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35th CRC Real World Emissions Workshop Conference Summary

Executive Summary

The *Coordinating Research Council* held its *35th Real World Emissions Workshop* in Long Beach, CA, on April 13-16, 2025. This 35th annual vehicle emissions workshop convened a diverse range of stakeholders in the field of vehicle emissions and honored decades of research that has improved emissions and air quality. The Workshop established new understanding of the engineering, technology, chemistry, and physics of automobiles through presentations, posters, and two keynote addresses. The topics have considerably evolved in response to research, policy, and community needs, and this year included the following areas:

- Air Quality and impact of regional emissions changes on environmental justice
- Alternate fuel and zero-emissions vehicles
- Low carbon technologies
- Decarbonization: Technologies, complications, and mitigation strategies
- Electric and hybrid vehicles
- Emissions measurement methods
- Emissions control measures
- Emissions modeling and inventories
- Impacts of infrastructure development for low-emissions vehicles
- In-use exhaust emissions: On road, off road, and non-road
- Non-exhaust emissions
- Real world policy impacts

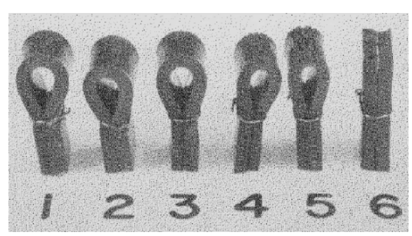
Oral presentations and keynote addresses are summarized in this document which can be found at https://crcao.org/35th-crc-real-world-emissions-workshop/.

Day 1 – Monday, April 14, 2025

Keynote Address: Kent Hoekman, Desert Research Institute

"*The Road to Clean Cars*"

The goal of this presentation is to explain the multi-decade successful effort to reduce vehicle emissions to the currently lower levels. The approach involved a literature review including journals, regulatory documents, anecdotes, and difficult-to-locate older materials. The project's planned final report has 11 chapters with each time period covered from the 1940s up to 2010's and beyond (7 decades!). The history includes solving problems, discoveries of new problems, technological improvements in vehicles, modifications to



fuels, and personal stories of some involved. The mid-1940s brought the first occurrence of unusual air pollution in LA. Motor vehicles were not suspected initially. In the 1950s the unique strong oxidizing behavior of LA smog was noted as well as its episodic nature, often daily. Total oxidant was measured initially and the "rubber cracking test" was used. Much of the oxidant was later determined to be O_3, but not all. Air pollution pioneers included Dr. Frits Went (botanist and biologist) and Dr. Arie Haagen-Smit. Dr. Went demonstrated vegetative damage from LA smog. Dr. Haagen-Smit showed that higher olefin content in gasoline led to increased smog formation. These findings were repeated on many vehicles in the 1950s. In the 1960s, the first exhaust emissions standards were enacted for HC and CO, but not NOx. One of the first emissions controls occurred for crankcase blowby gas emissions, an important non-tailpipe HC emission, that was eliminated with the introduction of PCV valves, introduced in CA in 1963 and 1968 nationwide. Fuel tank emissions from refueling and carburetor leaks were also controlled and/or modified. The 1970s were a very active time in vehicle emissions studies, during which the Clean Air Act (signed by then President Nixon) defined the NAAQS and included NOx in the federal tailpipe standards. Engine modifications were made to control air-fuel ratios. Oil spills became a growing environmental concern. The EPA was established in 1970 and forced technology to meet emissions standards. Oxidation catalysts were introduced in the 1970s to control HC, CO and NOx, and electronics were introduced to control air-fuel ratio, fuel injection, spark timing, EGR, and 3-way catalyst in order to maintain the lowest NOx, CO, and HC. The Energy Policy and Conservation Act (EPCA) of 1975 required huge improvements in fuel economy from 1974 and 1985 and established Corporate Average Fuel Economy (CAFE) standards. The 1980s transitioned from exhaust standards to evaporation standards and innovative studies began, including the idea of O_3-forming reactivity studies of emissions adopted in CA and introduction of oxygenated wintertime fuels to reduce CO. The 1987 Van Nuys Tunnel study showed that measurements exceeded expected emissions. The 1990s saw a lack of progress in O_3 reduction with the vehicle emissions reductions and led to reformulating fuels and initiation of I/M programs. The nonlinearity of O_3 formation with respect to NOx and VOCs was demonstrated using isopleths from chamber experiments and the EKMA model by EPA. The 2000s and beyond led to many low emission vehicle categories and the focus is on renewable fuel standards established to address CO_2 and other GHG concerns. GDI (gasoline direct injection) is an important new technology but increases PM emissions concerns. The article Hoekman, *SAE Int. J. Fuels Lubr.* (2020) shows additional improvements since 1970s in HC, CO, NOx. Summary – O_3 is now lower from (light duty) vehicles as a result of decades of combined efforts from industry, regulators, academia, and others. The problem of GHG emissions is very different – not to be confused with vehicle criteria pollutant emissions. More detail about the early years can be found in a review by Hoekman and Welstand in *Atmosphere* (2021).


President Nixon signing Clean Air Act in 1970

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SESSION 1: Air Quality and Regional Emissions Impacts

Stephen Reid, Bay Area Air Quality Management District
"*Addressing Diesel Pollution in Environmental Justice Communities: A West Oakland Case Study*"

The goals are to discuss Assembly Bill 617 background, efforts to reduce diesel PM, and a case study of West Oakland, CA. AB617 was signed into law in 2017 to establish the Community Air Protection Program (CAPP) to address criteria air pollutants in burdened communities and reduce emissions of toxic air contaminants. CARB adopted a new CAPP Blueprint 2.0 in 2023 for guidance on implementing AB 617. Diesel PM was a primary concern for all 15 community emissions reduction plans (CERPs), including Long Beach, due to HD trucks, ports, locomotives, and agriculture. Over 60 communities across California were consistently nominated under AB 617. With the CERP Action Types and Library, one can search each community's strategies for reducing emissions and exposures, e.g. changing truck routes. West Oakland, in Alameda County, CA, is adjacent to the Port of Oakland and encircled by freeways. It is the first community selected for CERP development. Technical analyses included AQ modeling, emissions inventory development, and a modeled exposure assessment conducted by BAAQMD. The West Oakland Community Action Plan (WOCAP) was approved in 2019 containing 80+ actions to reduce emissions and exposures. Strategies included vegetative barriers and land use changes, which involved state, regional, and local agencies. Statewide actions included Advanced Clean Trucks and I/M of off-road equipment to benefit West Oakland. The impacts of these strategies were forecasted for 2024 and 2029 and compared to real data in 2024 and 2017. DPM emissions decreased 31% with largest improvements for port-related diesel trucks and harbor craft. Anticipated growth is expected to significantly offset the improvements forecasted for 2029, but emissions are better than expected for 2024. Residential DPM exposures decreased by 56% from 2017 to 2024 even though truck emissions reductions were 31% because of the locations near the residents. Black carbon measurements showed average reductions of 38% from 2017 to 2024, adding to the data that improvements are occurring. Summary – AB 617 has allowed local actions for targeting DPM in environmental justice communities of California. West Oakland is a success story that long-sought emissions reductions are being achieved for this community. BAAQMD has funded 114 projects that are expected to reduce 1000+ tons of PM, NOx and ROG in West Oakland. More information on WOCAP is provided on the BAAQMD site.

Sahar Fazelvalipour, University of Southern California
"*Community-Level Equity Analysis of Truck Emissions Based on High-Resolution Emission Inventory*"

The focuses are truck emissions and equity. Heavy Duty trucks are a major source of NOx and PM2.5 and disadvantaged communities (DACs) are often near freight corridors with large numbers of HD trucks. There is a need to quantify the base year emissions under no ZEV regulations and the impact of zero-emission regulations that include ACT and ACF. The objectives were to build a high-resolution emission inventory with a base year of 2019 when there were no ZE regulations, and integrate the emissions with demographic data to determine disparities. Would like to evaluate the impact of future truck ZE truck regulations for scenarios of baseline (no ZEV regulations), ACT only, and both ACT+ACF regulations on these disparities. Question: What would the result of ACT and ACT+ACF have been if kept in place with predictions out to 2045? Methods involve a geospatial analysis by overlaying emissions data with demographic data as well as socioeconomic data. The emissions inventory was integrated using EMFAC for county tailpipe and non-tailpipe emissions. Telematics data was used for high-resolution vehicle activity data. Geospatial equity analysis included Senate Bill 535 (SB535) DACs and AB617 DACs within the South Coast Air Basin (SCAB) study domain. Many of the neighborhoods with higher fractions of Hispanic residents are located in DACs and VMTs are unequally distributed between white and Hispanics. When there is higher VMT and truck VMT per area, there are more Hispanic residents with a lower income. Zones with higher idling NOx emissions have more Hispanic residents. Higher NOx emissions from Class 7 and 8 exist in DACs than in non-DAC communities. Similar trend for PM2.5 per unit area, indicating DACs are facing more truck-related pollution than non-DACs. Both brake wear and tire wear PM2.5 emissions were also shown to be higher in 2019 in DACs with predominantly Hispanic residents. The analysis showed that by 2045, NOx emissions in the SCAB could decrease by 22% with ACT in place and up to 77% if both ACT and ACF were still in place (relative to base year with no ZEV regulations). These predictions suggest ACT and ACF regulations will be successful for NOx. Next steps: to extend the analysis by developing emissions inventory for the 2045 future scenario. Development of an emission inventory at a finer resolution of 1x1 km is planned, and to use these emissions as input into an air quality model for future pollutant concentration estimates. Equity assessment is planned to determine the impact of ZE truck regulations on overall emissions and disparities in DACs.

Hamid Niakani, California Air Resources Board
"*The Impact of Phase 2 GHG Regulation on California Heavy-Duty Vehicle Inventory and Emissions*"

The presentation covers an overview of the first three years of implementation of Phase 2 GHG regulation, trends in HD vehicle production volumes, and comparison of EV standard versus enhanced certification procedures, among other items. In 2016, EPA announced Phase 2 GHG emissions standards, adopted by CARB in 2018. Phase 2 regulations and optional ZEP regulations and enhanced EV procedures were introduced for model year 2021. There are 2 paths for ZEV certifications: Manufacturers can choose Path 1, the Enhanced Vehicle Executive Order (EO), in which they first certify ZEP families with CA ZEP test procedures or use an already-certified ZEP by a different manufacturer, and then certify ZEV families using enhanced certification requirements. Path 2, the Standard Vehicle EO, involves certifying vehicle families using the standard Phase 2 GHG procedure. From 2017 to 2020, the number of HD vehicles doubled, but then steeply declined in 2021, which may have been induced by supply chain issues during COVID. A strong increase was noted again in 2023. The fuel mix for HD vehicles in CA is primarily diesel (~82%), with gasoline as second (~10%) for model year 2023. Hydrogen fuel use is very low, reflecting a lack of infrastructure. Other fuel types are low. For 2017-2023 model years, all-EV HD vehicles in CA grew from ~30 to ~1600 vehicles. When looking at by percentage, the HD EV percentage increased for MY 2017 to 2019, but dropped for 2020, grew again, and dropped again for 2023, but there is a general upward trend. A comparison between enhanced EV-certified vehicle families and standard EV-certified families shows a gradual shift toward standard EV as it becomes more widely adopted. The criteria pollutant credits earned are increasing by 48% from 2022 to 2023 for NOx, 47% increase for PM, and also increasing for NMHC credits. Federal CO_2 ABT (Advanced Business Technologies) credits: light HDV (class 2b-5) are not changing, but medium HDV (class 6-7) and heavy HDV (class 8) and custom chassis are increasing, indicating manufacturers are making significant progress in increasing the number of compliant vehicles. By fuel type, diesel fuel vehicles have made a significant increase in CO_2 ABT credits; electric vehicles are also increasing significantly. This suggests good progress as well. Summary – Over 80% of model year 2023 HD vehicles sold in CA were diesel powered and sales of HD all-electric vehicles have increased from 2017-2023. About 30% of MY23 HD all-electric vehicles sold in CA were Enhanced EV certified. Seeing notable increases in total generated NOx and PM credits from 2022-2023 and significant increase in CO_2 credits were found for the diesel and EV from 2021-2022.

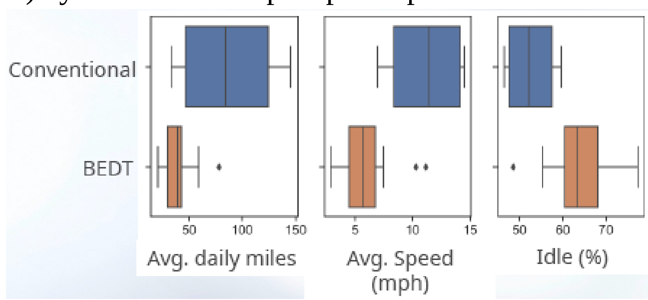
Karl Ropkins, University of Leeds
"*Attributing Source Contributions to Environmental Changes*"

The goal is to examine environmental change related to vehicle emissions. While national and local traffic-related regulations are combined to yield air quality action plans, the associated air quality benefits are difficult to quantify, but tools are presented here to routinely measure environmental changes resulting from these regulations. References are provided for software introduction and papers on applications including Ropkins and Tate (2021) and Ropkins et al. (2022). Additional impact assessment reports are contained within the slides. An example is shown of how input data, including air quality and local meteorology, are used to disaggregate data by removing background and seasonal air quality, as well as weather, to observe local changes. R software is used to accomplish this and is freely shared, called AQEval. Several air quality monitoring networks are present in the UK that share data, but their site types, species measured, and timescales all vary from one another. The network of sites includes rural, suburban, and urban regions with low and high traffic, and species monitored include PM10, benzo[a]pyrene, iron, and sulfate. Treatment and control methods may indicate there is a change present, but more info from source apportionment is needed to understand why. By comparison, conventional source apportionment methods may have lots of source information, but few sites have enough co-located sampling to confidently apply them. In London in 2012, the method using benzo[ghi]perylene and chrysene as PAH markers indicated that the air quality was controlled by vehicle emissions, but this changed over time. To improve detection of environmental change, the methods under development include (1) to build a multivariate source apportionment model where possible, (2) to build and validate marker-based source apportionment models at these sites, (3) to apply these at near sites, and (4) to use normalized profile clustering to investigate patterns. When the model was validated at the first site, it was then applied at a second site and could only be validated on PM10. Central London (Marylebone) shows that a drop in PM10 occurred in 2020 but this was not all attributed to COVID. The PM10 decrease was attributed to the ultralow emission technologies and furthermore had changed from a diesel profile to a cleaner exhaust profile that was due to the implementation of control strategies. The dust profile has been gradually increasing over time because cars are heavier. Note that this dust profile includes brake and tire wear. Looking across the UK, time profiles showed that the cluster around London changed around 2019. These trends are tentative because few locations are available for model runs and some notable cities are currently excluded. Additional background sites are needed for comparison. The comparison of the road dust contribution levels to the exhaust contribution is striking for London, but less so in north England. Summary – there are tentative but interesting observations for some of the UK pointing to differences in vehicle emission trends for London vs the rest of the UK and northern vs southern sites in the time period of ~2011 to 2025. Work is on-going to add additional sites for better representability. The methods are shared.

SESSION 2: Decarbonization: Technologies, Complications, and Mitigation Strategies / Electric and Hybrid Vehicles

Georges Saliba, California Air Resources Board
"*Vehicle Activity Profiles: A Study of Differences Between Heavy-Duty Battery Electric and Conventional Drayage Trucks*"

Emissions from HE ZEV, e.g. drayage trucks, are of concern. The current emission reductions estimate is based on laboratory test cycles for internal combustion engine vehicles (ICEV). Drayage trucks have ZEV requirements that began in 2024 and will be fully implemented by 2035. The goals are (1) to characterize real-world activity profiles for BEDTs and conventional drayage trucks, including speed and acceleration profiles, idle times, speed and temporal distributions of VMT, and (2) to use ICE-based drayage lab cycles to estimate energy usage of BEDTs. Data spans operation in SoCal and NorCal and includes 3 HD diesels and 1 CNG drayage truck for model years 2012-2019. Lab cycle data includes creep, near dock, local (most aggressive), and highway (least aggressive) cycles with example speeds provided. Differences were noted in how BEDT were operated compared with conventional DT. Lower idle times were found for conventional DT. Higher average speeds and higher average daily miles were found for conventional DT. BEDTs are 6-year-old technology and the gap is expected to decrease as the technology is improved.



