From: Todd R. Campbell <[redacted]>
Sent: Wednesday, September 17, 2025 8:34 AM
To: Ian MacMillan <[redacted]>; Sarah Rees <[redacted]>; Aaron Katzenstein <[redacted]>
Cc: Greg Roche <[redacted]>
Subject: [EXTERNAL] FW: **Document Available** Updated Ports Draft Cooperative Agreement

Good morning, Ian, Sarah, and Aaron:

I hope this e-mail finds you well. I took a quick read through the draft cooperative agreement and was actually surprised not to see any requirements for Omnibus-compliant trucks or even a plan to eliminate gate fees for said trucks. As you know, the federal actions not only have temporarily (and possibly permanently) removed both the Omnibus and CARB's 2010 standards for combustion engines. Remember, the 2010 standards were rescinded by CARB when the Omnibus was adopted. I am sure you share my concern that if the federal actions on the waivers hold, we will continue to see dirty engine purchases through 2026 and potentially through 2031 if EPA decides to roll back the 2027 standards for five additional years. If there are no financial or non-financial incentives to encourage fleets to purchase the cleanest ICEs, why would fleets purchase them and why would manufacturers make them?

Would you be open to meet with us before the workshop to discuss a possible plan to encourage clean combustion at the Ports. Specifically, would you be willing to explore a plan that encourages the ports to provide incentives for drayage fleets who buy engines that meet or exceed the Omnibus standard? I don't see how we ever reach attainment if we cannot encourage fleets that operate in the basin to make the right purchase decisions. I am including a list of actions that I provided to Lauren Sanchez and Steve Cliff earlier this month with the intent of finding ways to create more certainty for clean engine purchases. I think it would be really helpful to hold similar conversations with you to make sure we are getting every reduction possible from mobile source pollution.

Can we set up a time to discuss?

Thank you,

Todd

PS: I'm sure you have seen the attached UC Riverside/CE-Cert study, presentations, and further analysis by Energy Vision (https://energyvision.substack.com/p/uc-riverside-study-forecasts-most), but I am attaching them just in case.

Clean Combustion Truck Incentive Considerations for 2025-2026

Federal Actions have created tremendous uncertainty in California's truck marketplace.

- Congressional, DOJ, FTC, and four manufacturers have created CARB regulatory enforcement uncertainty.
- CARB ZEV regulations reduced to ACF mandates for public fleets.
- CARB's Manufacturers Advisory Correspondence issued on August 25 allows manufacturers to certify product with greater flexibility, but reserves the right to enforce its rules if victorious in court (we like this because it creates uncertainty for non-compliant 200mg NOx legacy product).

We view it as imperative to uphold CARB's clean combustion standards under the Heavy-Duty Omnibus rule through both financial and non-financial incentives that the federal government cannot block.

Financial:

- *HVIP grants*: $50,000/truck to both large and small end users (not the dealer). 500 – 1000 grants would be very helpful in persuading fleets to make clean choices. We can make up the other $50K as an industry.
- *Vehicle Sales Tax Exemption* – about $10,000/truck (Legislation required? If so, would like GO/CARB support) or equalize the sales tax between a diesel truck and a CNG truck.
- *No Port Gate Fees at California Ports* for 50mg NOx or cleaner Omnibus compliant trucks. Obviously, we have an eye on the 2027 standard as well set at 35mg NOx.

Non-Financial:

- *CARB full useful life guarantee* of a clean combustion truck (Omnibus or better) regardless of future regulations (adds certainty)
- *ISR Mitigation inclusion for regional and/or state programs* for Omnibus compliant clean combustion trucks through 2032.
- *New Truck and Bus Rule* that phases out MY 2015 or older trucks over the next five years.

The Role of OSAR in moving Towards a Sustainable Transportation Future

Keynote - OSAR Conference
April 2025

Presented By:

Thomas Durbin, Kent Johnson, Georgios Karavalakis, Zisimos Toumasatos, Grace Johnson, and Troy Hurren
University of California, Riverside
Bourns College of Engineering
Center for Environmental Research and Technology

UNIVERSITY OF CALIFORNIA, RIVERSIDE

Environmental Impacts of Transportation Emissions

- Mitigating the environmental impacts of transportation emissions is one of the biggest challenges of ours and future generations
- Transportation accounts for approximately 24% of worldwide and 33% of U.S. CO_2 emissions, with about 75% of this from on-road sources.[1]
- World Health Organization (WHO) estimates of air quality impacts include[2]
  - In 2019, 99% of the world's population was living in places where the WHO air quality guidelines levels were not met.
  - Ambient (outdoor) air pollution was estimated to have caused 4.2 million premature deaths worldwide in 2019.
  - The combined effects of ambient air pollution and household air pollution are associated with 6.7 million premature deaths annually.

1 https://ourworldindata.org/co2-emissions-from-transport; https://www.epa.gov/ghgemissions/global-greenhouse-gas-overview
2 https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

Global Warming – Potential Impacts

WORLD RESOURCES INSTITUTE

COMPARING RISKS FROM RISING TEMPERATURES:

EXPLAINING THE IPCC'S WORKING GROUP II REPORT (AR6)

	1.5°C	2°C	3°C	1.5°C vs 2°C	1.5°C vs 3°C
BIODIVERSITY LOSS Maximum percentage of species at high risk of extinction across forests and land	14%	18%	29%	1.3x WORSE	2.1x WORSE
DROUGHT Dryland population exposed to water stress, heat stress and desertification	0.95B PEOPLE	1.15B PEOPLE	1.29B PEOPLE	200M MORE PEOPLE	340M MORE PEOPLE
FOOD SECURITY Costs for adaptation and residual damage to major crops	$63 BILLION US	$80 BILLION US	$128 BILLION US	$17B MORE	$65B MORE
FIRES Increases in burnt area across Mediterranean Europe	40-54%	62-87%	96-187%	1.6x WORSE	3x WORSE
EXTREME HEAT Increase in number of days per year with a maximum temperature above 35°C (95°F)	45-58	52-68	66-87	1.2x WORSE	1.5x WORSE
EXTREME HEAT Increase in annual number of heatwaves in Southern Africa	2-4 TIMES	4-8 TIMES	8-12 TIMES	2x WORSE	3.3x WORSE
SEA LEVEL RISE Global mean sea level rise by 2100	0.28-0.55m	0.33-0.61m	0.44-0.76m	1.1x WORSE	1.4x WORSE
FLOODS Increase in global population exposed to flooding	24%	30%	NO DATA AVAILABLE	1.3x WORSE	NO DATA AVAILABLE
CORAL REEFS Further decline in coral reefs	70-90%	99%	NO DATA AVAILABLE	1.2x WORSE	NO DATA AVAILABLE

