastics and 6PPD / 6PPD-quinone. Tires can lose 10 – 20% of their mass from wear over their lifetime, and 10 – 15% of this is estimated to be PM10. Whereas vehicle electrification reduces tailpipe emissions, the added weight from the battery can increase tire wear debris emissions by 10 – 25%. While many of the larger tire wear particles fall to the road surface, these can be re-entrained by subsequent traffic. They can also impact water quality from surface water runoff.



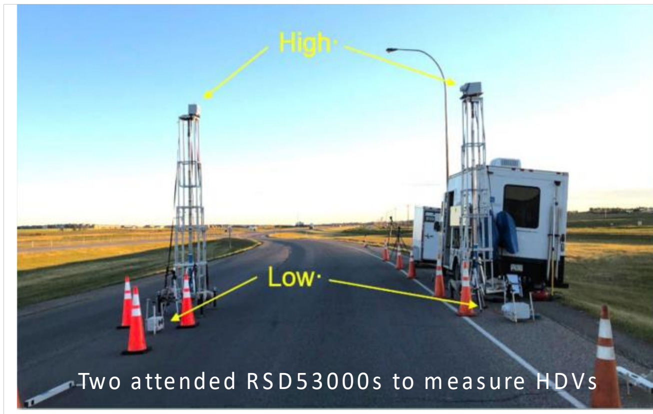
6PPD is an additive used in tires to slow rubber oxidation / degradation. Once released into the atmosphere it can react with ozone to form 6PPD quinone. In 2020 researchers linked the presence of this compound in the marine environment to premature coho salmon mass mortality events. It has subsequently been found to adversely affect other species, including Chinook salmon, white spotter char, steelhead and various trout species. The impact on fish populations has primarily been studies in the Pacific Northwest, but these fish are found in other regions of the US as well. The best-established route into the marine environment is via surface runoff, but another possible route is via atmospheric deposition. Besides motor vehicle tires, other potential sources include crumbled tires found in playscapes and sports fields, rubber added to asphalt, tire derived aggregate used in fill and leaching and burning of scrap tires.

There are a variety of mitigation strategies that can be considered. These include storm water management, green infrastructure, street level control including sweeping, on-vehicle collection and 6PPD alternatives with lower environmental impacts. Policy and research activities by the EPA and other agencies include granting a petition submitted by several Pacific Northwest tribes, releasing an analytical method for 6PPD-quinone measurement and a pooled fund project on 6PPD groundwater mitigation by six states.

An Assessment of the Impact of Exhaust Tampering on the Total Emissions of the Heavy-Duty Fleet in Edmonton, Alberta, Vahid Hosseini, Simon Fraser University

Vahid Hosseini closed out Session 5 and the Workshop with a talk on the impact of exhaust tampering on heavy duty vehicle emissions in Edmonton, Alberta. Tampering with emissions control devices can greatly increase NOx and PM burden from the HD fleet. This involves physical or software changes, such as removal of the diesel particulate filter (DPF), modifying the exhaust gas recirculation (EGR) valve, deleting the selective catalytic reduction device (SCR), not supplying urea to the SCR and re-programming the engine control unit (ECU). Remote sensing in Vancouver (2013) indicated high emitters constitute roughly 20 – 30% of the HD fleet and, thus, a potentially significant adverse impact on air quality and health.

The Roadside Optical Vehicle Emissions Reporter (ROVER) III remote sensing project was a short-term study to measure diesel truck emissions in Alberta. The measurement setup included both low and high sensing paths to account for the two common truck exhaust pipe locations. Measurement sites included Edmonton and Calgary as well as more rural sites. Vehicle speed through the measurement zone ranged from ~4 – 15 mph and acceleration mostly between +2 and -2 m/s^2. About 52% of trucks newer than 2007 exceeded 0.2 g/hp-hr NOx and ~72% exceeded 0.01 g/hp-hr PM emissions, suggesting a significant fraction of tampered or malfunctioning HD vehicles.



Vahid and coworkers used an equivalent age approach to reconcile these high emitters with the MOVES model. Thus, the ages of trucks with emissions higher than expected from model year and speed bin data were increased to match the observed emissions rates. This extended the observed 15-year age distribution to ~30 years for both NOx and PM high emitters. The age adjustment increased MOVES NOx emissions estimates for the fleet by 35% and PM estimates by 240%. The NOx increase arises from an increase in the fleet fraction of vehicles older than 2005 from an actual value of 10% to an age adjusted 37%. In the case of PM, the actual fraction of 29% increases to an age adjusted value of 73%. Thus, tampering or malfunction makes the Edmonton HD fleet look significantly older emissions wise than it actually is.