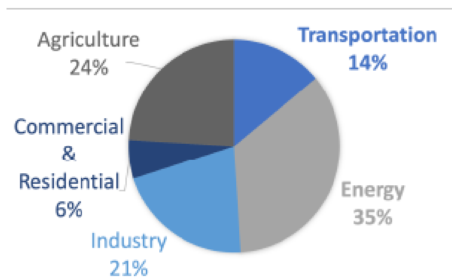
BEDT spend less time at full highway speeds and more time at lower speeds compared to conventional DT. The max speeds are also different possibly due to speed caps. The lower observed max speed for BEDTs is likely due to limited highway operation. Significant NOx benefits are expected from switching a conventional DT to a BEDT. NOx emissions tend to be highest at lower speeds, so this will be minimized if we switch to a BEDT. Examining VMT distributions, BEDT spend more miles at low speed than conventional DT, although there is a speed bin peak at 50-55 mph for the BEDT in the plot provided. Conventional DTs are spending a lot of time at higher speeds and operating on highways. BEDTs did not operate at night likely due to charging needs or operational needs. Switching gears, real world operations vs lab cycle comparisons showed that the composite DT cycle represented the real-world activity of conventional DTs. In contrast, the composite drayage cycle does not represent BEDT operations well. When the highway segment is removed from the cycle, BEDT operations are better represented. Similarly, VMT frequency is represented well for conventional DT with a composite cycle. For BEDT, the composite cycle with no highway represents BEDT VMT a little better, but still underestimates the BEDT VMT at low speeds and overestimates it at higher speeds. The latter indicates potential for significant NOx reductions upon transitioning to BEDTs. Summary – Differences were observed in BEDTs and conventional DT activity patterns. BEDTs were pilot vehicles and were operated on shorter/slower trips. The majority of BEDT VMT were driven at low speeds, < 20 mph compared to conventional DT, and did not operate at night. Replacing a conventional DT with a BEDT, even if operating on shorter trips, will likely yield significant NOx benefits. The ICE-developed composite cycle when excluding the highway segment was better representative of real world BEDT activity. As BEDT technology evolves, continued monitoring is needed.

Will Northrop, University of Minnesota, Twin Cities
"*The Cost of Speed in Minnesota: Insights from a Large Vehicle Dataset*"

Speeding was responsible for 65% of fatal crashes in Minnesota in 2021. In CA, there are similar percentages with over 70% related to unsafe speed. Speeding leads to increased emissions. Minnesota drivers were found to speed more after COVID on rural and urban roads and on interstates, and this has not generally not decreased since then. A study in 2008 used emissions and fuel economy models along with real-world driving data to show that 55 mph has the lowest grams of CO_2 per mile. The goal was to determine how driver behavior affects fuel economy in Minnesota and in the US using a large dataset, in which the start and end points of 100,000 trips and their full trajectories were recorded on one day in 2021. Fifteen vehicle classes for Minnesota were included, which are representative of the US as well. The dataset was matched to overall speed limits to determine when drivers were over-speeding. The average maximum over-speeding was 4.5 to 6 mph above the speed limit, sorted by different vehicle types. A vehicle model is trained to match the fuel consumption and emissions data from the vehicle set, and the average energy consumption is determined for each model. An example drive cycle is presented for a 10 min drive cycle in which the vehicle reaches ~60 mph where the speed limit was 50 mph. Drive cycle interventions are implemented by first capping the over-speeding segments at speed limit and preserving segment-wise distance. Second, both speed and acceleration are limited in the positive direction only. Third, eco-driving speed compliance is also implemented. The result is that fuel is saved through these interventions that the driver likely would not notice, with regard to fuel used or overall time spent driving. The overall savings was 1.9% less fuel used and 400 mt-CO_2 for the 100,000-trip dataset, which is a tremendous savings of fuel when extrapolated to many people! Interestingly, standard pickup trucks save the most fuel even though they do not do the most speeding. Acceleration modifications had the largest savings near urban areas. When extrapolated to the entire fleet, the dollar savings is large as well. Finally, seasonal results are provided for speed reductions as well as speed+acceleration modifications showing the number of gallons of fuel saved, dollars saved, and tons of CO_2 reduction.

Polina Alexeenko, National Renewable Energy Laboratory
"*Assessing Impacts of Vehicle Electrification on Criteria Pollutants*"

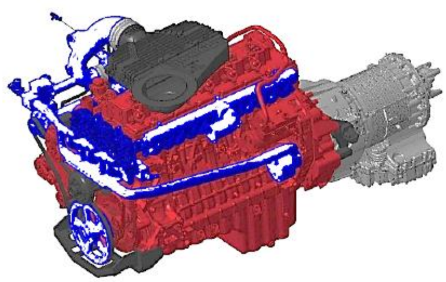
Tailpipe criteria air pollutants (CAPS), including NOx, SOx, and PM, are eliminated upon vehicle electrification, but emissions related to energy production are introduced (see figure). The impact depends on the operating location, vehicle duty cycle, and the grid generation mixture. This study compares the sensor diesel vehicle NOx emissions and estimated electrical NOx emissions. Vehicle data are obtained from the FleetREDI database developed by NREL, 1 Hz CAN-bus vehicle data, and ~70 vocations across the US. Data from Siler-Evans et



CAPs production by sector

al. (2020) show marginal NOx per additional MWh from generators depending on the region and time of day and year. The Midwest region of the US has the highest NOx, while Florida sees some of the highest and lowest emissions. Tailpipe NOx production included trucks, tractors, and buses. NOx production has substantial variation. The fleet including UT-Shuttle, CO-Food truck, FL-Refuse truck, and SC-Fuel truck has much less NOx, but higher emissions. Some of the NOx production violin plots are bimodal, while some are unimodal. The highest and lowest NOx emitters are given in the violin plots as well. The net NOx change under electrification shows that CO-Line OH-Line haul tractor fleets have the majority of their change on the side of decreased NOx (positive values), while the UT-Shuttle shows an increase in NOx (negative values). Most fleets have a tailpipe NOx that outweighs the electrification NOx. However, these scenarios did not incorporate operational pattern changes and consideration of the vehicle schedule is needed. Some fleets show that the departure and arrival patterns are very concentrated in the middle of the day, with extended time in which the vehicles may charge overnight, e.g. SC-Fuel truck. Others, e.g. CO-Food truck and UT-Transit, have very little charging time and are operating around the clock. While general electrification tends to decrease NOx, there are some operations changes that are expected to increase NOx, i.e. NOx may increase for UT-Transit and CO-Food when considering these operations. The SC-Fuel truck and FL-Refuse truck operations will likely allow NOx reduction. Future work is to consider locations of tailpipe and generation NOx. Summary – In-use NOx emissions were compared with simulated electrical emissions, considering 8 fleets across 6 states and 6 vehicle vocations. For certain fleets, electrification reduces NOx relative to conventional fuel. For some fleets, electrification increases NOx with operational patterns strongly influencing NOx impact. Future work involves consideration of the locations of tailpipe and generation NOx as well as incorporating minimum-price scheduling and infrastructure choice.

Bryan Zavala, Southwest Research Institute
"*H2-ICE Aftertreatment for On-Road Heavy-Duty Applications*"



Red – Cummins X15N Engine
Gray – Allison 4000 HS Transmission
Blue – H_2 ICE Specific components
Black – Vehicle Specific Components

The focus is on a platform of hydrogen internal combustion engine (H_2-ICE) and aftertreatment emissions compliance utilizing field cycles examples. The base platform is a Cummins X15N converted to operate with H_2. The particulate filter was replaced with an SCR (selective catalytic reduction) since there is no soot generated. This is expected to drive down NOx emissions. Aftertreatment system included a hydrogen oxidation catalyst (HOC), SCR, ammonia slip catalyst (ASC), and particulate filter (PF). How the aftertreatment system is tested is important. Parts were aged hydrothermally to a mileage of 435,000 miles. All H_2-ICE cycles are less than 0.01 gram/horsepower-hour and all lower than the comparable diesel engine. The H_2-ICE is significantly better than the best diesel low-NOx. CO_2 cannot be used to bin the load into a low or high load bin. Since there is very little CO_2 generated from an H_2-ICE engine, cycle work was used to bin data, but there are other options listed. Some NOx was detected from the aftertreatment system from the tailpipe, but when compared to diesel, bin 1 and bin 2 are still much better. Tailpipe NOx data was examined and cycle average tailpipe NOx was only 0.8 ppm. Tailpipe NOx was usually below 1 ppm raw. Key differences between diesel ICI and H_2-ICE include that the H_2-ICE generated lower tailpipe NOx emissions, and the diesel ICE had a wider temperature range. The engine-out NOx was lower out of the engine going into the aftertreatment system. The H_2-ICE temp range was more favorable for aftertreatment operation. Summary – a Cummins X15N was converted to operate with H_2. The aftertreatment system included an HOC + SCR + ASC + PF. Testing was performed using partial CARB southern NTE and WVU drayage cycles. The main conclusion is that the H_2-ICE platform generated significant margin to the standard and the system indicated viability for in-use emission compliance. The next steps include to continue developing the platform and generate vehicle data, continue emissions testing, and test safety and diagnostics.

Christopher Sharp, Southwest Research Institute
"*Overview of Long Term Metals-Phosphorus and Biodiesel Durability Impact Assessment Program*"

Maintenance of the biodiesel specification for ASTM has been an ongoing effort. Decarbonization has led to an increased demand for more biodiesel and renewable diesel blends, such as B50 and B100. However, there are new emission regulations for model year 2027 and later, which will lead to significant change to diesel engines and their aftertreatment systems. Research efforts are in progress to examine effects of high blend levels running in Ultra Low Emission Diesel Engines (ULEDE). A recent historical example of specification changes showed that metals increased the ash loading in diesel particulate filters (DPF). The solution was to use low metals. We will now have new technology in play that will reduce tailpipe emissions of NOx. Questions – Are the metals levels going to be a problem for this system? How much of these metals get to the aftertreatment system? Is the 10 ppm metals limit sufficiently protective of the modern diesel aftertreatment system? The metals and P specification for B100 sets the value for B100 used to produce blends below B100, e.g. if B100 pure fuel blend specification is 1 ppm, then the B100 used to make B50 could be 2 ppm. The current B100 specification for blends up to B5 is 10 ppm total metals, i.e. 5 ppm Na+K and 5 ppm Ca+Mg. The industry objectives are to get information on (1) B100 metals and P that are needed for blends up to B5 and B20, and (2) B100 metals and P for B100 compatibility as a pure B100 fuel in ULEDEs. The strategy is to conduct a durability run to look at Na and K, plus P, which will impact NOx performance versus any impact of B100 on combustion. A Diesel Aftertreatment Accelerated Aging Cycle (DAAAC) is currently being run with Ultra Low Sulfur Diesel (ULSD) with doped metals and P. A subsequent run on B100 with doped metals and P will allow verification of acceptable NOx durability performance. This will separate out metals/P impact versus potential B100 specific combustion impacts. The target metals/P levels for the initial run are 2 ppm total (Na+K+Ca+Mg) with 1 ppm Na, 1 ppm K, and 1 ppm P. The methodology is to age the aftertreatment system to 800,000 miles to compare to the original system, which would have been aged. Full system details are found in SAE papers 2023-01-0357 and 2021-01-0589. The test uses a 2017 Cummins X15 engine with advanced low NOx aftertreatment. DAAAC is not a single cycle, but is a protocol for developing aging cycles for specific applications, and requires inputs to generate an accelerated aging cycle, such as aftertreatment temperatures, exhaust flow rates, fuel consumption, and lube oil consumption. A stage 3 DAAAC-based accelerated aging cycle example is presented which shows that 1839 hours of DAAAC aging equals 18390 hours of field aging or 800,000 miles. The initial run has reached the 650,000-mile test point and some degradation has been observed, but results appear to be insufficient thus far. The next steps are to review with the steering committee to determine what additional data is needed to develop a consensus on metals/P value.

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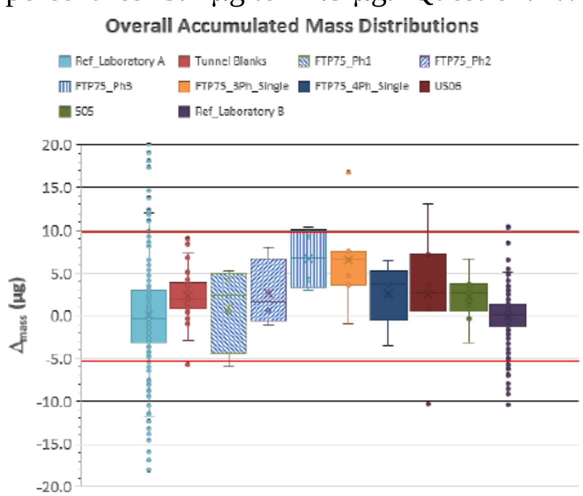
SESSION 3: Emissions Measurement Methods

Benjamin Shade, AVL

"*Challenges and Successes of Measuring Near-Zero PM Levels over Chassis Dynamometer Certification Cycles*"

The EPA's Multi-Pollutant Emissions Standards for model years 2027 and later LD and MD vehicles, Tier 4, sets a lower standard than Tier 3. With lower mass being collected on filters, how much PM can be measured with high certainty? The Gravimetric Filter Survey (CRC E-99), presented by Ken Johnson et al. in 2015, is the method being used. That study recommended robotic filter weighing to reduce variability, but this is an expensive investment for laboratories. For low-level PM sampling, EPA recommends using PTFE membrane filters to reduce gas phase artifacts, static charge removal using an alpha emitter, and increased filter face velocity. In the experiments here, filters and holders are manually loaded. PM filters were weighed before and after loading at two facilities to compare environments. In Laboratory A, there were seven months of reference filter data totaling 364 weight measurements. Data presented showed the 5th to 95th percentiles are -9.7 µg to +9.2 µg. New filter personnel were introduced to weigh filters during the time of the measurements, suggesting human uncertainty and variability could exist. There was a tighter distribution in Laboratory B: 5th to 95th percentiles -5.1 µg to +4.3 µg. Question: Which one is correct? Are they both correct? Are they all zero? Next measurements were Constant Volume Sampling (CVS) Tunnel Blanks: in the data shown, it appears as if the blank test mass may be increasing over the 10-month period, but there were fewer samples taken in the last few months than in the earlier months. The average filter mass was 2.3 ± 2.6 µg (1 sigma). Moving on to vehicle tests in Laboratory A for a gasoline vehicle with a PM filter, the FTP results are compliant with the 0.5 mg/mi PM standard, with the 4-phase single-filter having the tightest distribution. The US06 test cycle results were highly variable with outer quartile data going above compliance. The Phase 3 multi-filter FTP has higher filter mass than both phase 1 and phase 2 masses. In laboratory B for a diesel vehicle equipped with PM filter, the average PM was 0.18 ± 0.21 mg/mi (1 sigma) with one test exceeding the 0.5 mg/mi PM standard. Several filters were transferred to AVL and weighed in their clean room, and two filters were installed but not used, to serve as trip blanks. Comparisons between weighing at Laboratory B and at AVL showed good correlation between the two laboratories and suggest that handling of filters causes less variability than expected. Laboratory B vehicle tests showed repeatable near-zero soot emissions. A real time measurement measures a surrogate of exhaust emissions and is more insightful than a batch measurement. Summary – Single-filter vehicle tests have less variability than multiple-filter vehicle tests. It is difficult to discern between PM mass accumulation on filter media during tests and mass "accumulated" on reference filters. This is also true for tunnel blanks from a single laboratory. A real-time surrogate measurement is a good way to determine pass/fail for PM, but what is a surrogate for zero? There appears to be a bias shift toward the positive, but is



not driven by reference filters. Next steps are to continue to gather more data with improved processes and examine samples from robotic weighing.