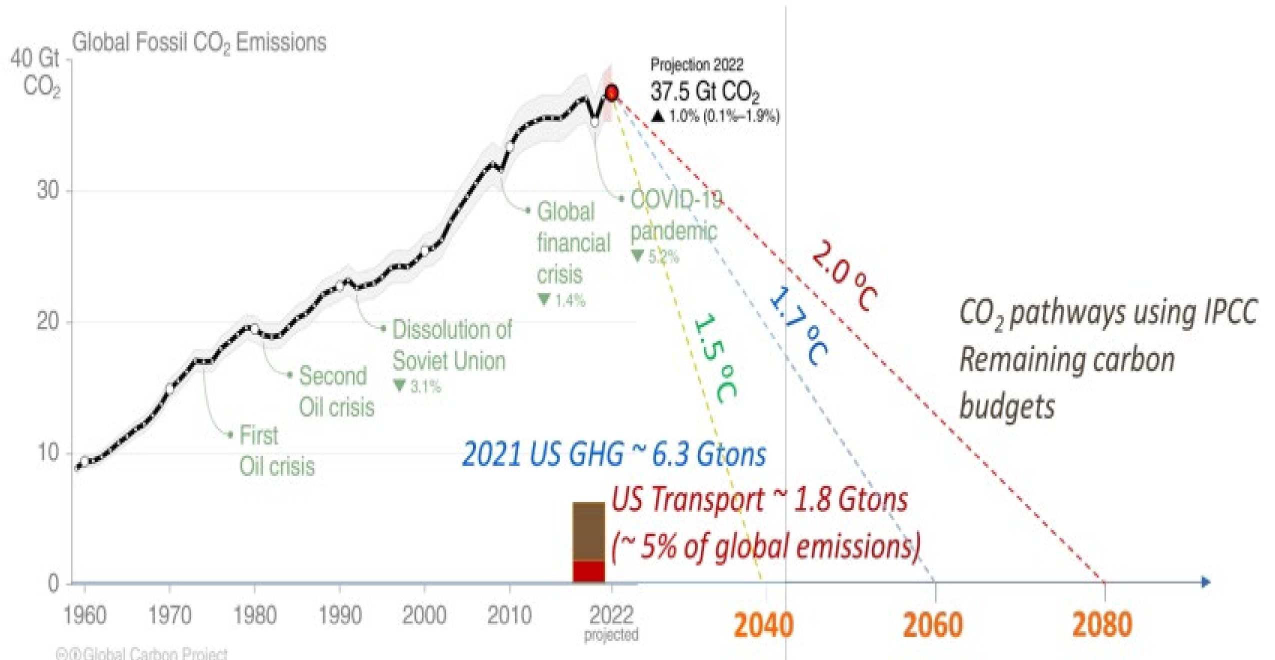
Source: World Resources Institute. https://www.wri.org/insights/2023-ipcc-ar6-synthesis-report-climate-change-findings

Costs of Global Warming

- **Costs of US$ 143 billion per year attributable to extreme events due to climatic change.[1]**
- **In U.S., 400 weather /climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion (including CPI adjustment to 2024). The total cost of these 400 events >$2.785 trillion.[2]**
- **From 2000 to 2019, extreme weather events globally, like hurricanes, floods and heat waves, have cost an estimated $2.8 trillion. This is around $143 billion/year or $16.3 million/hour.[3]**
- **The global cost of climate change damage is estimated to be between $1.7 trillion and $3.1 trillion per year by 2050. [3]**

1. Newman, R., Noy, I. The global costs of extreme weather that are attributable to climate change. *Nat Commun* **14**, 6103 (2023). https://doi.org/10.1038/s41467-023-41888-1.
2. National Centers for Environmental Information (NCEI) http://www.ncei.noaa.gov/access/billions
3. World Economic Forum. https://www.weforum.org/stories/2023/10/climate-loss-and-damage-cost-16-million-per-hour/

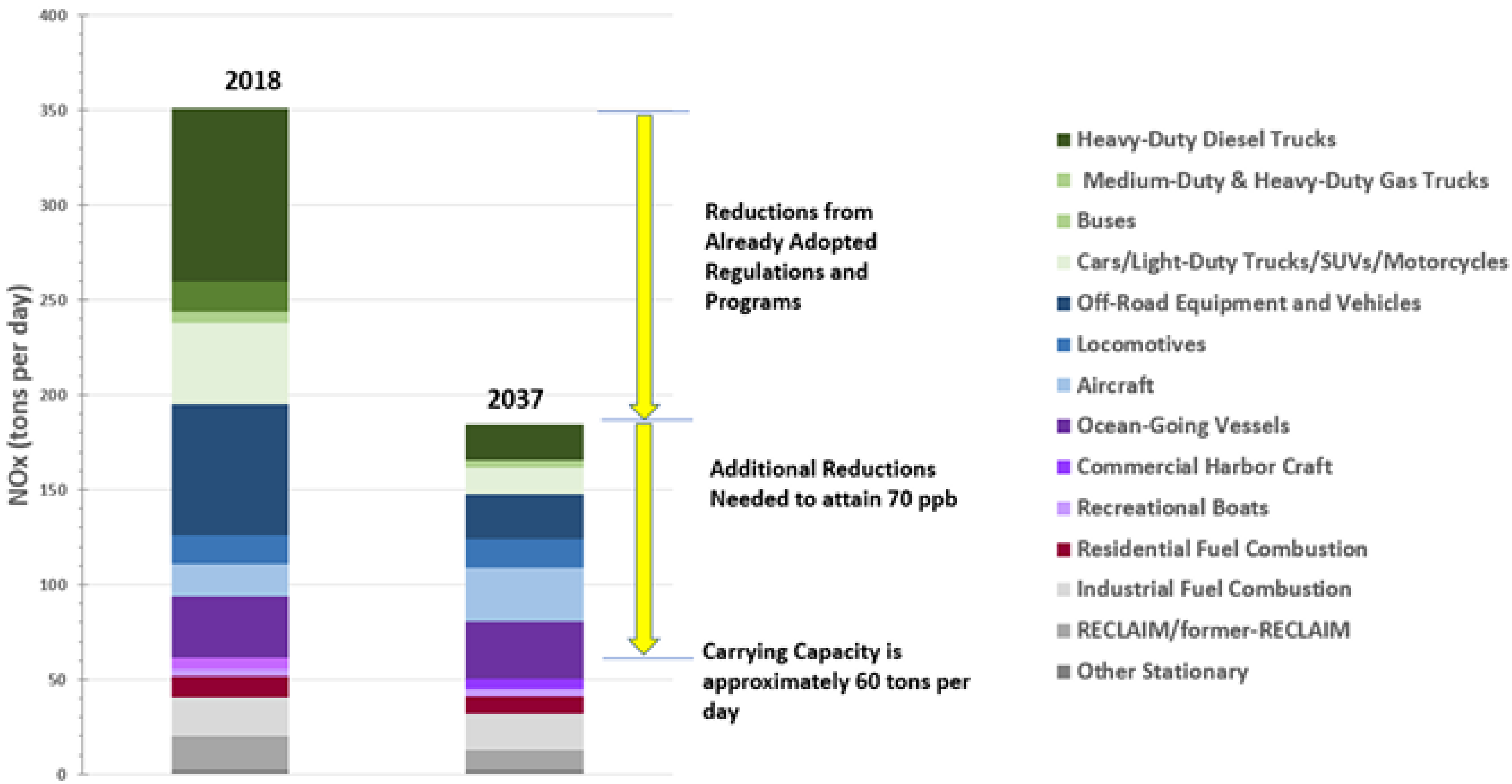
Global Warming – Mitigation Goals



Source: Global Carbon Project 2022 - chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.globalcarbonproject.org/carbonbudget/22/files/GCP_CarbonBudget_2022.pdf

- **But some studies suggest global costs of net zero goal on order of $200 (BloomburgNEF)[1] to $275 (McKinsey Global Institute)[2] trillion.**
  - **Global assets: stock market $115T[3] residential real estate $300-500T[4]**

Need for Further Emission Reductions in LA



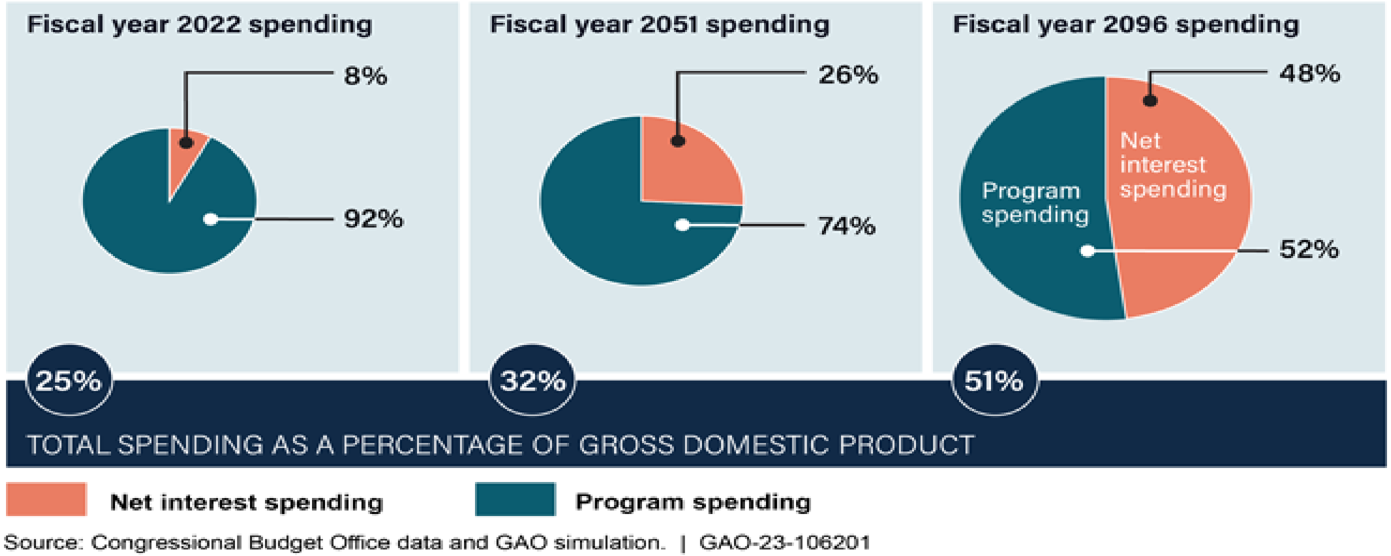
Source: South Coast Air Quality Management District, 2022 Air Quality Management Plan, Adopted December, 2022.

Economic Challenges going into 2030s - I

- **Government debt is increasingly becoming a problem**
  - CFOs, bankers (Jamie Diamond), the Fed and others see government debt as looming crisis[1]
  - Overall debt $36.7 trillion[2] 1/10/25, U.S. stock market $52.0 T,[3] U.S. residential real estate - $49.7T[4]
- **Federal Government Spending is very high and continuing to grow**
  - $6.75 Trillion for 2024[5] ($52,656 per household), 51.8% higher than pre-COVID levels
  - Social Security/Medicare/Medicaid + Interest $2.51 Tril. ($19,640/house) in 2019 to $3.89 Tril. ($30,307/house) in 2024
  - ~ All private real estate in 12 mid-west states (IL, IM, IA, KS, NE, MN, MI, MO, OH, WS, ND,SD)[6]
  - ~ Market cap Autos, Oil, Telecom/TV, Retail (Major+specialty), + many Food Companies combined[7]
  - ~ U.S. Retail sales revenue minus motor vehicles, auto parts & gas stations[8]
- **Federal government deficit is growing at historic levels**
  - $1.83 Tril. in 2024[5] ($14,275/house) (~$3,000/house Aug 2024[9]), 86% higher than pre-COVID levels
  - Equivalent to the value of all residential real estate in Colorado and Oregon combined
  - All profits of the 220 most profitable U.S. companies in 2022[10]

Economic Challenges going into 2030s - II

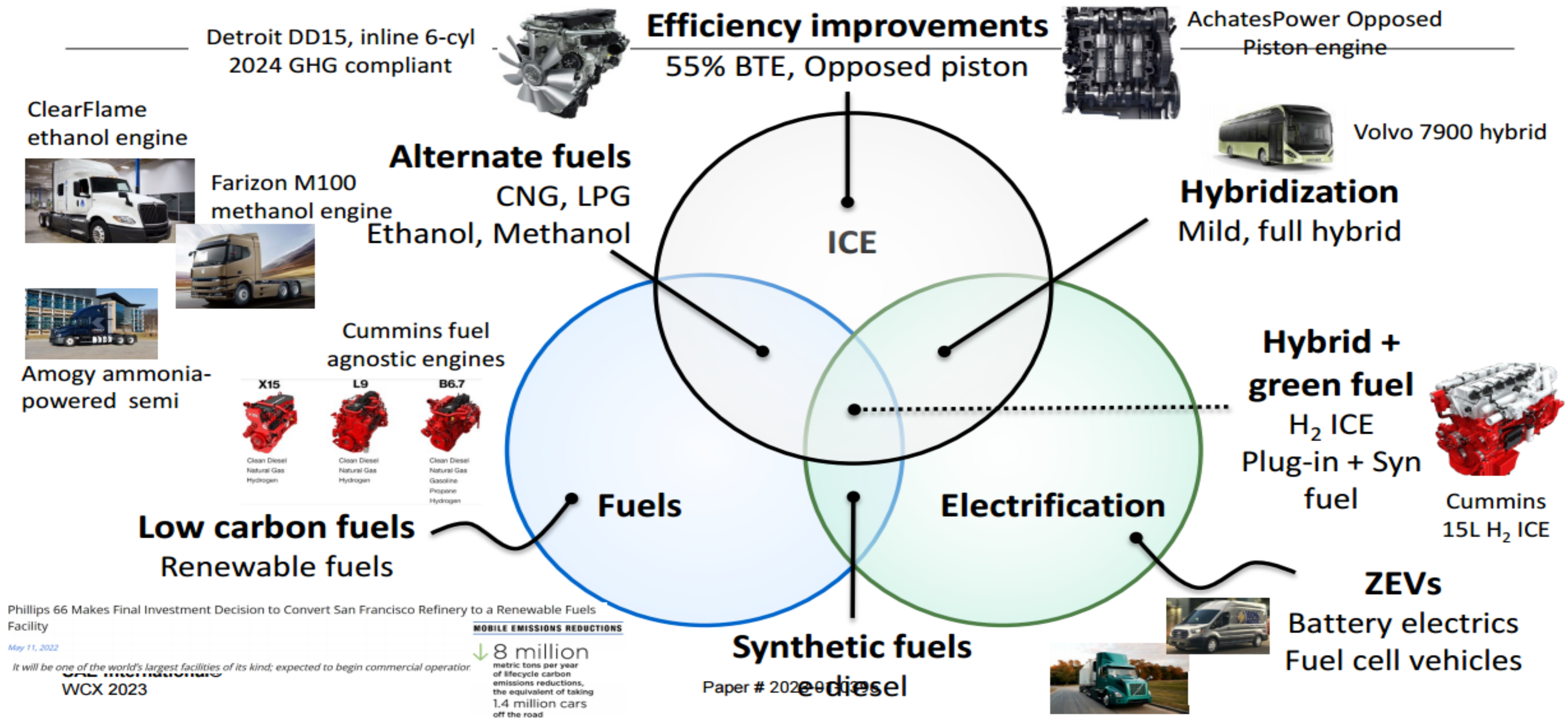
- **Solutions will be problematic - higher taxes / slower economy, increase money supply /inflation, probably in combination with less services**
  - Interest payments
    - $892 B in 2024 - $6,958 per household[1]
    - 2051 - 8% of GDP - $16,486/household[2]