Matt Panec, 44 Energy
"*Light Duty PEMS Phase 3: PEMS Performance at Altitude, Grade and Low Temperature Test Program (CRC Project No. E-134)*"

The goals are to (1) determine and compare the repeatability of a Constant Volume System (CVS) and PEMS during chassis dynamometer testing, (2) determine repeatability and accuracy of PEMS on road, (3) determine if PEMS unit can detect differences in PMI of fuel, and (4) determine correlation between CVS and PEMS exhaust flow measurements. Testing was carried out in Aurora, CO at TRP Laboratories in Winter 2024 to Spring 2025 with four test vehicles, in which vehicle E was unique to this project and A, C, and D were used in a previous CRC project. Two test fuels were used, high- and low-PMI, and both chassis dynamometer and on-road testing were carried out, with the on-road test comprising city, highway, and rural conditions for ~44 minutes. Comparing the PEMS and CVS for exhaust flows, PEMS seems to measure up to 10% more total exhaust flow and correlations were poor for all vehicles. Variability in CO_2 measurements was similar between PEMS and CVS, and they were both more variable on the road. Observations were similar for the E-122-2 project. NOx variability between PEMS and CVS is also similar, but the road test had some higher variability for vehicle A compared to on the chassis dynamometer. Similar observations made for the E-122-2 project. For PM, there was similar variability for PEMS and CVS. However, there was higher variability in this E-134 project than in the previous E-122-2 project. Observations of CO variability again showed similar behavior for PEMS and CVS, except that road test variability was lower than for chassis dynamometer testing, especially for vehicle A. This is because there is correlation between driver behavior and CO variability. With more dynamic behavior of the accelerator pedal position, there tends to be higher CO emissions. Taking CVS as the gold standard method, the bias of the PEMS measurements was presented relative to CVS. PEMS bias is consistent across vehicles and PEMS road test bias tends to be larger than PEMS chassis dynamometer bias. Comparison of the two fuels showed that there were higher PM emissions using higher PMI fuel. The difference varied with vehicle but was consistent between PEMS and CVS, with larger gaps for E-134 relative to E-122-2 project. Correlation between THC and higher PMI fuels was inconsistent for E-134 and E-122-2, suggesting that PMI is probably not a key factor in THC emissions. There was a varied impact on CO for the two fuel types. Higher PMI fuel led to higher CO_2, but there was no difference in NOx for the two fuels. Summary – All testing was carried out under high altitude, steep road grade, and low ambient temperature conditions. Measurement variability was consistent across CVS vs PEMS, and similar for road testing versus chassis dynamometer testing in most cases. PEMS road testing bias tended to be higher relative to chassis dynamometer testing and was higher in E-134 than E-122-2. PEMS responded similarly to CVS for changes in PMI of fuel, but PEMS measured up to 10% more total exhaust flow than CVS.

Heejung Jung, University of California, Riverside
"*Application of a Diffusion Charger to Quantify Transient Particle Emissions from Very Low to High Emitting Light-Duty Vehicles*"

This study is carried out in collaboration with CARB and some details are given in Jung et al. (2021). For exhaust particle measurements, there are different types of mobility classification, detectors, and charging methods. Scanning mobility particle sizers (SMPS) use condensation particle counter detectors (CPC) with a bipolar charging method, while the engine exhaust particle sizer (EEPS) and differential mobility spectrometers (DMS) use an electrometer as the detector with a unipolar charger. There are others available on the market as well. A mathematical description of electrical aerosol detector (EAD) response is presented, described in detail in Pham and Jung (2016). Conversion of EAD response to CPC response requires the use of the Hatch-Choate equation. Vehicle specifications were provided for 4 vehicles with MY 2009 and 2012 that include PZEV and ULEV emission categories and different engine technologies: gasoline direct injection (GDI), port fuel injection (PFI), and a diesel with a particulate filter (DPF). Instrument specifications were provided for 5 instruments and models, including EEPS, EAD, and different CPCs. EEPS measures 5.6 - 560 nm particle number distributions, EAD measures 10 nm - 1 um via active area, and 3 CPCs provided measures of varied ranges of particle number concentrations, one with a catalytic stripper (CS). A CVS sampling system diagram was shown with all instruments connected. Comparing EEPS measurements with EAD particle active surface area (PS) shows that the EEPS is not able to measure low particle surface area for the various engine technologies / vehicles. For particle number, the electrometer (EAD) measured 5 orders of magnitude in range. Summary – Applying a diffusion charger for emissions measurement showed that a wide measurement range enables distinguishing concentration peaks from high-emitting events and allow measurement of transient events for low emission vehicles. Quantifying PM from a diffusion charger measurement requires prior knowledge of particle size distribution.

Jimmy Williamson, AVL Test System, Inc.
"*Influence of NOx Concentrations and Sampling System on Analyzer Noise*"

The motivation for this study is to use Accuracy, Noise, and Repeatability (ANR) to validate analyzer measurement data. The focus is on heated chemiluminescent NOx analyzer/detector (HCLD) performance under zero and non-zero concentrations. It was shown that the noise was influenced by the nonzero gas concentration in that the system (e.g. gas path) must be purged long enough to remove residual effects from the nonzero gas in order to determine the actual noise level. This means a longer settling time is needed. A noise level of 1 ppb for a concentration of 3 ppm is very acceptable. Noise results for 3-1000 ppm NOx showed that the noise was higher for the higher concentrations, but lower in terms of percentage. It is expected that the noise is independent of the range. Flow-weighted mean concentration (FWMC) is defined as "the mean of a quantity after it is weighted proportional to a corresponding flow rate." A gas analyzer's performance can be characterized around the FWMC, but must also capture the peak concentration during a test interval, which is difficult for combined standards. When QA/QC checks are performed at the factory or other site, the FWMC is not always known, so how to qualify the analyzer? The FWMC was determined by running preliminary cycles. When a manual zero is carried out and then ~2 min of NOx/NO gas is flowing directly to the analyzer (HCLD) before stability, a dip is often observed in the transitional data which is not understood for span gas systems. For zero gas, the signal has not reached stability even though the gas is flowing directly to the analyzer. If stabilized for 210 seconds rather than 30 seconds, the results were more comparable. The same slow decay is observed at zero over the probe as for direct. For an actual emission test, the span gas artifact could cause a positive bias. Looking at a transient response of the AMA SL HCLD compared to another HCLD, no cause for concern. Zoom in to look at low concentrations. Summary – Noise in NOx and NO determined with the ANR test is dependent on the settling time, which is influenced by the non-zero span gas concentration. Are we masking an issue in emissions testing? The next step is to develop recommendations on how to use ANR results to verify the analyzer capability to measure based on FWMC from individual tests.

Setayesh Fakhimi, National Renewable Energy Laboratory
"*Development of Heavy-Duty Electric Vehicle Energy Rates for EPA MOVES Model*"

The MOtor Vehicle Emission Simulator (MOVES) is the US EPA tool for estimating energy use and running exhaust emissions from on-road vehicles and non-road equipment. MOVES5 determines energy rates based on energy efficiency ratios (EER), that do not incorporate regenerative braking or detailed duty cycle impacts for HD EVs. NREL refined energy estimates for HD EVs under EPA guidance. The goal is to develop a generalized model to estimate EV energy rates and categorize by MOVES operating modes using two case studies. One criterion is the MOVES operating modes. These are defined by deceleration events with details found in the MOVES5 technical report, EPA-420-R-24-019. Operating mode 0 is braking, while the other modes are different speed bins. FASTSim, described in Brooker et al. (2025), is a model to account for drag, acceleration, road grade, rolling resistance, powertrain efficiency and limits, and regenerative braking at each time step. Case study 1 includes datasets for Class 8 transit BEBs. The National Park Service (NPS) route is the same every day, operating in Zion National Park, UT, with speeds below 35 mph, and the Valley Transit authority (VTA) route runs around San Jose, CA with higher speeds up to 60 mph and more variability in speed. There are 25 daily datasets for NPS and 227 daily datasets for VTA. Results for Class 8 transit BEBs are provided, in which negative values show net regenerative braking. Operating mode 0 is braking and two additional modes show negative values. Operating mode 11 shows coasting at lower speeds, and mode 21 shows coasting at higher speeds. The linear trend of increasing battery power with each successive speed bin is expected since the scaled tractive power (STP) increases, so battery power increases. At higher speed bins, limited data points exist. Case study 2 is datasets for Class 8 electric tractors. The study used diesel drive cycles including 848 daily datasets with drayage, line-haul, sleeper, and day cab trucks. Modeling used diesel drive cycle data since that was the only data available to model battery power. Diesel drive cycles had 3 scenarios: unloaded tractor, loaded tractor, and mass estimation. Line-haul and sleeper trucks drive longer distances and have highway driving, while drayage trucks have shorter, in-city routes. Results presented for Case study 2 show that the linear trend is similar to the last scenario, but now for a heavier vehicle. The unloaded case requires significantly less power to propel forward. For the loaded tractor case, mode 30 is low. The loaded truck cannot accelerate as quickly or reach the higher speeds required for those higher operating modes, and the data show up in mode 29 instead. Conclusions – We can model BEV energy rates and use them as potential inputs in MOVES. The model can be validated when measured BEV datasets are available for the vehicle type to compare against diesel drive cycle results. Future work includes assessing grid demands to power BEVs, which will help plan for reliable grid integration and peak demands.

Leo Breton (for Phil Roberts), Horiba Mira UK
"*Vehicle and Powertrain Empirical Digital Twining using On-Road Measurement Data*"

An Empirical Digital Twin is a pseudo-perfect digital representation of a physical object, in this case it is a model that is trained with real data to get emissions predictions. Data used for training is separate from the data to be predicted. The EDT contains empirical models of fuel economy, NOx, battery attributes, and power consumption. The benefit is that as standards become more stringent and difficult, there is a need to understand the operation of the vehicle over the entire operating space with fewer tests rather than more. A valued cycle is needed, rather than any cycle. Test worst case – simulate and predict regulatory envelope by testing the extremes. Then, what the emissions would be can be predicted using a different case using the worst-case results. The Horiba EDT toolset is composed of a test designer, a modeler, a predictor, and an optimiser. The focus is on the modeler and predictor for this presentation. The test designer was not used for this project. Modeler and predictor are used with real world data gathered from extensive road testing. The demonstration vehicle is a late model LDV with automatic transmission. OBD data were collected on engine speed and torque, vehicle speed, transmission gear, and pedal position. Data were collected at high altitude from the foothills of Pikes Peak, CO and some at lower altitude in Ann Arbor, MI. Data were presented on brake torque (approximately 0-275 Nm) versus engine speed (~800-5500 rpm) and used as inputs. The methodology is to extract speed and torque from sample road tests and perform modelling to lead to predictions, that could then be compared with the measured data. It would be left up to the user to decide how much error is acceptable. Tailpipe CO_2 was acceptable (~1% low), NOx was ~6% too high, and tailpipe PN and exhaust mass flow were very close to measured data. Instantaneous and cumulative tailpipe CO were also very good. The test systems suggest that we can have a very powerful prediction model for control systems that are not doing very well. Can be used on a chassis dynamometer to simulate altitude quickly so that laboratory data can be used to train the model. No requirement for PEMS. Summary – most data collected from multiple real-world locations using a light-duty SUV was used to train the model and some to build empirical performance. Models were validated for accuracy using other road test data that was not used for training, and can be used to predict emissions for any road drive using the LD SUV without installing a PEMS. This is a novel approach to reducing the amount of testing required to ensure engine calibrations are robust for non-typical real-world driving that OEMs may be interested in using.

Day 2 – Tuesday, April 15, 2025

Keynote Address: Wayne Miller, University of California, Riverside
"*We've Come a Long Way & Still Going!*"

To illustrate the title statement, photos are shown of a 1949 Ford truck and the modern Aspark Owl (an EV with a top speed of 260 mph!). We've come a long way! A quote from Charles Kettering about research is provided "…Research is an organized method of finding out what you are going to do when you can't keep on doing what you are doing.". The key areas in designing an automobile include safety, emissions, and customer features. Story #1: One of the first programs in the CRC was to look at the composition of fuel and how the emissions relate to them (Barry et al., 1985). A number of studies were done looking at the effect of composition of diesel on emissions (Wall & Hoekman, 1984; Ullman, 1989). The aromatics composition didn't change the particulate much and we came away with an understanding to control the

sulfur in fuel (Wall et al., 1987). The Fuel Sulfur Reduction for Control of Diesel PM Emissions study from Chevron showed that it was cost effective to reduce sulfur and leave the aromatics as they were because there was less change. Later it was shown that reducing aromatics did help reduce particulates. It was interesting that lowering aromatics lowered particulates but people saw that since 10% aromatics were good for diesel fuel, they must be good for gasoline. CARB showed that this was not true and HC emissions are not related to gasoline aromatic content. Story #2: In the late 1980s, nine cities were identified in the US as being the smoggiest. A New York Times article conveyed the prevailing attitude that those cities needed an alternative fuel to gasoline. Then-President Bush moved to require a proportion of automobiles that would not use gasoline. The Alternative Motor Fuels Act of 1988 pointed to global warming caused by manmade pollution and the need for alternative fuels. This issue still exists today. Studies of fuel changes led to reformulating gasoline by many oil companies. The composition was found to be complex and nonlinear. In May 1990, the President announced the reauthorization of the Clean Air Act. When they launched the program, Phase I allowed for $15M from the auto companies for emissions studies to be completed in 6 months. More funding was requested for Phase II and further research continued on fuel and vehicle emissions to improve air quality. This led to language for the Clean Air Act. For reformulated gasoline, the most important components were found to be aromatics, oxygenates (e.g. MTBE), olefins, 90% distillation temperature, vapor pressure, and sulfur. This research led to findings about MTBE, effects of aromatics, and that reducing olefins had little effect on mass exhaust emissions, among other results. However, then-President Bush still wanted EVs. Ford, Chrysler, Nissan, and Toyota announced new EVs in the early 1990s. We also came to recognize that the lab study was only part of the story. Real-world emissions studies were needed and tunnel studies were initiated again. Studies confirmed what was found in 1989 about olefins (Hajbabaei et al., 2013). Story #3: Working with CARB labs, UC Riverside obtained similar results and confirmed that laboratory and real-world are similar. John Collins' study showed this, as well as Johnson et al., 2008. Final part of story (Story #4): SULEVs are here! In 2003, Wayne shifted his research to ports, including ships and locomotives. The benefits of this led to geofencing, in which different fuels are used when ships are inside a certain range of the port. Vessel speed reduction was shown to be beneficial. Combustion generated (and non-combustion) gases and PM2.5 encompass many key air issues in that the majority of PM2.5 is formed from precursors which are not particles at the emission point (i.e. secondary PM). Scrubbers were introduced on roll-on/roll-off (RORO) vessels to reduce emissions. The world's first hybrid fuel tugboat was even initiated. A video of Long Beach Container Terminal automation, the first fully automated container terminal in the US, is provided on YouTube as an example of maximizing efficiency and minimizing environmental impacts. For ships, NOx has not reduced over 10 years, so there is still work to do! Toyota introduced their Harmonious Mobility Network for improved convenience and reduced energy consumption waste. We need to think beyond the science since most real-world issues are complex. Dr. Barbara Burger of Chevron, quote: "The world changes every day, and I need also to change." There is a lot of work to do!

The Aspark Owl has a top speed of 260 miles per hour and acceleration to reach 60 miles per hour in 1.72 seconds. The model goes 250 miles on all-electric.