- **Economic constraints / cost effectiveness will continue to play an important role in environmental policy for the foreseeable future**

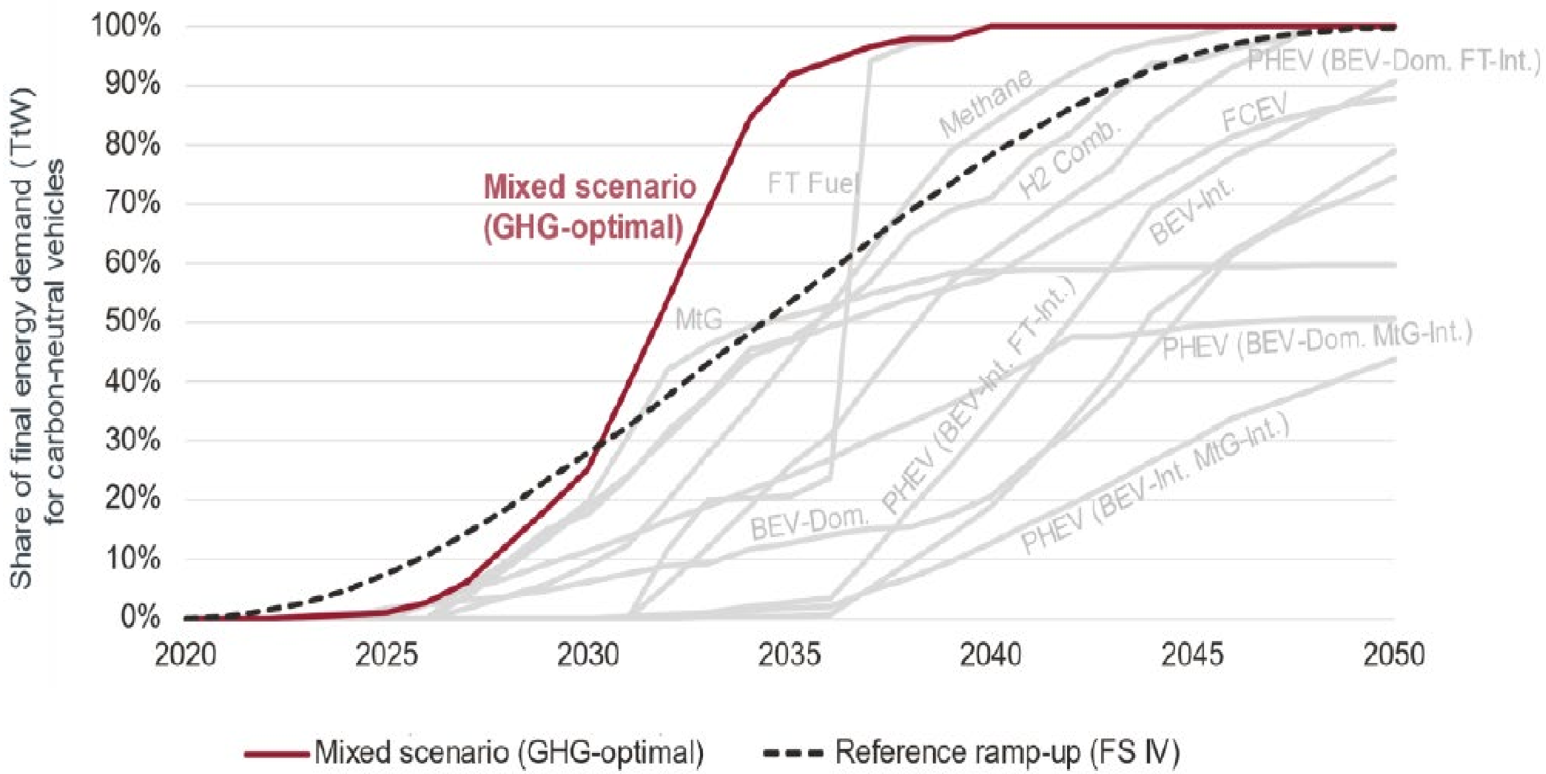
1 /https://www.cbo.gov/system/files/2024-11/60843-MBR.pdf
2. U.S. Government Accountability Office, 2023, https://www.gao.gov/assets/gao-23-106201.pdf

In a challenging environment, various pathways will likely needed to be pursued for transport decarbonization



Source: Joshi, A., 2023, “Year in review – Progress towards decarbonizing transportation and zero emissions,” presentation at Society of Automotive Engineers, WCX conference, Detroit, MI, April.

Various pathways will need to be pursued for transport decarbonization



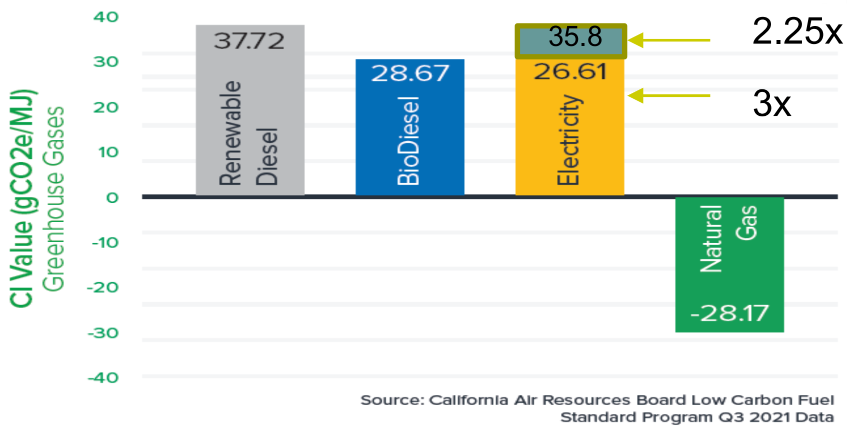
Source: Krammer, U. Bothe, D., Gatzen, C, et al., 2022, FVV eV // Science for a moving society (FVV), Future Fuels: FVV Fuel Study IVb Follow-up study: Transformation of Mobility to the GHG-neutral Post-fossil Age, Project. No. 1452.

Renewable Fuels

- In California, over 50% of diesel fuel is comprised of renewable fuels [Q1 2023][1], with diesel fuel for off-road equipment required to be renewable
- Renewable Diesel (RD) has ~70% (100%?) carbon intensive benefit of electricity (basis CA current grid)
- Biofuels provide carbon intensity benefits equivalent to electrifying
  - 35%-50% of the Heavy-duty vehicles (HDVs) + off-road engines (OREs) in CA
  - 70%-100% of off-road equipment (since RD required for off-road in CA)

Diesel 102

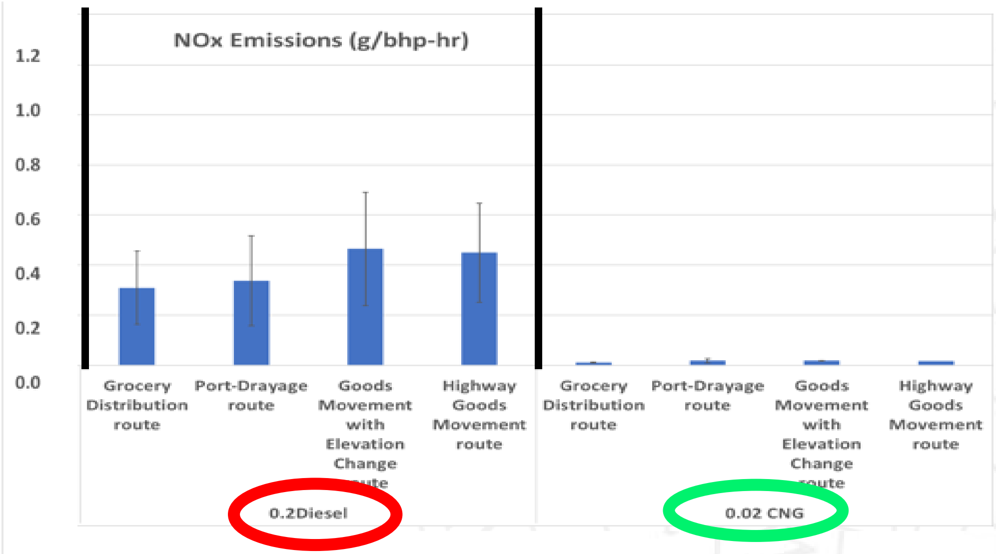
Base Electricity 80.55



--- [1]https://ww2.arb.ca.gov/news/first-time-50-california-diesel-fuel-replaced-clean-fuels
--- Diesel fuel = 102 gCO_2e/MJ
--- Electricity value from electrical grid value of 80.55 gCO_2e/MJ w/ BEVs being 3x more efficient. Probably overstated as diesel engines are getting towards 40% efficient now
--- Note negative carbon intensity for RNG is due to avoided methane emissions into the atmosphere

Biofuels + Ultraclean engines

- When biofuels are combined with ultralow NOx HDVs there is a potential for significant near and intermediate term benefits in both GHGs and exhaust pollutants, as the market transitions towards BEVs
- This could include both 2027+ diesel vehicles and current technology 0.02 g NOx CNG vehicles

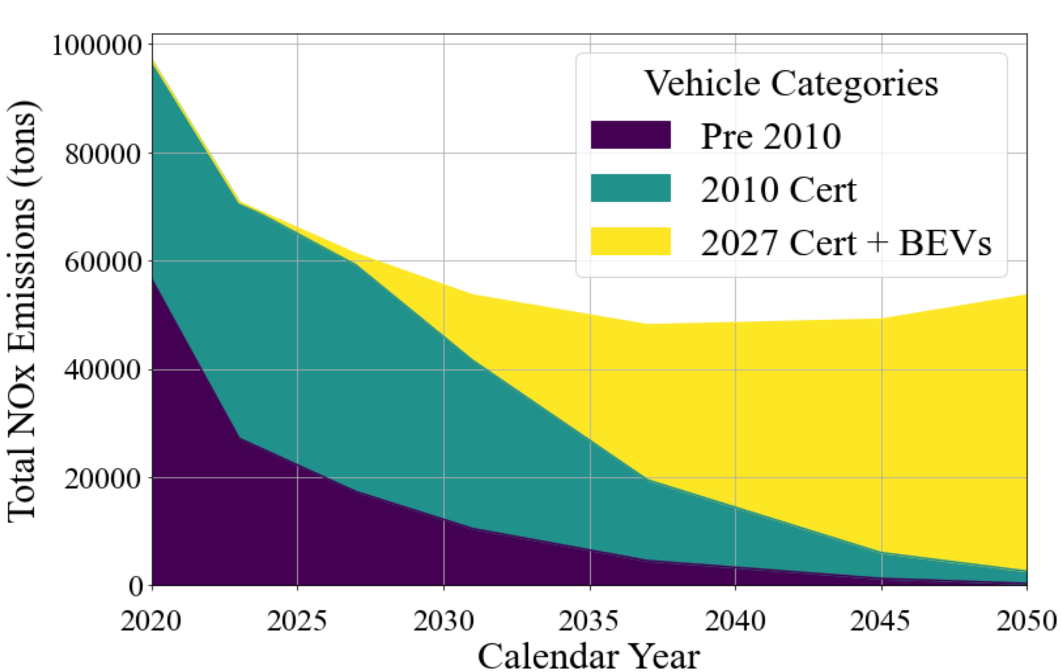


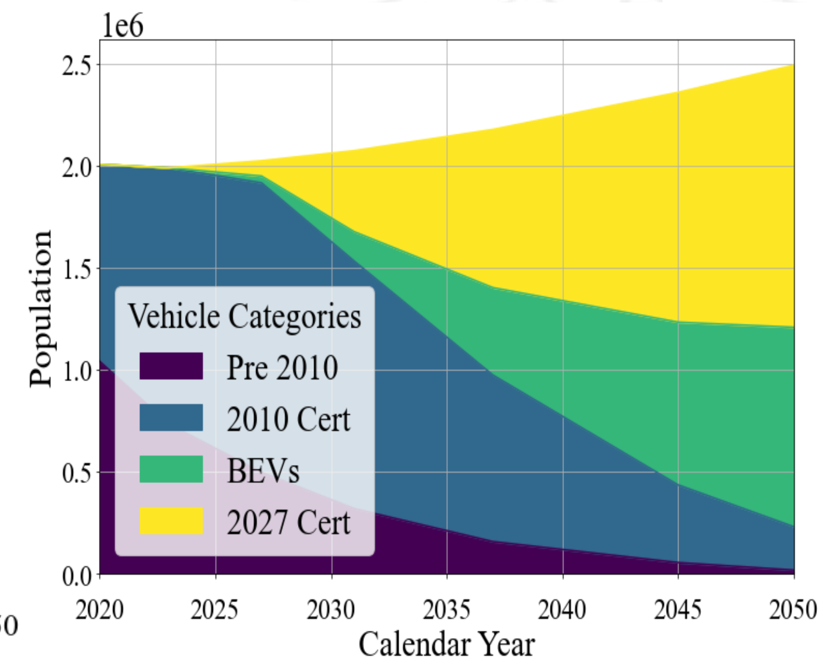
2010 SCR-equipped Diesels

2027+ Diesels + 0.02 CNG

Understanding In Use Emissions and Emissions Inventories

- Base case EMFAC emissions inventory modeling (without ultralow NOx diesel engines) shows increases in vehicle population could be an important contributing factor to emissions inventories