Written by Lisa Wingen, Ph.D.
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Author notes provided at the end

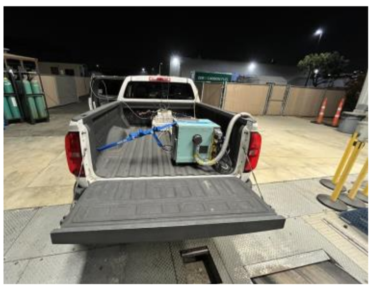
SESSION 4: In Use Exhaust Emissions: On Road, Off Road, and Non-Road

Axel Freund, CARB and **Daniel Zaragoza, CARB**
"*Mobile Hydraulic Dynamometer (MoHyD)*" & "*Exhaust Emissions from Off-Road Equipment on MoHyD*"

The goal of the project is to expand testing of MoHyD and regulatory considerations: verify MoHyD testing for engine control, compare to regulation, and examine emission differences between MoHyD-PEMS and Mobile Emissions Laboratory (MEL). MoHyD is a standalone system that uses the hydraulic system of off-road equipment to load the engine. It fills the gap between in-use PEMS and engine dynamometer testing. If we can control the load and speed, we can control test cycles. MoHyD relies on ECU data and can be combined with PEMS or lab environment. In terms of accuracy, it receives ECU data and there is no additional cost besides the equipment rental. Some advantages are that PEMS testing can be performed at any stationary location with no dirt movement and no risk of PEMS unit changing the center of gravity. MoHyD fits into a trailer and is quite mobile. There are big advantages in cost, and it can be used to simulate compliance and in-use cycles. The specifications include space -- fits in back of pickup truck; capability of various pump configurations; each of 4 sections can have 100 horsepower (75 kW), and could upgrade and add horsepower. The maximum pressure is up to 5000 psi. One goal was to compare cycles to see how it performs with regard to 40 CFR 1065 regulation. Testing schedule involved 4 days. Emissions testing: so far 2 Skid Steer, 2 Excavators, 4 Backhoes, and 1 Wheel Loader were tested. Focusing on wheel loader for this presentation, which is the least hydraulically controlled equipment. A 2017 model year wheel loader with 7 L displacement, 200.9 kW, ~3000 hours was used with further specs given on slide 11. It was tested over multiple time periods: June 2023, October 2023, and April 2024. An overview of the setup was presented in the standard MoHyD-PEMS setup, with the testing period during June and Oct 2023. Six certification tests were carried out: 3 RFC, 3 NFC, using AVL gas. In April 2024, UCR's mobile emissions lab was used with the MoHyD-PEMS setup. Comparisons between MEL and PEMS were made. PEMS data was processed by CARB staff and MEL data processed by UCR staff. Results were presented for Ramped Modal Cycle (RMC, n=3) on engine speed and engine load with slopes exceeding the target slopes and r-squared values of ~0.99. Results were also presented for cold Nonroad Transient Cycle (NRTC, n=3) testing, in which the slopes exceeded the target slopes, but the r-squared for engine speed was below the target of >0.97 (0.959) for a short time period. For hot NRTC (n=3), there were similar results with a low r-squared at one time point. The emissions results overview was presented, showing improvements from June 2023 to April 2024 for RMC and cold NRTC in that the CO_2 tracked more closely and there was greatly reduced scatter observed in the cold NRTC. The RMC cycle was shorter in June, from a missing cycle that was later added in April. Duty cycle improvements led to more reliable and repeatable measurements. Repeatability focus on CO_2 (slide 21) – zooming shows clearly how consistently the emissions tracked engine load. This was similar for total emissions. Cycles have low variation, confirming high test repeatability. The hot NRTC shows slightly higher variability, but results remain within a narrow range. Comparisons are presented for NOx as well. Emissions comparison between MEL and PEMS shows that PEMS measured higher CO_2. For comparison to certified levels, two differences were noted in the engines, but the engines are similar enough to be a useful benchmark. Summary – Improved MoHyD control led to more consistent duty cycle execution and emissions results; emissions trends were repeatable across tests, especially for CO_2; PEMS and MEL trends were similar, although PEMS measures higher CO_2; PEMS CO_2 is within 5% of certified levels. MoHyD can fulfill 1065.514 cycle validation criteria with high repeatability and in-field testing will continue. A video was presented at the end to show it in action and measurements being taken!

Elizabeth DeFrance, UC Riverside
"*Real-World Tailpipe Ammonia Emissions from Light-Duty Gasoline Vehicles*"

Ammonia (NH_3) can be formed as a by-product of three-way catalysts from the water-gas shift reaction with CO (see slides for chemical reactions). Tailpipe NH_3 is not regulated in the US, but contributes to secondary PM in urban and rural environments. The motivation of this research stems from a plot of the average US driving distances and times in different metropolitan statistical areas (MSA, i.e. population sizes) from rural to 3 million+ people. The average US driving distance in 2022 was ~20 miles or 26.7 minutes (one way) and light duty vehicles have been identified as the primary contributor of on-road NH_3. The study presents tailpipe NH_3 emissions measured for 11 light-duty gasoline vehicles with a tunable diode laser



spectroscopy system. The test route was informed from the average US driving distance so it was 22 miles (~60 minutes) including urban and highway driving in Southern CA. Several light-duty gasoline vehicles were selected with model years 2009 to 2024, a variety of manufacturers, and mileages of <5,000 to 177,000. The results showed that the highest NH_3 emissions were observed during cold start conditions as well as aggressive accelerations, with an example time trace shown for vehicle 2 (MY 2012 with 135,000 miles). Mean NH_3 mass flow rate was binned by acceleration and shows that high acceleration events led to higher NH_3 emission rates for all vehicles. Deceleration events (shown as negative acceleration) also led to increased NH_3, but this may be a delay of the instrument. High NH_3 emissions during high acceleration events are likely due to emission control systems being unable to react quickly enough. Most NH_3 was produced under high load and high engine speed conditions, which correlated with aggressive accelerations. Comparison of cold engine starts with hot engine emissions was carried out. Cold start driving accounted for 8-27% of total driving time. If drive time was cut in half, the cold start would account for more driving time. NH_3 emissions during cold start accounted 8-81%. Up to 80% of emissions are occurring in 20% of the time. Additionally, older vehicles generally had higher overall NH_3. Spikes in NH_3 occurred for all vehicles at all accelerations, even for the newer vehicle, but magnitude was larger for older vehicles. Air-fuel ratios also affect NH_3. The highest NH_3 events were normally distributed around in the equivalence ratio of 1. Model year and mileage effects were observed. There appears to be a moderate positive correlation of total NH_3 with mileage, but vehicle 5 may have biased this result. There also appears to be a weak negative correlation with model year, but vehicle 5 will be checked to confirm this. Summary – NH_3 emissions were characterized from 11 gasoline vehicles, with driving dynamics, e.g. aggressive accelerations, found to significantly impact NH_3 emission rates. Cold start driving accounts for up to 80% of total NH_3 emissions over daily US average mileage and could be more if the commute is shortened because the cold start period would account for more time. These findings can help shape future policies for tailpipe NH_3 and secondary PM.

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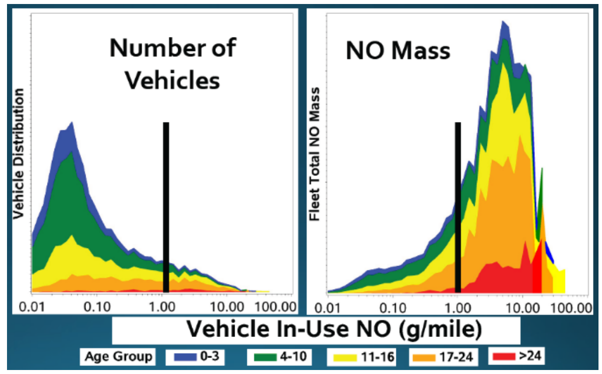
Carl Fulper, US EPA

"*Efforts to Identify and Quantify the Prevalence and Emissions Impact of Medium- and Heavy-Duty Vehicles*"



There is a continuing effort by EPA to quantify emissions from vehicles, specifically tampered vehicles. Data from the Colorado Dept of Public Health using remote sensing showed that 10% of the vehicles are high emitting vehicles and are making 80% of the emissions. Need to find these vehicles! Tampered is defined for the purpose of this study (not using the CFR definition) as vehicles where the emission control hardware is electronically and/or physically disabled and OBD software functions related to these systems were disabled or otherwise bypassed. The objective is that EPA would like to better understand the in-use emissions from the diesel fleet since the implementation of the MY2007/2010 regulations, specifically, what fraction of the fleet consists of high emitting vehicles for which engine manufacturers or vehicle types? Need to continue evaluating the performance of tamper detection tools against proven reference methods. A study was performed and presented at a 2024 CRC to evaluate commercial tools to detect vehicles with potentially high emissions in under 3 minutes. The tools had a 94% success rate of finding these vehicles. An HEM data mini streamer with OBD inspection software uses WiFi to produce a report to determine if it has been tampered with. EPA has evaluated tampering software sales to estimate the pact on the Class 2b/3 fleet, and there are lawsuits in this vehicle category. The percentage of tampered vehicles ranged from 2.7-25.6% for different states with an average of 14.7% over all states. A 2024 tampering test program in Colorado with OBD types J1939 and J1979 in CO showed that there is a possible 5% failure rate as shown by the HEM tool compared to the OBD devices. We also have support from NJ and Washington DC. State-supported testing results showed between 3% and 20% possibly tampered trucks using the HEM tool. EPA uses COTS (commercial off the shelf) tools that are convenient to use for others. NJ staff collected data at a scale house in South Jersey to gather in use vehicle data from around the country. CO staff performed testing as part of their Diesel Opacity Inspection Program. Washington DC performed testing by the DMV beginning in Jan 2025. Opportunities for additional data on tampering include vehicles being resold by auction companies and primarily class 6-8 heavy-duty vehicles from all manufacturers. EPA plans to investigate the fraction of tampered vehicles and the % of vehicles with DPF and/or SCR disabled. Next steps include expanding its protocols and methodologies to identify tampered vehicles and finding additional partners to loan detection equipment. They would like to determine how big the problem is and if it is growing, specifically diesels from 2007. This is currently a pilot program. Another next step is to examine class 6, 7, 8 vehicles. The modifications are hidden and are not obvious on visual inspection. Their devices find "possible tampering" and vehicles must be examined later to confirm if tampered has occurred. The illegal software that is being sold in some states turns off the OBD and makes it look normal, which is difficult to find.

SESSION 5: Alternate Fuel and Zero-Emissions Vehicles (Hydrogen, Non-Carbon Fuels, Battery-Electric Fuel Cells)

Imad Khalek, Southwest Research Institute
"*Fuel/Engine Combustion Technologies with High Solid Sub-23 nm Particle Number and Ultra Low Soot Mass*"

Low PM-emitting engines have in common that they emit high number of small solid particles below 23 nm in diameter. Examples of such engines are diesels with DPN with urea-derived species downstream of SCR, PFI gasoline, natural gas, compression ignition methanol and gasoline. These sub-23 nm particles are likely lube oil ash and/or urea-derived species. These engines meet US EPA PM mass emissions, but may not meet Euro 7 SPN10 emissions *without* an exhaust particle filter like DPF or GPF. The goal of this work is to show examples of particle number and mass emissions for different engine types and offer a path forward for regulations using the right metric. A study published by Khalek et al. (2018) shows that the diesel engine with DPF produces less particles in the <25 nm range than the natural gas engine as well as less particles in the >25 nm range than the natural gas engine. Both engine types meet the mass standard, but the natural gas engine emits more solid and ash particles. Although soot mass is very low / undetected from a methanol compression ignition engine, there are a significant number of 10 nm solid particles formed, also believed to be lube oil ash particles. For the H_2-ICE engine (1.3 L single cylinder, SS condition), there is a 10 nm particle mode and the majority of solid particles are <23 nm in diameter, with number concentration as high as a diesel engine without a DPF. For gasoline PFI, particles are mostly <23 nm (mode diameter ~12 nm), but GDI has many > 50 nm. The current Euro 6 standard for particles >23 nm does not apply to PFI, but the upcoming Euro 7 standard for particles >10 nm applies to both PFI and GDI engines. For upcoming US exhaust PM *mass* regulations, light duty regulations may be down to 0.5 mg/mi from 3 mg/mi by 2030 or 2035, an 83% reduction. An added component to the regulation is that you must meet FTP at -7°C. The challenge for low PM mass measurement is called "The Whining Factors", i.e. very difficult to measure that low because filter mass variability is too high, and there is additional concern about tunnel blank artifacts and subtractions. In addition, some of the PM is gas phase captured by the filter. Very recently, a complaint came up that people are getting negative filter weights. Light-duty brake PM mass and solid particle number compared to exhaust is much higher on a mass basis and much lower than exhaust on a number basis, as shown in Grigoratos et al. (2023) and Mathissen et al. (2023). Brake PM can be >10 times higher than exhaust PM for light-duty vehicles and >50 times higher than exhaust PM for heavy-duty vehicles. But brake PN is much lower than exhaust PN under normal operations. Question: Can we introduce solid particle number regulations where it makes more sense? The recommendation The EPA currently adopted particle number regulations for aircraft engines. Summary – Several examples were shown where engines emit high particle number while meeting PM mass regulations. It was also shown that brake PM mass emissions could be more than 10x higher than exhaust PM, while exhaust PN is more than 10x higher than brake PN.

Zisimos Toumasatos, UC Riverside
"*Influence of Hydrogen Blending on Engine Performance and Emissions from an Ultra-Low NOx Natural Gas Heavy-Duty Engine*"

California's low carbon fuel standard (LCFS) aims to reduce transportation fuel carbon intensity through 2030. Renewable natural gas (RNG) and H_2 are expected to play a major role. There is a need to check engine performance and pollutants by adding small volumes of H_2 injected into natural gas pipelines. The goal of this study is to test how different blends of hydrogen in renewable natural gas affect engine performance and criteria pollutants with no modification to the engine or its control unit. An ultra-low NOx natural gas engine (MY 2019, 8.9 L, 6-cylinder, 12.1 compression ratio with 3-way catalyst) was used as delivered directly from the manufacturer and tested in UCR's CE-CERT facility. Instrumentation included a VisioKnock Sensor and pressure transducer. After the catalyst, both volatiles and solids were measured with Gas PEMS (CO, CO_2, NOx, THC), an APC 23 nm + CPC 7 nm + EEPSs and other equipment. Three experiments were run for each of four fuel blends: baseline, 1%, 3%, and 5% H_2 by volume added. Eight steady-state points were tested. NOx measurements showed that slightly higher NOx was observed under 5% H_2 conditions. The majority of particles measured are in the nucleation mode (~10 nm) and there is no significant difference for PN in fuels at each steady-state point. Particles might be formed from lubricant oil combustion. In all cases, they are far below the new Euro 7 standard. Transient solid particle number showed an order of magnitude more solid particles were measured at the 7 nm cutoff size compared with 23 nm. This is a significant finding given the new Euro 7 standard using a cutoff size of 10 nm as compared to 23 nm. This finding did not change significantly between fuels. Steady-state in-cylinder pressures showed that the 5% fuel blend exhibited the highest peak cylinder pressure, whereas 1% and 3% fuel blends generally experienced lower peak cylinder pressure than baseline. In all cases, they are far below the threshold. The 5% blend showed the earliest start of combustion and combustion phasing. The longest delays were observed in the 1 and 3% blends. The majority of NOx emissions come from transient spikes. Higher blends of 9% and 11% were tested and resulted in 4- and 6-times greater NOx than baseline, respectively. Transient particulate metals were collected on Teflon PM filters and analyzed with X-ray fluorescence (XRF). Ca, Zn, S, and P are major components of the additive lubricant oils. These metals generally increased with increasing % H_2 for the cold start FTP cycle (CS FTP), but decreased with increasing % H_2 for the hot start (HS FTP). A third test was a series of engine motoring and firing events to understand the role of lube oil. These were custom designed to promote oil introduction into the cylinder. Longer periods of motoring resulted in more soot, which suggested lube oil involvement. In-cylinder light intensity measurements results showed higher light intensities and longer light events that indicate diffusion flames originating from oil deposit combustion. Summary – Renewable natural gas with blends of 1, 3, and 5% H_2 were tested in a heavy-duty engine compared to the baseline fuel with no added H_2. Higher NOx emissions were observed with higher H_2 added and higher peak cylinder pressures and earlier combustion phasing correlated with higher NOx emissions. Metals found in particle mass emissions indicate lubricant oil consumption.