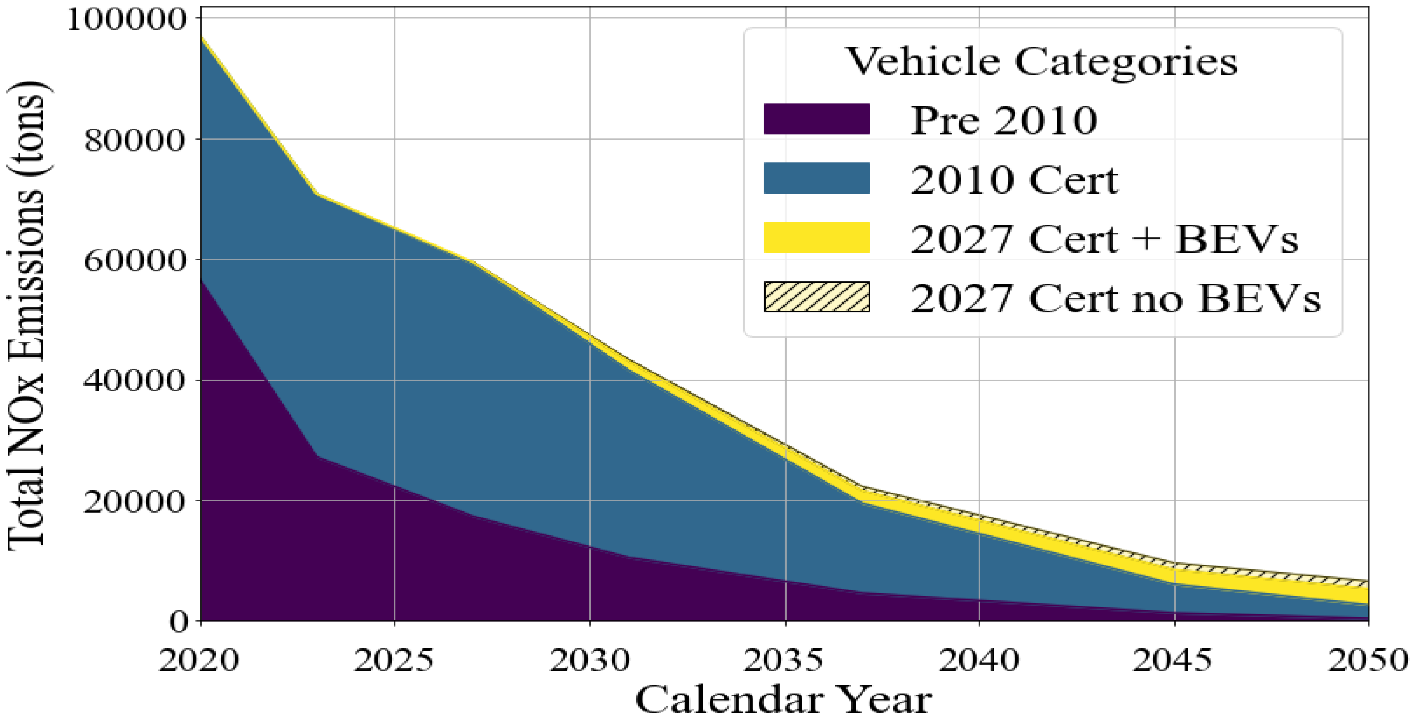




Potential Importance of Ultralow NOx Engines

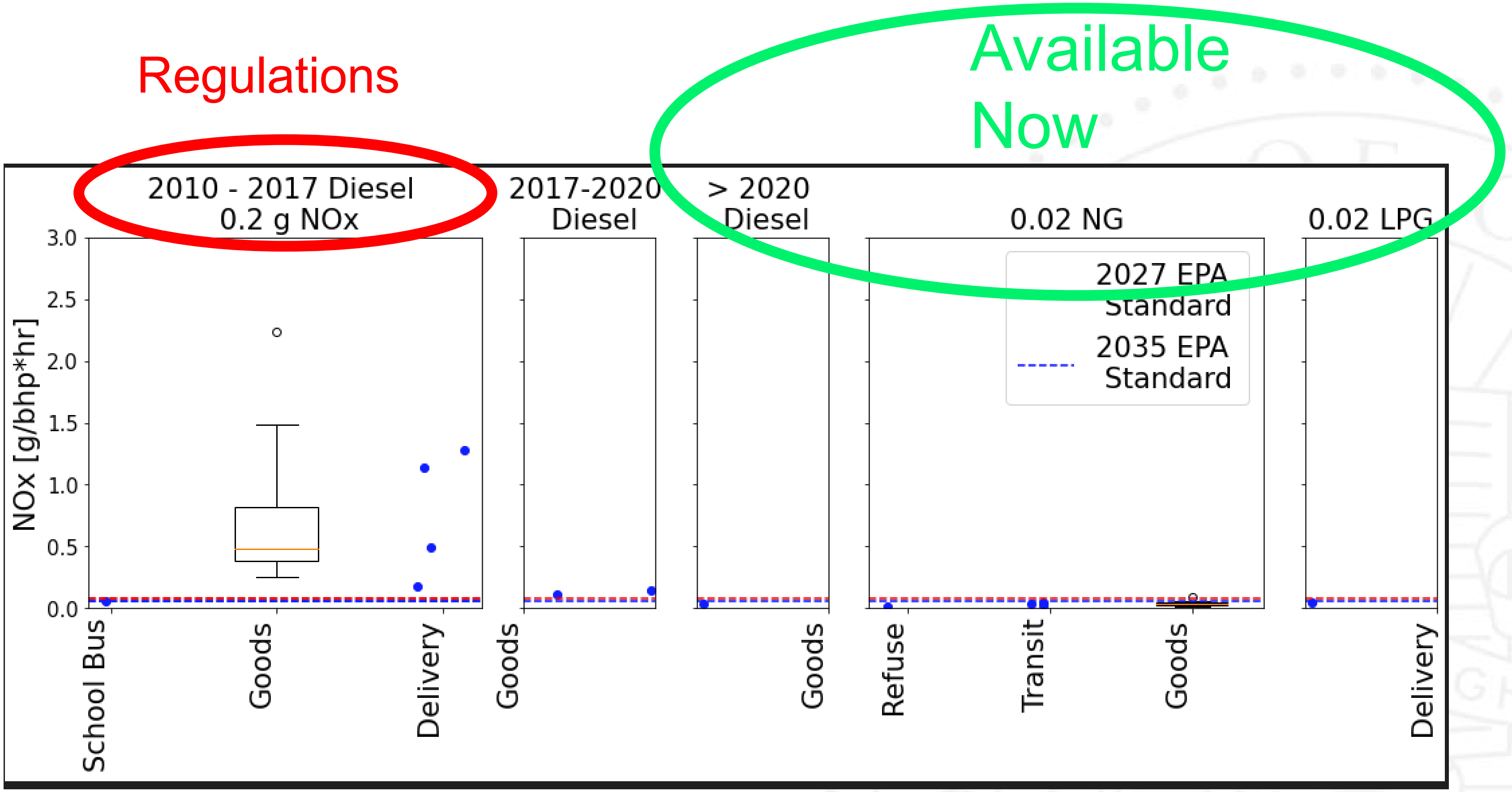
- Incorporating ultralow NOx diesel engines could have a dramatic impact on emissions inventories.
- 95% of the NOx emissions reductions between 2025 and 2040 for heavy-duty vehicles could come from fleet turn over with ultralow NOx diesel vehicles……

If we can keep the vehicles clean



Source: Troy Hurren; Thomas D. Durbin; Kent C. Johnson, Georgios Karavalakis, 2025, The Impacts of improving heavy-duty internal combustion engine technology on reducing NOx emissions inventories going into the future, submitted to Science of the Total Environment.