Carl Desouza, Imperial College London
"*Particle Size Distribution*: *Multi-Gas Combustion Engine for the UK Construction Sector*"

Diesel is the predominant fuel used on construction sites in the UK. Construction sites wanted to switch due to regulations. Generators are the highest emitters of air pollution on construction sites. Generators account for more than half the total NOx emissions on construction sites. The goal was to measure tailpipe gas and particle emissions from a multi-gas engine used in a generator with different fuels. Three fuels were tested: LPG, H_2, and 12% renewable dimethyl ether (rDME) in LPG were tested. The latter was tested because new 2023 documentation (UN/SCETDG/63/INF.19) will allow to use up to 12% by mass of dimethyl ether added to LPG. The test procedure was ISO 8178 type G2 test procedure for constant speed SI engines with 5 load points tested as well as idle emissions that are not part of the test procedure. The test points ranged from idle to 12 kW, the engine's rating. Several emissions measurement systems were used. An engine dynamometer with a chiller was used to reduce water vapor. Other equipment included an eDiluter, Zephyr ultra-low gas analyzer, iPEMS, electrical low-pressure impactor (ELPI+) for number size distributions, eDiluter particle measurement system, and an Exhaust-mass Flow Meter (EFM). Exhaust mass flow results was greatest for H_2. CO_2 emissions in g/kWh were lowest for H_2. CO emissions were also lowest for H_2, where the dashed line is the EU Stage V diesel emissions at 6.60 g/kWh. HC + NOx emissions were also presented for each fuel. Again, all engine low points are well below the standards. The theoretical particle size distribution for diesel is presented by particle number and mass, along with the typical diesel exhaust composition. Carbon makes up 41%, while unburnt oil is 25%, sulfate and water are 14%, ash and other is 13%, and unburnt fuel is 7%. LPG and DME both generate mid to high 10^4 particles/cm^3 (dlog scale). H_2 also generates in the low 10^4 particles/cm^3 range (dlog scale) but gives a bimodal distribution. Summary – In a single engine on a dynamometer, 3 different fuels were used: LPG, H_2, DME-blended LPG. Gaseous pollutants were orders of magnitude below the EU Stage V emission limits for spark ignition (SI) engines. There are no particle emission limits for SI engines. For H_2 combustion, there are different, bimodal particle number size distributions noted. Should we get rid of the EU 23 nm regulation? Should future regulations include particle emissions for SI engines?

Michelia Dam, CARB
"*Comparison of Braking Activity from Zero-Emission and Conventional Heavy-Duty Vehicles*"

This work presents an analysis approach to brake wear emissions in order to characterize braking activity for conventional and BEVs operating on-road in different vocations. California's mobile source programs have significantly reduced tailpipe air toxics and greenhouse gas emissions. A plot based on EMFAC shows that exhaust PM2.5 has decreased since 2015 with clean transportation in use, and is expected to continue declining, while *default* brake- and tire-PM2.5 emissions will continue or slightly increase. A prediction is shown for brake PM2.5 for clean transportation, which is expected to reduce friction braking since aero emission vehicles (ZEVs) are equipped with regenerative braking technologies. However, technologies and their benefits vary widely over vehicle type and vocation. The benefits of regenerative braking have not been fully characterized, especially for heavy duty vehicles (HDV). Two different approaches exist: on-road brake activity measurements versus brake dynamometer emissions measurements. A research gap is that there are no robust brake wear emissions for electric HDV, but have dynamometer measurements. In addition, brake wear emissions from HDEVs require further testing. The two types of data present the opportunity to improve characterization of brake wear and determine the emissions reduction potential from CARB's mobile source program. The research questions are (1) what type of data collection and analysis can be performed to understand the differences in braking activity for ZEVs and diesel vehicles, and (2) how can brake activity data be leveraged to support understanding brake-wear emissions? Drayage trucks were investigated for this study, including 14 BEV and 3 diesel vehicles, operated in the Ports of LA and Long Beach with OBD data logging with shorter duration and range routes and no driver training. Driving was slightly different for BEV versus diesel. An example of BEV braking is shown in which negative battery current means the driver has removed their foot from the accelerator but has not hit the brakes, i.e. regenerative braking is

occurring. A regenerative braking + friction braking event occurred in the second braking period, noted by the brake switch percentage shown. The third period is a friction-only braking period since the battery current does not become negative. Using this analysis for BEV drayage trucks, 54% of deceleration was attributed to auto regenerative braking, while 46% was brake switch on, i.e. applied braking. Brake-switch braking was further divided up into regenerative+friction and friction-braking only. During regen+friction braking periods, the percentage of friction brake being applied cannot be determined; having an additional readout such as brake pressure would help parse this out. A comparison of the braking duration for BEV and ICEVs shows that braking duration is slightly shorter for BEVs. Data also showed that auto regen occurred at slightly higher initial speeds for BEVs and higher powered braking is handled by the auto regen system which allows drivers to use brakes more gently. A correlation exists between particle number and mass emissions with kinetic energy using brake dyno testing, which suggests sensitive on-road testing is not necessarily needed because of this data. Summary – This is a moving target with rapidly changing technology, so understanding BEV braking activity is important to assess co-benefits of mobile source programs. There is a need for non-standard OBD parameters to assess braking activity, additional parameters to fully characterize regenerative braking periods, and location information to determine the areas of most braking impact based on frequency and power. Correlations between PN and PM emissions with kinetic energy can be supplemented with emissions measurements for EV's to reduce the gap in EV emissions measurements.

Elana Chapman, General Motors
"*Coordinating Research Council Sustainable Mobility Committee Program Overview*"

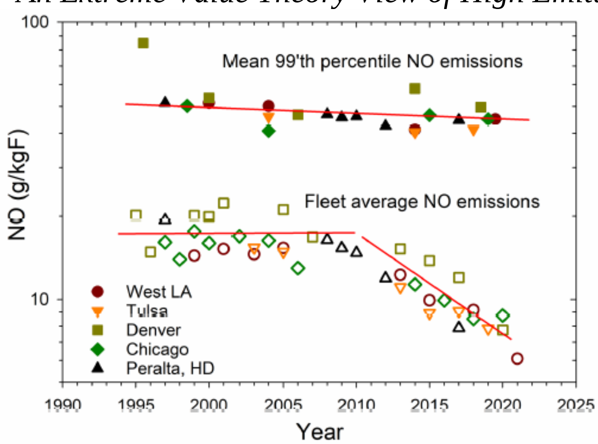
The CRC's mission is direct scientific cooperative research in developing the best possible combinations of fuels, lubricants, and equipment, and to afford a means of cooperation with the government on matters of national interest in this field. The CRC objectives are to be a focal point for cooperative pre-competitive research, to provide a forum for all stakeholders to participate in the research, and to make technical information available to stakeholders. CRC is expanding its research focus to include brake and tire wear, wildfires, electrification, hydrogen, and others. It is also expanding industry membership to include medium- and heavy-duty and nonroad, bio- and renewable fuels, electrification equipment, which includes new stakeholders. The vision of the Sustainable Mobility Committee (SMC), co-chaired by Elana Chapman and Heather Hamje, is given as well, which is focused on pathways toward a carbon neutral future and significant GHG reductions from mobility, while seeking to understand tangential impacts. The steering committee is shown with many industries represented and is open for new members. Partner members were presented as well and they meet frequently to discuss opportunities for collaborative research programs and to leverage their data. Some of the technical areas they work in include battery electric vehicles & equipment, grid readiness and resiliency, low carbon and sustainable fuels, aviation and e-fuels, energy feedstocks, air quality, infrastructure, carbon capture, life cycle analysis, etc. The SM-E Electrification working group's mission & focus are presented with links to recent publications SM-E-16, SM-E-18 / E-142, and SM-E-20. The SM-F Fuels working group has its first project published SM-1 and another recent publication SM-F-2 / A-134. The SM-HCR Hydrogen and Novel Carbon Reduction working group has recent publications including SM-CR-9 and SM-1. The SM-LCA Life Cycle Analysis working group has recent publications SM-LCAW 2023, SM-1, and SM-LCA-17. This group is continuing to look for partners. CRC Workshops & Technical Meetings are coming up in May 2025 and 2026 for Aviation and in October 2025 for Life Cycle Analysis of Transportation Fuels. The cost of membership in the steering committee is presented for charter members and funding members. Members and outside partners may also co-fund specific projects through in-kind or cost-sharing. All 14 current CRC Sustaining Members contribute $200k/year and one voting seat is recognized for each company. No single company will be accorded more than 25% of the voting seats. More information can be obtained at www.crcao.org. CRC benefits include synergy between industries and cooperative science, including independent, balanced results available to the public, program value of much larger size than individual contributions, expertise from peer researchers in a noncompetitive environment, and policies for intellectual property and compliance with antitrust regulations. CRC began in the 1920s with the Cooperative Fuels Research (CFR) Committee of the Society of Automotive Engineers (SAE) and has evolved to cover military research for aviation and vehicle performance, air quality with light-duty vehicle focus, and now takes on a global sustainability view. All CRC research projects follow the same process for Committee approval and review, regardless of how they are supported. The Advanced Vehicle/Fuel/Lubricants Committee co-chaired by Ivan Tibavinsky and Steve McConnell has 11 active projects. The Atmospheric Impacts Committee is co-chaired by Sandy Winkler and Chris Rabideau with 11 active projects. The Emissions Committee is co-chaired by Michael Moore and Paul Loeper with 15 active projects. The Performance Committee is co-chaired by Beth Raney-Pablo and Russ Lewis with 8 active projects. Links to Understanding CRC, Membership in CRC, Impact of CRC Research, History of CRC, CRC Organization, and CRC Events were provided in the slides and are included here.

SESSION 6: Emission Control Measures: I/M, OBD, Technologies and Strategies

Thomas Durbin, UC Riverside
"*Heavy-Duty Vehicle Inspection and Maintenance Program in California – The Clean Truck Check, CARBTest Referee Program*"

Heavy duty diesel vehicles (HDDVs) represented 52% of on-road NOx and 54% of on-road PM in 2020. CARB field testing showed that a malfunction indicator light was on for ~11-17% of HDDVs, suggesting maintenance or repair was needed. Senate Bill 210 directed CARB to develop a comprehensive heavy duty I/M program (SB210, Leyva, Chapter 5.5). The Clean Truck Check (CTC) Program for HDVs > 14,000 lbs is expected to be the most impactful CARB program in decades, with projected statewide emissions reductions of 81.3 tons per day NOx and 0.7 tons per day PM in 2037. There are many projected health and financial benefits over the time period 2023-2050. The idea behind the program is to provide independent evaluations of HDVs and services for vehicles with inspection incompatibilities or compliance issues. Vehicle owners would like their tests by a CARB-compliant facility, but with a third-party in nature. There would be a free testing assistance program for more complicated inspection cases. For pre-2013 vehicles there would be a smoke opacity inspection and for post-2013 vehicles there would be an OBD scan. It would also offer motorhome inspections. The organizational structure involves UC Riverside as the prime contractor and CSU Fresno as the subcontractor. Three regions of California are involved and 10 different referee sites throughout California. The initial CARBTest deployment involved several test sites, most of which are at community colleges including CCDET (California Council on Diesel Education and Technology). Photos of Phase I and Phase II CARBTest sites are presented with a map of SoCal locations, including UC Riverside CE-CERT, CSU Fresno, Rio Hondo, Santa Ana, Palomar, Miramar, Alameda, Bakersfield, Las Positas, and Sacramento. In addition, they will have a virtual tester through Zoom in which the person is directed to show their catalyst, etc. There is an online support unit to make appointments, answer questions, and view results, which are sent directly to CARB. It is aimed at reducing high emitters. The next steps are to complete the CARBTest referee network, to ramp up inspection (no provisions for avoiding full scans) as the CTC program continues to be fully implemented, and to integrate with the CTC-VIS website.

Matti Maricq, Forest Glen Consulting
"*An Extreme Value Theory View of High Emitter Trends from Roadside Remote Sensing Data*"



The motivation of this research is to evaluate the impact of high emitters on fleet emissions. This journey started with a question from a friend and colleague: Can extreme value theory be used to look at high emitters? Will be examining how high emitter emissions have changed over time and how well have regulation policies addressed high emitters. Extreme value theory defines a high emitter as the max of a sample of n vehicles, e.g. if n=100, it is the 99th percentile emitter. A random sample is taken e.g. for CO emissions, and the maximum is found, then another sample is taken and repeat. For large n, the Fisher-Tippett theorem states that the maxima will follow an Extreme Value Distribution that is independent of the population distribution. The normal way of discussing is a standard cumulative distribution function of probability versus emission level. Instead, switch the axes: probability is plotted on the x-axis as its inverse natural log, and the y-axis is the emissions level not exceeded by any vehicle. An example is provided for CO exceedance levels from gasoline vehicles from 1999 to 2021 in West Los Angeles. The curves plotted for earlier years 1999-2018 have convex shape while 2021 is more linear or curved upward instead. The plots are similar for hydrocarbons, with 2005-2021 curving upward. Next looked at NO from gasoline vehicles, but in this case, there was not much difference from 1999 to 2021. Now take 100 as the group size and look at the mean 99th percentile. For gasoline vehicles high CO emitters trends, there was a ~3-fold decrease in high emitter emissions versus 6-fold for the fleet average. Tulsa, OK has never had an I/M program, but the other cities (Chicago, Denver, West LA) have I/M programs. Chicago shows a lower improvement likely due to a newer fleet. Similar plots for HC and NO show that there was little high emitter improvement over ~25 years. Tulsa (no I/M) trends are the same as the other cities with I/M. Now add heavy duty vehicles (black diamonds, slide 10) and it is difficult to distinguish them from the others once scaled by fuel usage. Fuel-based LD and HD emissions are similar. CO and HC fleet average emissions show continuous decline, while high-emitter CO and HC have similar decline in Tier 1 but remain flat for Tier 2 and 3. Finally, looking at NO, 2010 diesel regulations improved the fleet average but had no impact on the high emitters. Summary – There are no differences between cities with I/M versus no I/M. Tier 1 led to reductions in gas and diesel high-emitter CO and HC emissions. Tiers 2 and 3 and 2010 regulations had no statistically significant impact on high emitters, except for gasoline vehicle CO! OBD does not appear to impact high emitters. This research is published by Maricq and Bishop (2025).

Yang Li, Cummins Corp R&T
"*Emission Measurement with NOx Sensors in the Presence of HC's and H_2*"

On board monitoring relies on the vehicle's sensors to continuously monitor for emissions compliance, system repair, or fleet emissions inventory measurement. NOx sensors measure both O_2 and NOx but can be cross-sensitive to several species on each channel. This study characterizes and discusses NOx sensor cross-sensitivities to various reducing agents in the context of stoichiometric CNG engines. It is well known that they have cross-sensitivity on their NOx channel to NH_3. For stoichiometric-ICE applications both NOx (lean) and NH_3 (rich) may be present. The proposed method is to use the oxygen signal from the NOx sensor to determine between when the NOx channel is responding to NOx vs NH_3. Questions for this study: What species or factors impact the sensor's O_2 readings that may negatively impact this ability? Is the sensor's NH3 cross-sensitivity consistent across both rich and lean operation? Are there any situations in which you will have the simultaneous presence of NOx and NH_3, or NOx when it is rich and NH_3 when lean? Are OEM and aftermarket NOx sensors capable? Methods – Sensor Exerciser and Test Instrument, SETI. Will test up to 9 sensors at a time with reference instruments including FTIR, O_2 analyzer, NDUV (NOx), thermal and Coriolis MFCs, humidity and pressure sensors. Two HC mixtures were tested: Mix 1 has 1% CO, 3000 ppm H_2, 3000 ppm CH_4, and 0 ppm NO, at 150°C. Mix 2 has no CO and no H_2, but has 2200 ppm CH_4, at 350°C. The concept of "Net O_2" is introduced, which is the O_2 concentration less the concentration of reducing agents as considered based on the amount of O_2 needed to fully oxidize said reducing agents. The OBD NOx and O_2 sensors are designed to measure "Net O_2", not O_2 concentration. When "Net O_2" is 0%, this is considered to be the stoichiometric condition. "Rich" conditions are defined by "Net O_2" <0 and lean conditions are >0. O_2 channel accuracy testing had multiple points for each sensor at each "Net O_2" condition. Sensors with technology A, B, C technology are showing a negative bias up to -1.1%, while sensor D technology shows a different trend. For mix 1 there is an error with one sensor's readings. The NOx sensors are under-reporting the O_2 level and they read rich when it is lean. For mix 2, H_2 has high diffusivity and could cause a bias. The NOx sensors are slightly under-reporting the O_2 level and could distinguish rich vs lean. Sensor suppliers also tested HC mixtures. Schaeffler used fixed concentrations of C_3H_6 with variable O_2, CO, and H_2 and found that the presence of the heavy molecule C_3H_6 might be the cause of an observed lean bias under some conditions. NOx channel sensitivity to NH_3 was variable with O_2. The NOx sensor's NH3 cross-sensitivity dropped off as Net O_2 crossed zero. Summary – Found that sensor's O_2 readings are particularly impacted by H_2 which induces a rich bias under both truly rich and truly lean conditions. If H_2 is present under lean conditions, it could lead to NOx values to be erroneously associated with NH_3

emissions. There is also possible positive drift caused by slower molecules like C_3H_6 (Shaeffer's method). The method considered for NOx monitoring on stoichiometric applications may have issues under some conditions while working fine under others. Next steps include getting a better understanding of the real-world H_2+HC+CO concentrations at the tailpipe for both healthy and degraded systems. The NOx sensors are electrochemical sensors, so a plan is to characterize alternative technologies.

Day 3 – Wednesday, April 16, 2025

SESSION 7: Emissions Modeling

Cynthia Yañez, CARB
"*An Overview of EMFAC2025 Updates*"

EMFAC2025 will be released next month. EMFAC is our official inventory of California's on-road vehicle activity and emissions. It is based on (1) vehicle population by model year, age, fuel type, and class with data from the DMV, IRP (International Registration Plan), Ports, and ALPR (Automated License Plate Recognition); (2) vehicle miles traveled and other activity data with data from survey & smog check, odometer data, real world data logger studies, and fuel sales; and (3) emissions inventory including on-road CO_2, NOx, ROG, CO, NH_3, CH_4, PM, N_2O, SOx emissions for different processes. An inventory of greenhouse gases is produced and includes non-exhaust emissions such as tire wear. EMFAC is used by many agencies and research institutes, and is updated every 3-4 years based on vehicle activity datasets. EMFAC will always include the latest regulatory measures. There are many updates not provided here, but highlights are provided. Emission rates using chassis dynamometer and PEMS tests have been updated to incorporate the latest data for light- and heavy-duty vehicles. Emissions from classic vehicles are now included for vehicle ages 45 years and older, and it is now considering VMT and emissions at speeds >70 mph. Other major updates include ZEV adoption using a collaboration with LBNL (#22AQP010). ZEV are not being adopted uniformly across the state, so those counties with more ZEV are now included. Additionally, new vehicle sales are included using a contract with UCSD (#21AQP018) to consider the economics, regulations, and VMT to project new car sales. Previously it used an economic consideration, but now the interactions between the new and used markets are being incorporated. The model takes VMT into consideration and is also mapping truck activity. Previously, they used DMV registration data and an assumption of where they were operating in the state, but new real-world data allows knowledge of where the activity is actually happening. This accounts for those who register in a different location than they operate. There are new regulatory measures for light-duty vehicles that will be taken into account. For heavy-duty vehicles, the Clean Truck Check Program, which requires periodic testing, the Federal Clean Trucks Plan, and the Phase 3 GHG rule, which increases the stringency of GHG standards for HD vehicles starting in model year 2007, will now be incorporated into EMFAC. The Advanced Clean Fleets program requires ZEVs to be phased into targeted HD fleets. Statewide results are presented that compare the draft EMFAC2025 with EMFAC2021. The VMT is expected to be lower than for 2021 because there is a lower human population forecast in CA. For medium- and heavy-duty vehicles, the methodology remained the same and the CalTrans forecast is still used to model VMT. Vehicle population has been updated based on vehicle population. In the fleet fuel mix, electric is expected to make a higher contribution. Similarly, for medium- and heavy-duty, fuel cell and electric will become a higher contribution. NOx emissions for light-duty vehicles increased due to the updated speed correction factors and age 45+ vehicles, but are expected to be reduced in the future ~2030 from the impact of ACC II (Advanced Clean Cars program). NOx emissions for medium- and heavy-duty vehicles are expected to decrease from the impacts of the CTC, Federal Clean Trucks Plan, ACT and ACF programs. PM2.5 emissions for light-duty vehicles are expected to decrease in the future due to the impact of ACC II. PM2.5 emissions for medium- and heavy-duty vehicles are expected to decrease in the future as well due to the CTC, Federal Clean Trucks Plan, ACT, and ACF. ROG emissions for LD vehicles are impacted by age 45+ vehicles in 2000-2035, but are expected to decrease near 2040. ROG for medium- and heavy-duty vehicles are decreased from 2000-2050 due to updated Class 2b-3 emission rates and impacts of ACT and ACF. For CO_2 emissions, there is a big impact of ACC II for LD vehicles and a big impact of ACT and ACF for HD vehicles. All medium- and heavy-duty emissions predictions exclude drayage and high-priority fleet requirements. The next steps for EMFAC2025 is that its final version is expected in early May 2025. The release of EMFAC technical documentation and submission to the US EPA for approval is expected in Summer 2025. EMFAC can be accessed at https://arb.ca.gov/emfac or previous year models at https://ww2.arb.ca.gov/our-work/programs/msei/on-road-emfac.

Megan Beardsley, US EPA
"*MOVES5 Updates and Result Comparisons*"

MOVES, the Motor Vehicle Emission Simulator, is EPA's model for estimating air pollution emissions from cars, trucks, motorcycles, buses, and some non-road equipment, used by US EPA, states and local governments and others. The focus of the presentation is what has changed in MOVES5 compared to 4. MOVES5 now accounts for EPA's light- and medium-duty multi-pollutant rule. The rule is more stringent for CO_2, PM, and NMOG, so we expect to have more EV in the projected fleet. MOVES5 also now accounts for EPA's Heavy-Duty Greenhouse Gas Emissions-Phase 3 Rule, which is also more stringent for CO_2. Energy consumption values for heavy-duty EVs have also been updated. Another improvement was with brake wear: For model years 2011 and later, MOVES5 incorporates new data from a light-duty brake dynamometer and a heavy-duty data set from Caltrans, both of which have been presented in previous CRC RWEW (2023 & 2024, see slide 5). PM10 / PM2.5 ratios have been updated in MOVES5 based on these studies. The current MOVES5 Brake & Tire Wear report shows how brake and tire wear were treated. Fuel properties have been updated: In MOVES4 and earlier, gasoline properties were primarily based on volume-weighted fuel production information. In MOVES5, there is data from the gas stations themselves (see poster from Aron Butler from this workshop for more detail). Biodiesel content and sulfur content has also been updated. For more information, refer to the MOVES5 Fuel Supply Defaults report. The age distribution of vehicles has been extended to do calculations for vehicle ages 0-40+ years, which better quantifies emissions from vehicles in the 31-40 age range compared to MOVES4, which reflected ages 0-30+ years. The change allows pre-OBD vehicles and is a big improvement in the model. With each update updates to VMT and the population of vehicles using inputs from FHWA and the Energy Information Administration. Updates to national default source type, fuel type, regulatory class and age are from 2023 vehicle registration data, EV sales forecasts consistent with new GHG standards, and increased E85 fuel usage. Other changes to MOVES5 include updated NH_3 emission rates for CNG vehicles, updated program details for state vehicle

I/M programs, updated global warming potentials, and improved MOVES user interface, among others. Emission graphs include national comparisons presented in log space and county comparisons with the same local inputs used as in MOVES4, except for fuel mix (with new standards reflected in MOVES5) and vehicles 40+ are now included. National on-road NOx shows that MOVES5 has slightly higher NOx than previously and that in the future NOx emissions are lower. The county example for on-road NOx is shown with both MOVES4 and 5 already including the heavy-duty NOx rule (HD2027). The detailed accounting of ages 30-40 vehicles causes higher NOx pre-2040. National on-road PM2.5 includes brake and tire wear emissions, in which brake wear continues to dominate future on-road PM2.5 emissions, even more so with MOVES5. National on-road exhaust CO_2 shows big improvements with MOVES5. Improvements are seen on the county scale as well, especially in later years. The MOVES5 Overview Report includes graphs for on-road comparisons of VMT, gases and particles with sample county graphs. It also includes non-road national SO2 comparisons and gas and particle summary graphs. MOVES versions can be downloaded from the website and questions can be emailed to mobile@epa.gov.

Lucas Algrim, CARB
"*Updating LD VMT Speed-Distributions and Speed Correction Factors in EMFAC2025 to Better Capture Emissions of High-Speed Driving*"

In the CARB surveillance test plans shown, Freeway Cycle 7 has an average speed of ~73 mph, the highest speed being measured for emissions factors. Telematics data recently showed that over 25% of VMT is driven at 70 mph or faster (if you have driven in CA you well know this!). EMFAC2021 used VMT data from Metropolitan Planning Organizations (MPO) in each geographical area, which cut off after 70 mph and may overestimate the fraction at lower speeds. The statewide distribution as a function of speed bin is bimodal, but the lower speed mode is not observed in all areas. The goal is to update the light duty NEI speed distributions. Also see the poster by DenBleyker et al. One data source was the NEI Streetlight dataset, using only Jan and Feb 2020, with the top speed bin of 75 mph. A UC Davis datalogging study (CARB Contract 12-319) was used to provide 200+ vehicles for 1 year in which the top speed bin is not limited. The resulting LD NEI dataset maxes out at the 75-mph high-speed bin so there was a need to adjust the high-speed tail. The high-speed mode at 75 mph decreases by 90 mph for county-level and the statewide average, based on the UC Davis dataset. The next aim was to generate LD high-speed emissions data to improve EMFAC2025. For this, all relatively new model year vehicles, 2015-2013, were used and the freeway cycle was adapted to include average speeds of ~80, 90, and 100 mph (Freeway Cycles 8, 9, & 10) for 2024. The 10 vehicles tested are included in emission factor updates and had a range of mileage. The updated speed correction factors led to higher hydrocarbon and NOx in the higher speed bins for the 10 vehicles tested relative to EMFAC2021. There are increases at lower speed as well, but the higher speeds had been a flat line with EMFAC2021. Addition of the 10 vehicles test results gives much larger emissions, especially for CO. CO_2 is also increased by adding the 10 vehicles. A comparison of EMFAC2025 in default mode versus EMFAC2025 with SIP/MPO, i.e. with the LD vehicle emissions updated from the high-speed results, is provided with CO on a separate scale since it is so much higher. ROG, PM2.5, NOx, CO_2, SOx are shown. All else equal, ROG will be 15% higher and NOx will be 6% higher from LD vehicles when used for SIP and transportation conformity. There are plans to incorporate the High-Speed Program in EMFAC2025 for release in April 2025. Future work includes testing 20 more vehicles to total 30 vehicles by summer

2026 for the next EMFAC version, and to test a wider range of vehicles, high-speed cycles, and levels of acceleration. The policy implications are that increased emissions must be accounted for in future air quality and transportation planning processes. To reduce emissions at high speeds, will we need more stringent certification processes, better enforcement or speed limit reductions, more ZEVs on road? The vehicle population with an updated high speed SCF (speed control function) is shown to increase to over 85% of the population by 2034.

Yejia Liao, UC Riverside
"*Enhancing Air Quality Impact Assessment of Freight-Related Emission with Large-Scale, Real-World Truck Activity Data*"

Inland Southern CA is impacted by increasing HD trucks on roads and highways, creating public health concerns for local communities that experience high NOx and PM2.5. The goal is to develop an integrated air quality model to assess and predict freight-related air quality across the Inland Empire (IE). The workflow to generate on-demand traffic can be summarized into 3 major groups. The second portion uses real-world truck traffic data. The final piece is using traffic volume data in the IE. In the method proposed to generate accurate truck trips, truck OD was extracted from Southern California Association of Governments (SCAG) and Geotab data was leveraged to refine the truck trips. Finally, real-world truck-related facilities were used to locate the warehouses. Step 2 is a truck demand visualization presented for 9 am to 9:10 am showing the hotspots. A traffic simulation using BEAM which is a mesoscopic simulator is also shown to convey major traffic routes (BEAM = Behavior, Energy, Autonomy, and Mobility simulation platform developed by the Lawrence Berkeley National Laboratory). Simulations were compared to real-world traffic data using PEMS. For the I10 east and west, the Groundtruth and simulated traffic volume are shown to compare well. With the traffic model, the next step is to develop a regional traffic emission inventory. Vehicle emission modeling using data from EMFAC, BEAM simulations, and PeMS outputs. A visualization of link-based PM2.5 is shown at 9 am with red conveying higher PM2.5 levels from 0.9 to 4 ug/m3. Geotab stop analysis shows that Long Beach and the surrounding areas have a longer duration for truck idling. A similar visualization is shown with elevated NOx emissions in the same locations. Combined results for traffic and idling (running and idling vehicles) shows that emissions are higher along the highest traffic roadways. To model the air quality in other locations, WRF-chem was used to capture the weather patterns and real-world traffic emissions used for simulations. To enhance accuracy, the Shape Constrained Additive Model (SCAM) was used to ensure monotonicity. Results show that model predictions versus observed NOx plots capture the diurnal variation. PM2.5 is harder to predict with low uncertainty as there is less Groundtruth data and complex secondary PM2.5 involved. Conclusions – A high-resolution, data-driven framework was developed to model freight related emissions and air quality impacts, with real-world truck telematics integrated for inland Southern California. It was found that idling contributes 40% of NOx emissions, despite being only 1% of PM2.5 emissions. The framework bridges the gap between traffic, emissions, and air quality modeling and provides insight for freight policy and exposure mitigation.

Rodolfo Souza, Texas A&M Transportation Institute
"*Development of Texas-Specific Drive Cycles for Electrical and Conventional Vehicles Using WEJO Data*"

Drive cycle is an important input for MOVES emission estimates. Current drive cycles from 1990 to 2013 may not fully represent local patterns, so connected vehicles data will be used to address this and define specific cycles. WEJO data contains several parameters, including speed, timestamp, heading, ignition status, vehicle class ID, and others. The majority of vehicles are light-duty and data from Dallas-Fort Worth area were used from Sept 18-25, 2022. To process the data, trips were filtered where data was captured with a 1-second time interval. Data privacy was obeyed by removing coordinates, and road functional type was matched with the MOVES database. Trips were classified into 34 categories based on urban or rural area, MOVES road type, and average speed binned from 0 to 60+ mph. For each group, the vehicle specific power (VSP) was calculated and the operate mode was defined as a function of VSP and vehicle speed. For the internal combustion engine, there are high numbers of trips on certain paths. Comparison of MOVES to Texas-Specific drive cycles shows that more stops are observed for the Texas-specific drive cycle. Vehicle speed impacts the emission estimate process in that low speed (<20 mph) increases emissions. Emission rates sharply decrease after the vehicle starts moving, but again increase above approximately 40 mph. Comparison of the default drive cycle to the Texas-Specific drive cycle shows that CO increased by almost 6%, while PM2.5 and PM10 increased by ~3% and NOx and VOCs changed by <1%. The small changes can add up. Another topic was EV drive cycles: the vehicle type ID in WEJO data includes EVs. Data are needed that capture an interval of >1 second; speed interpolation methods were tested for using 1 second data from IC engine. Comparing an EV drive cycle to IC engine shows that EV trip duration is longer than IC engine and EV average speed is higher. EV operating mode 30 is almost twice more often than IC engine. Operating mode 30, defined by $30 \leq VSP$ and $25 \leq speed \leq 50$, has one of the highest energy demands and has the highest emissions. A plot of output power versus operating mode is shown and can be found in an EPA presentation. Summary – Texas-specific drive cycles were successfully developed using real-world connected vehicle data and showed differences from the EPA MOVES defaults, especially in average speeds and stop rates. Flexible filtering allows segmentation by hour, day, vehicle type for targeted applications. The approach enhances emissions modeling and supports transportation planning to enable data-driven policy.