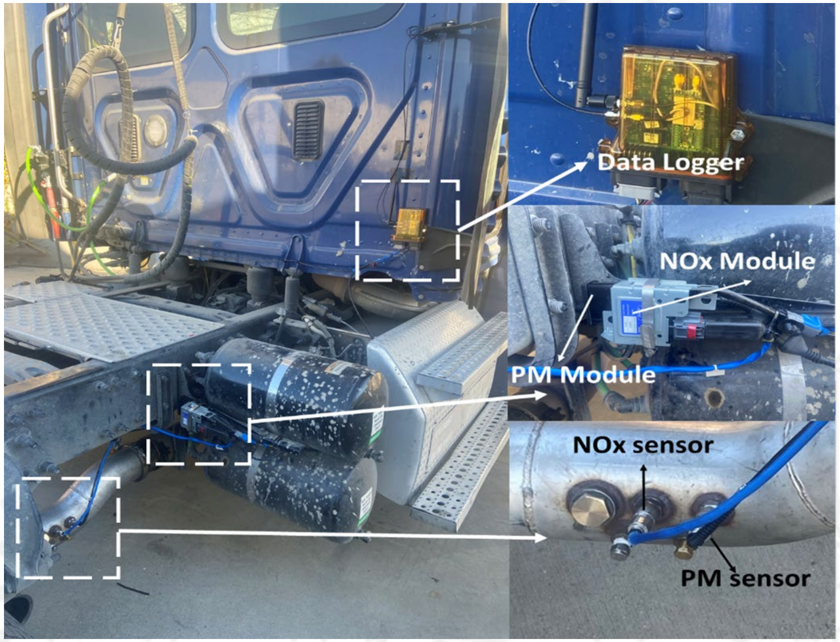
Trends CE-CERT is examining in heavy-duty vehicle emissions



CE-CERT Methodology is On Board Sensing and Reporting (OSAR)

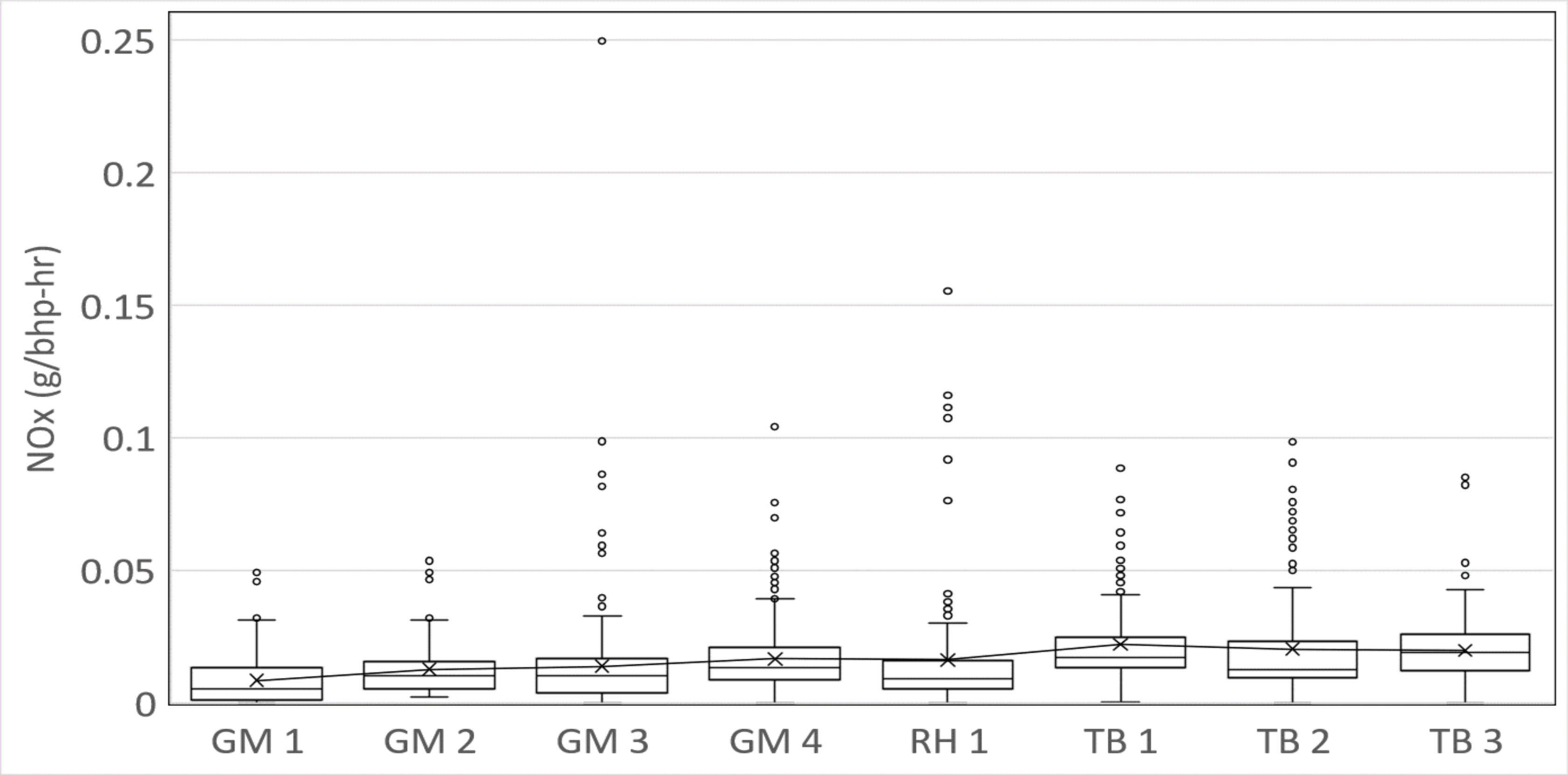
- Onboard Sensing Analysis and Reporting (OSAR) was developed for continuous monitoring of diesel technologies annually
- OSAR started out as a consortium lead research initiative, but has now grown to over nine funded programs
- OSAR includes
  - NOx, PM, GPS, CAN, and other sensors
  - Auto starting and shutdown to capture cold starts and all truck operation