Jaehoon Han, US EPA
"*Development of a Research Tool to Estimate Emissions Inventory Impacts of Tampered Heavy-Duty Diesel Vehicles*"

This presentation focuses on a "research-grade" analysis tool that could estimate emission impacts of tampered heavy-duty diesel vehicles. Tampering is defined as "intentional" disabling of vehicle emission controls, as opposed to mal-maintenance and normal deterioration. EPA is currently developing tools to identify high-emitting HD vehicles and quantify their emissions impacts. EPA's Office of Enforcement and Compliance Assurance (OECA) reported on tampered diesel pickup trucks in a Review report. OECA estimated that about 15% of class 2b and 3 diesel pickup trucks have undergone tampering based on sales of software and hardware that "tune" vehicles to defeat emission controls, with observed sales varying by state. The goal is to allow "what if" analysis for various tampering frequency scenarios to work with MOVES5. The tool is a "research grade" tool only and will not be part of MOVES or approved for official use. The scope of the tool was defined to cover several classes of MD and HD diesels, NOx, PM, HC, and CO pollutants for running and crankcase running, HC and PM extended idling, and model years of 2007 and newer. There are several important assumptions presented, including that while based on older data, existing MOVES estimates of emission effects from emission control malfunctions are reasonable, and that some malfunctions are likely caused by tampering, and some are the result of mal-maintenance. Tampering causes several failures, which are discussed in EPA-420-R-24-015, Appendix B. One additional step taken is to categorize intentional versus unintentional tampering. For a full-delete tampered vehicle, it is assumed no other malfunctions are relevant. Comparisons are given for the MOVES5 Case of default rates to the Tampered Case, which assumes 100% tampering frequency input for model years 2007 and newer (note log scale in slides). The general trend is that tampered vehicle emissions of 'NOx Running' are much higher, and the increase generally becomes much larger for newer model years. In 2027 there is a sharp drop in the MOVES5 emissions due to Clean Trucks regulations. Tampered vehicle elemental carbon running emission rates are also much higher than MOVES5. Tampered vehicle non-elemental carbon running emission rates are similarly much higher than MOVES5. Summary – Additional research is needed to understand the emission impacts of tampered HD diesel vehicles. A potential "research-grade" analysis tool could provide rough estimates of emission impacts of tampered HD diesels. The plan is to make a beta version for external testing with user documentation and to obtain feedback.

SESSION 8: Non-Exhaust Emissions

Seungju Yoon, CARB
"*Mobile Source Non-Exhaust Emissions (NEE): Research Needs for Regional Air Quality, Community Exposure/Health Effects, and Greenhouse Gas Emissions in California*"

California's strict tailpipe standards have reduced exhaust emissions and brake- and tire-wear emissions, which have potential adverse health effects, have increased in relative importance. Based a plot showing proposed EMFAC2025, VMT will continue to increase but exhaust PM2.5 will continue to decrease. Brake- and tire-wear PM2.5 sources have always existed, but are becoming more important to consider. The focus of the presentation is on three main questions about NEE: *Question 1* – What will be the impact of particle and gaseous non-exhaust emissions on regional air quality? Work is in progress to characterize emission factors for primary PM and gases emitted from tires and obtain emission factors for mobile source inventories. One goal is to understand if these gases will lead to secondary PM formation and carry out regional air quality modeling with chemical speciation profiles of secondary PM. The gas component from brakes and tires was not included in the brake wear / tire wear (BWTW) impact between 2016 and 2028, so the inventory must be updated for these species. *Question 2* – What will be the potential adverse health effects and near-road community exposure to non-exhaust emissions? A quantitative understanding of the compounds emitted is needed to examine the exposures and health effects in communities. A plot is presented that shows that the more disadvantaged communities have the highest PM2.5 mass, OP^{OH}, and OP^{DTT} relative to the average, and was published in Shen et al. (2022). One goal is to examine opportunities to reduce exposure through future clean transportation and community air protection programs. *Question 3* – What will be the effect of clean transportation-greenhouse gas programs on non-exhaust emissions? The clean transportation programs provide co-benefit opportunities such as regenerative braking and tire reformulation technologies. Brake-wear PM for EVs is 50% lower than conventional vehicles based on representative brakes and tires. Research needs include to continue to characterize NEE particle and gas emissions, to characterize cleaner vehicle

technology advancements, and to promote innovative transportation technologies that maximize recuperation of braking energy, lighter vehicle weight with higher energy density batteries, less toxic friction and tire-additive materials, and changes in driving behaviors. CARB's current projects are summarized beginning from 2017 to completion in 2028 to convey the search for collaboration with multiple agencies. Projects include brake-dyno tests for LDV, HDV and LDEV, health impacts of brake and tire PM, roadside NEE measurement, on-road measurement of non-exhaust PM, gaseous tire-wear from on-road vehicles, train activity NEE, off-road NEE, health impacts of BWTW in the San Joaquin Valley, and ZEV brake-wear characterization. Summary – Stricter regulations have reduced exhaust emissions substantially, leaving non-exhaust emissions to form a larger fraction of the remaining vehicular PM emissions. The NEE research areas are (1) impacts of particle and gas NEE on regional air quality; (2) potential adverse health effects and exposure to NEE for near-road communities; and (3) effects of clean transportation-greenhouse gas programs on NEE. CARB is always seeking collaboration with research, industry, and governmental partners.

Elizabeth DeFrance, UC Riverside
"*Light-Duty Vehicle Tire-Wear Particle Emissions*"

A plot of PM10 from various MOVES3 sources shows that the relative contribution of brake and tire wear emissions are increasing while exhaust emissions are decreasing and the trend continues out to 2050. There are three phases of this research on tire wear, with Phase 1 as the focus here. Phase 1 includes a funnel system to understand particle number generation mechanisms. Phase 2 will develop a fully-enclosed sampling system and pilot test on a chassis dyno and Phase 3 will include on-road testing with this system. Phase 1 included a laboratory tire sampling system with a funnel to collect particles near the tire on a chassis dynamometer. Volumetric and temperature flow measurement was based on the exhaust flow meter (EFM) module, HR ELPI+ was used for real time PN measurements, and Toxic-Metal Aerosol Real-Time Analysis (TARTA) was used for real time metals. Temperature was measured over the entire surface of the tire. Particle loss evaluation was carried out by introducing soot using a mini-cast soot generator with evaluation of particle loss at 0, 30, and 60 mph. There was impaction occurring at the funnel inlet that led to large losses in the <2 μm range with a strong effect of vehicle speed. In experiments, original tires with >70,000 miles and brand-new tires were used with recommended pressures ±25% (corresponds to a range of 26-44 psi, where a warning would light). Test cycle US06x4 was used. Increases in tire temperature were also studied throughout the cycle. For the original tires with different pressures, the temperature profile over the tire was the same, although it was expected that the underinflated tire would show warmer temperatures at the outside of the tires. Temperatures for the new tire were similar. Particle size distributions for the original (used) tire showed that particles were generated with 11, 45, and 120 nm modes. Interestingly, the original tire used at the recommended pressure has a stronger peak in nucleation mode (11 nm), while the under- and over-inflated tires gave less particles in this mode. The new tire has an additional peak at 300 nm. Under-inflation by -25% slightly increased particle concentration, which was expected since more surface area touches the dyno for under-inflated tires. The effect of temperature on the size distributions was presented for temperatures ≤ 50°C. Similar size modes were observed with peaks at ~11, 45, 120 nm for the original tire and the additional mode at ~300 nm for the new tire with similar effects of pressure as before. For temperatures >50°C, much higher particle concentrations were observed! Real-time size distributions showed that the recommended pressure for the original tire has smaller particles. For the new tire, -25% under-inflated gives higher particle concentrations, suggesting more friction on the tire itself gives more small particles. Metals from the TARTA instrument show high Fe, Zn, Cu, Ni, and Mg. The original tires have slightly higher metals relative to the new tires; original tires were driven on-road for a little while so the metals may have influence from road dust. Summary – Increased temperature and age of tire increase PN emissions. Elevated PN emissions were seen during decelerations and were a function of driving duration and temperature. Increased emissions for tire under-inflation were observed from the new tire only. The new tire had higher levels of Mg. The original aged tire had higher metal emissions for most metals, while the new tire had higher levels of Mg.

Okjoo Park, CARB
"*Characterizing Non-Exhaust Emissions from Conventional and Electric Vehicles over Chassis-Dynamometer Test Cycles*"

Significant progress has been made in exhaust PM emissions, but there are growing concerns over non-exhaust PM emissions, including brake-wear (BW) and tire-wear (TW). There is a considerable knowledge gap including the impacts on non-exhaust emissions of driving cycles, brake and tire technologies and materials, and regenerative technologies. It is not known how the heavy weight of EVs will impact PM. The goal of this research is to measure BWTW PM emissions in the Running Loss - Sealed Housing for Evaporative Determination (RL-SHED) for gasoline and electric light duty vehicles. Refer also to the poster by Ma et al. The testing facility RL-SHED has a 4-wheel chassis dynamometer with a 48" roll, 4 wheels x 2 motors. There are two measurement stations, one near the brake pad, one behind the tire. Real-time instruments for particles included DustTrak, APS, CPC3776, and EEPS, spanning ~2.5 nm to 20 µm. A thermocouple was installed for brake pad temperature, and the brake pad was weighed for reference. Several brake cycles were used, including NYCC (New York City Cycle, low speed stop and go), US06 for high acceleration and aggressive driving, and FTP for city driving. The test vehicles included 2022 and 2023 model years, with two gasoline ICEVs and one compact BEV. Brake pads included one semi-metallic and two ceramic. Real time data samples show that brake temperatures for the ICEVs reach almost 200°C, while the EV brake pad temperature stays at 50-60°C. The test cell is a sealed housing so the ambient temperature is controlled outside the housing. Vehicle 1 with semi-metallic pads was the lightest weight but emitted the most BW particles. Measurements at position 2 had particles being generated from behind the tire as well as from brake wear, and the trends at position 2 are similar with vehicle 1 emitting the most BWTW particles. The semi-metallic brakes on vehicle 1 lost more mass, consistent with the higher particle emissions. A comparison of vehicles showed that the BEV had much lower PM and PN emissions, despite the heavier vehicle weight relative to the ICEVs.

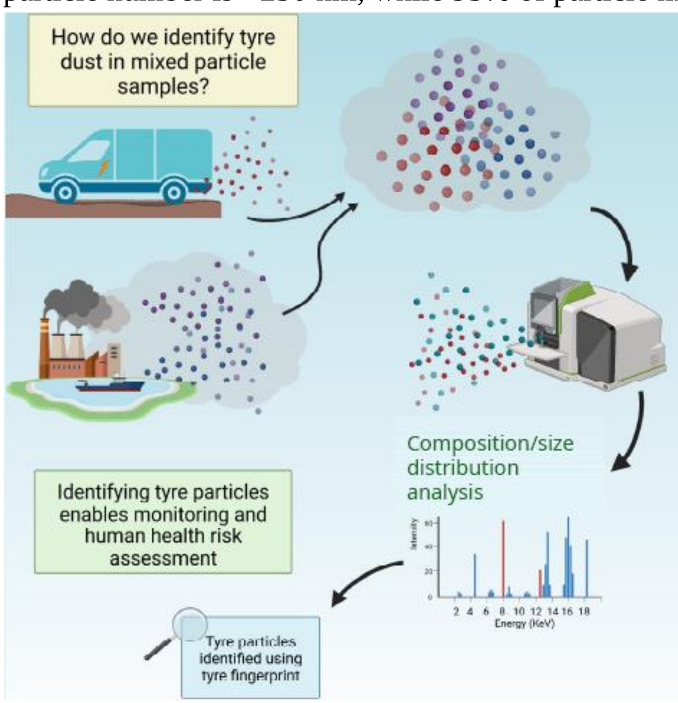
A comparison of PM2.5 and PN for different drive cycles showed that the EV had higher BW and BWTW emissions when running the US06 drive cycle. Summary – Brake- and tire-wear emissions measurements were taken at the RL-SHED. Semi-metallic brake pads emitted much higher PM than ceramic pads, even on a lighter vehicle. The BEV had substantially lower PM emissions compared to ICEVs, despite its heavier weight. This is due to regenerative braking that was applied almost exclusively during the NYCC and FTP cycles. Friction brakes were used occasionally during the US06 cycle, contributing to the majority of PM from the BEV. Future plans include additional vehicle testing, including an ICEV, HEVs, and BEVs of different weight categories.

Véronique Perraud, UC Irvine
"*Identification of Organic Volatiles as Specific Markers from Brake (and Tire) Wear*"

Our team is interested in characterizing the organic material from brake wear, and tire wear in the near future. A custom brake dynamometer was built in which light duty passenger vehicle brake pads are installed. A lathe spins the rotor at an effective speed of 18 mph with a caliper and brake pads installed on the rotor. One of the major components in brake pads is phenolic resin, an organic compound that may decompose during braking. Braking is carried out in two regimes: lighter and heavier braking are carried out with torques and pressures in the range of typical braking with on-off braking cycles presented. Both ceramic and semi-metallic brake pads are studied. Gases are measured with a number of online and offline techniques, including PTRMS, I-CIMS, whole air canisters, and sorbent tubes. Particles are also measured in a range of diameters, also with online and offline methods including TDCIMS, SMPS, APS, AMS, and filters for UHPLC-orbitrap MS analysis. The braking regime 1, lighter braking, shows a temperature rise and an increase in particles with sizes of 1 μm and higher from friction. Regime 2, heavier braking, brings on a lot of organics at the higher temperatures which nucleate new ultrafine particles. PTRMS spectra indicate a number of nitrogen-containing VOCs as shown by the even-m/z peaks. There are many nitriles identified from PTRMS and whole air canister analysis that may be markers for brake wear, with ceramic brakes producing the most N-species compared to semi-metallic pads. Details can be found in Perraud, Blake et al. (2024). A second feature of the mass spectra is phenol and derivatives, which are likely from the decomposition of the phenolic resin present in brakes. The poster by Rojas et al. has additional details on phenolic resin thermal degradation from braking. In addition to organics, inorganic reactive N-containing species were emitted during braking with both ceramic and semi-metallic pads, including nitrous acid (HONO), which is an important atmospheric trace gas. HONO is believed to be formed from chemistry between unsaturated VOCs and NO_2 in the hot plume emitted during braking. Trace amounts of $ClNO_2$ and N_2O_5 were also generated, and details are found in Cooke et al. (2025). High resolution aerosol mass spectrometry was used to measure ultrafine particle composition and indicates that there is a substantial fraction of N-containing compounds found in the particles also, ~18-19% for both brake pad types. Offline ultrafine particle composition analysis shows that a nitrogen-containing compound, dicyclohexylamine (DCHA), was identified and confirmed using LC-MS and comparison with a standard. Preliminary results from a field campaign at the I-5 in Santa Ana in Dec 2023 are shown in which DCHA was measured and found to correlate somewhat with I-5 freeway VMT and reduced vehicle speeds. DCHA was identified in brake pad heating-only experiments, in phenolic resin heating experiments, and in the field measurement, suggesting it may be a promising marker for brake-wear. Summary – High concentrations of VOCs are emitted from brakes, especially during hotter, heavier braking conditions. The VOCs likely originate from thermal degradation of phenolic resins and other proprietary organic fibers in brake pads. N-containing compounds including nitriles and DCHA may be ‘tracers’ for brake wear in ambient measurements. HONO was measured in brake emissions! Future work includes organic chemical characterization of brake pad linings, secondary chemistry from brake emissions, and analysis of a second field study at the AQMD site near the I-710 freeway. Additional studies on brake wear particles were published by this team as Thomas et al. (2024).

Adam Boies, Stanford University
“*Tire and Road Wear Nanoparticle Emissions: Where Do They Come From and How Many Are There?*”

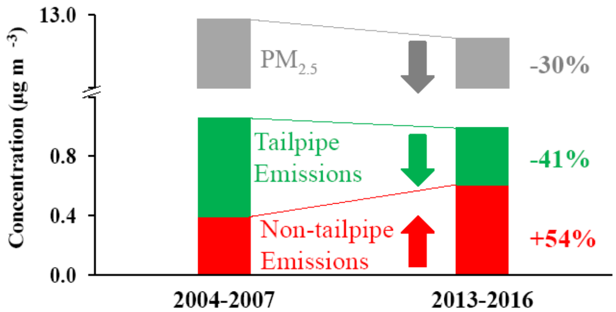
The focus of this presentation is on tire wear components. An evaluation of tire and brake wear signatures was carried out under UK NERC funding, published as O’Loughlin et al. (2023), in which ~100 vehicle tires were studied and the chemical signatures found were similar to existing literature. The 2021 study examined vent spews using ICP-MS. There are often signatures of some tires, for example the low-cost tire has higher Mg. Another study was carried out measuring nanoparticles from tire and road interactions, published as Haugen et al. (2024), to distinguish between emitted tire nanoparticles and road particles through composition and size distribution analysis, in which tyre particles are identified using a tyre fingerprint. 95% of particle number is <250 nm, while 95% of particle mass > 1 micron. Some of the particles are solid, but >70% are semi-volatile, making tire emissions analyses more complicated. High emitting events contribute more larger particles than nanoparticles. The standard procedure is to introduce particles to understand where the wear comes from. The mass-based distribution is dominated by larger particles, which is not surprising. The nanoparticle concentration decreases when a catalytic stripper is being used. The final analysis has been on where tire emission measurements came from. A reanalysis paper was published on exposures and emissions, Saladin et al. (2024). The early emissions estimates in MOVES and other EPA work has largely increased over the years which is surprising because the literature shows that it has decreased. There are errors in the literature that were tracked back to one paper that was wrong by a factor of 200 times. The next steps are to distinguish tire and road wear through tracer species. One goal will be to change the road surface and keep the same tires to distinguish chemical signatures from asphalt versus concrete. Another goal is to determine the emission factor using a tracer like SF_6 to calculate dilution. Another project is to understand where the emissions come from with respect to what are the tires composed of. A Soxhlet extraction is carried out to collect tire extract from the tire tread, for which preliminary data are shown. Cryo-milled tyre tread loses



12% of its mass after the first extraction in cyclohexane, then 2% after a second extraction in toluene. The extender oil is likely a culprit for the ultrafine particles since it is the fraction that goes away when the catalytic stripper is used. The untreated tires have substantially more particles emitted relative to those. Summary – Fingerprints exist for tires, but an independent fingerprint from road wear is challenging. There are no good signatures for the organic species for the tires yet, but the metals are promising. TWP nanoparticles are primarily organic and semi-volatile, and difficult to study with ICP-MS. Tire emissions factors appear overestimated and the "true" emissions factor is not known.

Cheol-Heon Jeong, University of Toronto
"*Spatiotemporal Characterization of Non-Tailpipe Emissions from Mobile and Stationary Measurements*"

In a study by Jeong et al. (2020), non-tailpipe emissions (NTE) are shown to be increasing, and primary tailpipe emissions (TE) are decreasing due to regulations. NTE PM2.5 contributed a large fraction of redox-active trace metals. Resuspended road dust (RD) and brake wear dust (BD) have emerged as a dominant local source of PM2.5 and PM10 in urban areas. The goals of this research are to conduct mobile measurement field campaigns along various roadways in Toronto, Canada to assess the spatial variability of both TE (tailpipe emissions) and resuspended RD.



Another goal is to conduct simultaneous stationary filter sampling at up to 40 sites in the urban area to differentiate NTE sources through marker trace element analysis. Three seasonal field campaigns are also carried out to capture seasonal variations in TE and NTE sources. Stationary filter sampling was carried out in Fall 2023, Winter 2024, and Summer 2024 with weekly PM2.5 and PM10 sampling using 25 mm Teflon filters, gravimetric analysis of PM2.5 and PM10 mass, and trace elemental analysis using XRF. Simultaneous sampling in the wheel well and at the window was carried out using an EV in the Fall and two vehicles in Winter and Summer. PM2.5, PM10, ultrafine particles (UFP), black carbon (BC), and CO_2 were measured. Resuspended PM was calculated from the difference in the wheel-well PM and the window PM, with speed correction applied. Details can be found in Jeong et al. (2025). Mapping of the UFP and resuspended PM are presented. UFP is a key marker pollutant related to TE. Expressway has much greater UFP than local roads for tailpipe emissions. For non-tailpipe emissions, the expressway has much less UFP than local roads. The resuspended PM2.5 is highly localized with spikes near construction areas. There is a greater "potential" for resuspended PM (road dust) on less-traffic roads. Resuspended PM2.5 is higher for local roads compared to expressways and major arterial roads. The trend is opposite for UFP, BC, and PM2.5, where the expressway has the highest concentrations of these markers, with UFP exhibiting the strongest trend with traffic volume. Busy traffic keeps resuspending road dust, preventing it from accumulating on the surface. Winter tires likely led to significantly elevated resuspended road dust during dry winter days. Additional sources in winter for road dust include road salt and increased road friction due to winter tires. Part II of the presentation discussed stationary sampling to identify marker trace elements related to NTE in air. Forty sampling sites were characterized based on road types. PMF analysis was carried out over long-term to quantify

NTE sources. Road dust contained mostly Ca, Fe, Ti, and Mn, while brake wear contained Ba and Cu, and tire wear contained Zn. Brake wear was highest on the expressway, being two times higher than on local roads. The strongest spatial variations in brake wear emissions were characterized by Ba. Construction sites often had higher activity than all other road categories for brake wear, road dust, and tire wear. Seasonal trends did not exist, although summertime PM2.5 and PM10 were slightly higher than winter. Summary – Mobile sampling using wheel-well and window sampling works well to distinguish spatially between TE and resuspended road dust. Local roads had higher potential for resuspended road dust per unit of traffic compared to major roads. Strong seasonal differences were observed in resuspended road dust, likely driven by winter road maintenance practices. Ba, Ca, Ti, Fe, and Mn are markers for NTE and exhibited significant spatial variability. Among NTE sources, brake wear emissions have the most spatial differences for the different road types. Ambient concentrations of NTE sources did not have a consistent seasonal trend.

Nick Molden, Emissions Analytics
"*Tyre Emissions Factors, Environmental Risks and Mitigations*"

Emissions Analytics works with industry, authorities, and academia to study the environmental impact of vehicles. There is a lot about tire emissions that remains unknown. Need to know what is the best current understanding of the problem, risks, and potential mitigations. The presentation will touch on 4 areas: real-world tyre wear rates; chemical speciation and toxicity; ultrafines, VOCs, and air quality effects; and size distribution and spatial distribution. In total 6 million tonnes of tire wear globally per year are released into the environment as volatile organics and particles that can be inhaled, transported into soil, water, and food, or undergo chemical reactions. An example mass-based size distribution is presented showing that particle diameters from real world tire emissions are in the size range <0.1 μm and >10 μm, while air quality monitoring typically measures the range in between. Are we looking in the wrong place for tire wear emissions? Should we measure around 1-10 μm? In addition, some errors in the literature have led us in the wrong direction. Miech, Herckes et al. (2024) reported an emission factor of 0.005-0.22 mg km^{-1} veh^{-1} and had difficulty publishing it because the values were lower than the MOVES model. Other errors have included that Cadle and Williams (1978) reported mass concentrations of total suspended particles (TSP, not PM10), the US EPA reported 4 times too high when per vehicle was confused with per tire, and a 1998 study quoted 6 mg/kg but was not easily found in the literature. A second topic is to understand tire composition. Measurements using pyrolysis TD-GCxGC-TOF-MS on the tread block of 501 new tyres from the US and Europe, retail and wholesale are presented. Large components include lipids and lipid-like molecules, benzenoids, and hydrocarbons. With 410 compounds on average per tyre, the challenge is to identify those products that are known to be in the original tyre and separate them from breakdown or reaction products. Major organic categories include naturally-derived chemicals, synthetic polymer breakdown products, PAHs, vulcanization accelerators, terpenoids, PPDs, and benzothiazoles. Examples are that the breakdown products of synthetic polymer include benzene, and vulcanization accelerators produce fatty acyls. A third topic is deployment of off-gassing measurements. A small chamber was built to enclose the whole tire with controlled temperature and sampling points at different heights with thermal desorption tubes. Need to know if the off-gassing of volatiles in itself is an air quality problem or generates secondary aerosol. Test results showed hundreds of VOCs are released in each chamber exposure, in which background VOCs were measured in the chamber and subtracted from those emitted from tyres. Recurrent species in all samples included aniline, methyl isobutyl ketone, benzothiazole, cyclohexane and derivatives, and simple aromatics, which were common in new and old tyres, and small and large tyres and had emission rates of ~$(0.01\text{-}3)\times10^{-2}$ g h^{-1} per tyre. These emission rates were used with applied O_3 and SOA formation potentials, assuming 1 km well-mixed boundary layer, 25°C, 2.3 million vehicles (LA city), $[OH]=5\times10^6$ molecules cm^{-3} (midday peak in LA). This resulted in a prediction of 322 ppb O_3 and 7.6 μg m^{-3} SOA, which are probably overestimates due to model assumptions, but are non-negligible compared to a summer 2024 maximum $[O_3]$ of ~50 ppb and SOA ~30 μg m^{-3}. This is an overlooked source of secondary pollutants in urban environments. The final topic is spatial distribution, i.e. where does the material end up? Larger particles are often from the rough road surface, while ultrafines are formed under braking and cornering. Particle sizes were measured from different zones of the tire and showed that all sizes from 10 nm to 100 μm are measured in zone 1 (lower sidewall), while the trend is toward UFP in zone 3 (upper half of the wheel, including wheel arch). Comparison with measurements in the Colorado Rocky Mountains showed that wind-blown particles are transported thousands of kilometers in elevation and deposited on snow, as published in Reynolds et al. (2024)! Potential mitigations were discussed, including on-vehicle collection, trapping in infrastructure, and wear mass reduction, but there is a low chance of reducing UFP and VOC without reformulation. Summary – Tyre emission factors have probably been misunderstood; large particles and UFP dominate the fine particle emissions; off-gassed VOCs are likely significant; the toxicity is driven by problematic chemical groups; populations may suffer from effects on water, food chain, and UFP. There is no simple mitigation, but a range of approaches exists.

FINAL THOUGHTS

Michael Moore, Stellantis

Save the date – The *36th CRC Real World Emissions Workshop* will be held on March 8-11, 2026, at the Hyatt Regency Mission Bay, San Diego, CA. There were 175 registrants from 10 countries. We would like to thank keynote speakers for their history and technology background. We also thank the workshop co-sponsors (NREL, CARB, SCAQMD) for their support. A very big thank you goes to the CRC staff: Rebecca Kane, Jan Tucker, Amber Leland, and Chris Tennant! We value your feedback – please fill out the survey in order to get the Workshop Proceedings! Thank you to those who have already provided feedback!

Note from the author:

To the attendees, workshop organizers, and sponsors: I thoroughly enjoyed this workshop and the presentations! I visited a number of interesting posters, talked with old friends, and made new ones. The collaborative nature and the range of research backgrounds of the CRC RWEW attendees is impressive, welcoming, and best of all, conducive to fruitful progress in this field. As my own research is in only a small area of this field, I humbly hope this summary helps us all to further contribute to the decades of ground-breaking research that have come before us. To facilitate research outside one's own expertise, a list of acronyms used in the presentations has been included here. The presentations and the attendee list have been provided to attendees by the CRC organizers that we may contact the authors if there are questions or potential for collaborative or cooperative work.

This summary is intended to capture the main points of each presentation. Having said that, it is possible that some of these points have been missed. Please forgive any errors or misinterpretations. While this summary does not include the posters, it is not from a lack of interest! For any corrections, contact me so that I may edit the document and resubmit it to the CRC Organizing Committee for online posting at https://crcao.org/crc-real-world-emissions-workshop/.

List of Acronyms:

ACC	Advanced Clean Cars regulation introduced by CARB
ACF	Advanced Clean Fleets regulation introduced by CARB
ACT	Advanced Clean Trucks regulation introduced by CARB
ANR	Accuracy, Noise, and Repeatability
APS	Aerodynamic Particle Sizer
AQIRP	Air Quality Improvement Research Program
AQMD	Air Quality Management District
BAAQMD	Bay Area Air Quality Management District
BC	Black Carbon
BEB	Battery-Electric Buses
BEDT	Battery Electric Drayage Truck
BEV	Battery Electric Vehicle
BWTW	Brake-Wear and Tire-Wear
CAPP	Community Air Protection Program
CARB	California Air Resources Board
CE-CERT	College of Engineering - Center for Environmental Research and Technology (at UC Riverside)
CERP	Community Emission Reduction Programs
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CPC	Condensation Particle Counter
CRC	Coordinating Research Council, Inc.
CS	Catalytic Stripper
CTC	Clean Truck Check program
CVS	Constant Volume Sampling
DAAAC	Diesel Aftertreatment Accelerated Aging Cycles
DCHA	Dicyclohexylamine
DMS	Differential Mobility Spectrometer
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
DRI	Desert Research Institute
DT	Drayage Truck
EAD	Electrical Aerosol Detector
EEPS	Engine Exhaust Particle Sizer
EGR	Exhaust Gas Recirculation
EKMA	Empirical Kinetics Modeling Approach
EMFAC	EMission FACtor, emissions model
EPA	Environmental Protection Agency
EV	Electric Vehicle
FHWA	Federal Highway Administration
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection
GHG	Greenhouse Gas
GPF	Gasoline Particulate Filter
H_2-ICE	Hydrogen Internal Combustion Engine
HC	Hydrocarbons
HD	Heavy Duty
HONO	Nitrous Acid
HR ELPI+	High Resolution - Electrical Low Pressure Impactor®
ICEV	Internal Combustion Engine Vehicle
I/M	Inspection and Maintenance program
LCFS	Low Carbon Fuel Standard
LD	Light Duty
LPG	Liquefied Petroleum Gas
MD	Medium Duty

MOVES	MOtor Vehicle Emission Simulator
MPO	Metropolitan Planning Organization
MY	Model Year
NAAQS	National Ambient Air Quality Standards
NEE	Non-Exhaust Emissions
NEI	National Emissions Inventory
NMOG	Non-Methane Organic Gases
NOx	Nitrogen Oxides (NO + NO_2)
NREL	National Renewable Energy Laboratory
OBD	On Board Diagnostics
OECA	Office of Enforcement and Compliance Assurance at EPA
OP^{OH}	Oxidative Potential determined by the hydroxyl radical (OH) assay
OP^{DTT}	Oxidative Potential determined by the Dithiothreitol (DTT) assay
PAH	Polycyclic Aromatic Hydrocarbon
PCV	Positive Crankcase Ventilation (valve)
PEMS	Portable Emissions Measurement System
PFI	Port Fuel Injection
PM	Particulate Matter or Particle Mass (concentration)
PM2.5	Particulate Matter with diameters less than or equal to 2.5 μm
PM10	Particulate Matter with diameters less than or equal to 10 μm
PMI	Particulate Matter Index
PN	Particle number (concentration)
PTI	Periodic Technical Inspection program
PZEV	Partial Zero Emission Vehicle
rDME	Renewable (and Recycled) Dimethyl Ether
RFG	Reformulated Gasoline
RNG	Renewable Natural Gas
ROG	Reactive Organic Gases
RWEW	Real World Emissions Workshop
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SCR	Selective Catalytic Reduction
SFTP	Supplemental Federal Test Procedure
SOx	Sulfur Oxides
SMPS	Scanning Mobility Particle Sizer
SPN10	Solid Particle Number emissions >10 nm
SPN23	Solid Particle Number emissions >23 nm
SULEV	Super Ultra-Low Emission Vehicle
TARTA	Toxic-Metal Aerosol Real-Time Analysis
THC	Total Hydrocarbons
UFP	Ultrafine Particles
ULEV	Ultra-Low Emission Vehicle
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
XRF	X-Ray Fluorescence
ZEP	Zero-Emission Powertrain
ZEV	Zero-Emission Vehicle