NOx/O2 Module PM Module Data Logger (CAN, GPS, LTE) GPS & LTE Antennas



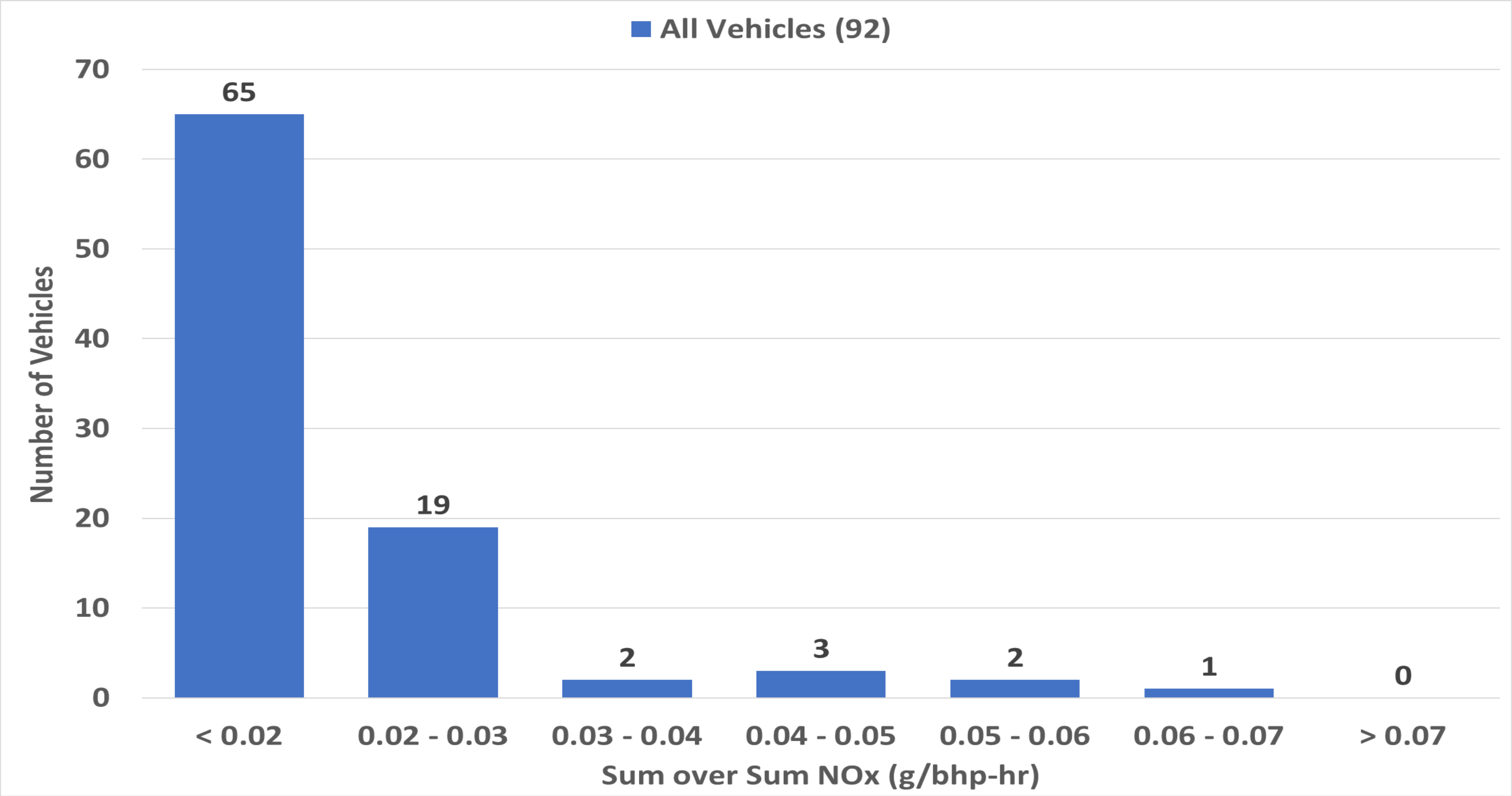
OSAR Monitoring of CNG Vehicles - I

- The average trip emissions for most fleets are on the order of the 0.02 g/bhp-hr level
- But there are outliers that have higher emissions



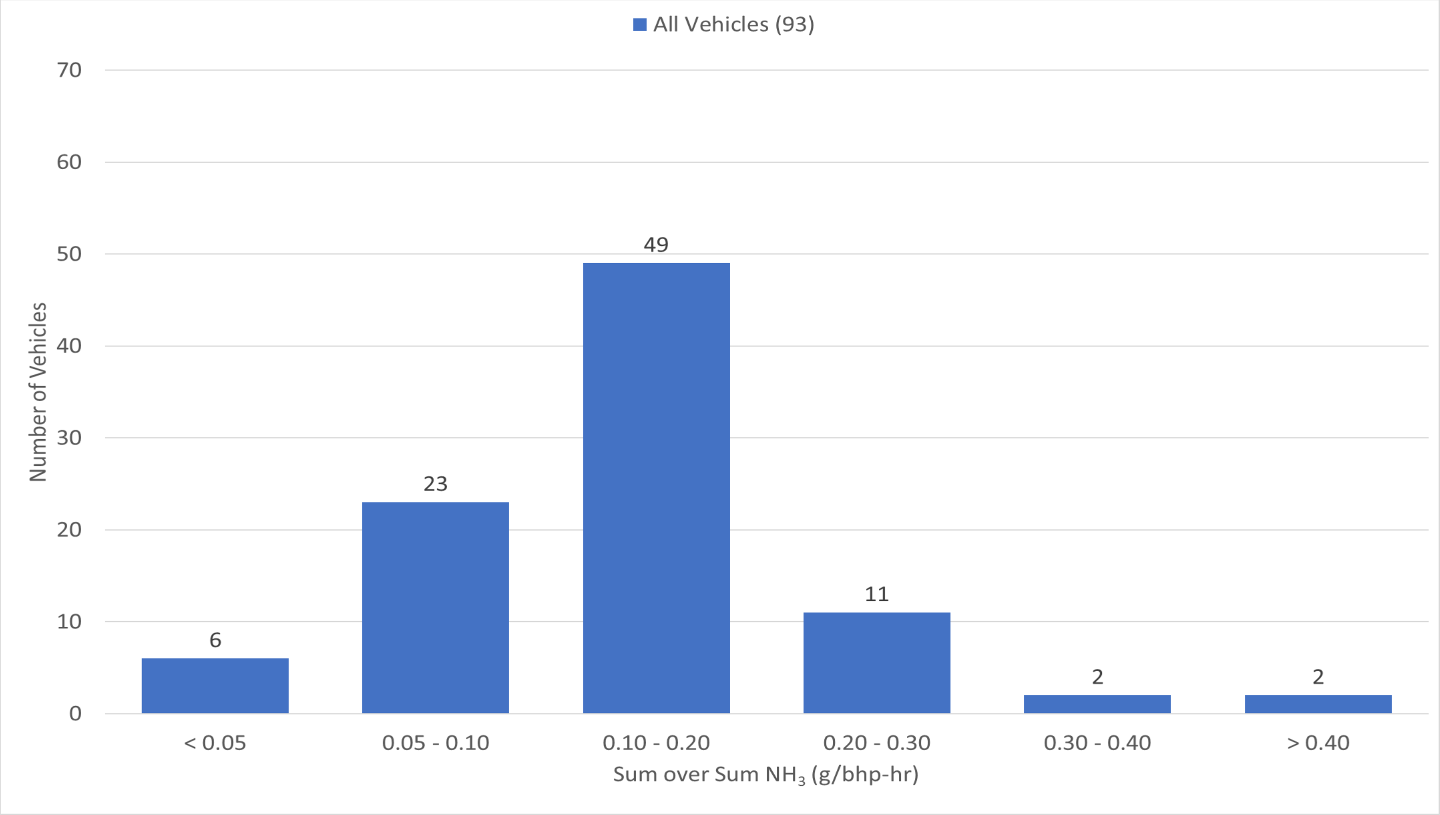
OSAR Monitoring of CNG Vehicles - II

- Based on sum of all NOx emissions over all work for each vehicle
- Most vehicles are operating within 2x of the 0.02 g/bh-hr limit



CNG Vehicle Histogram NH_3 Emissions

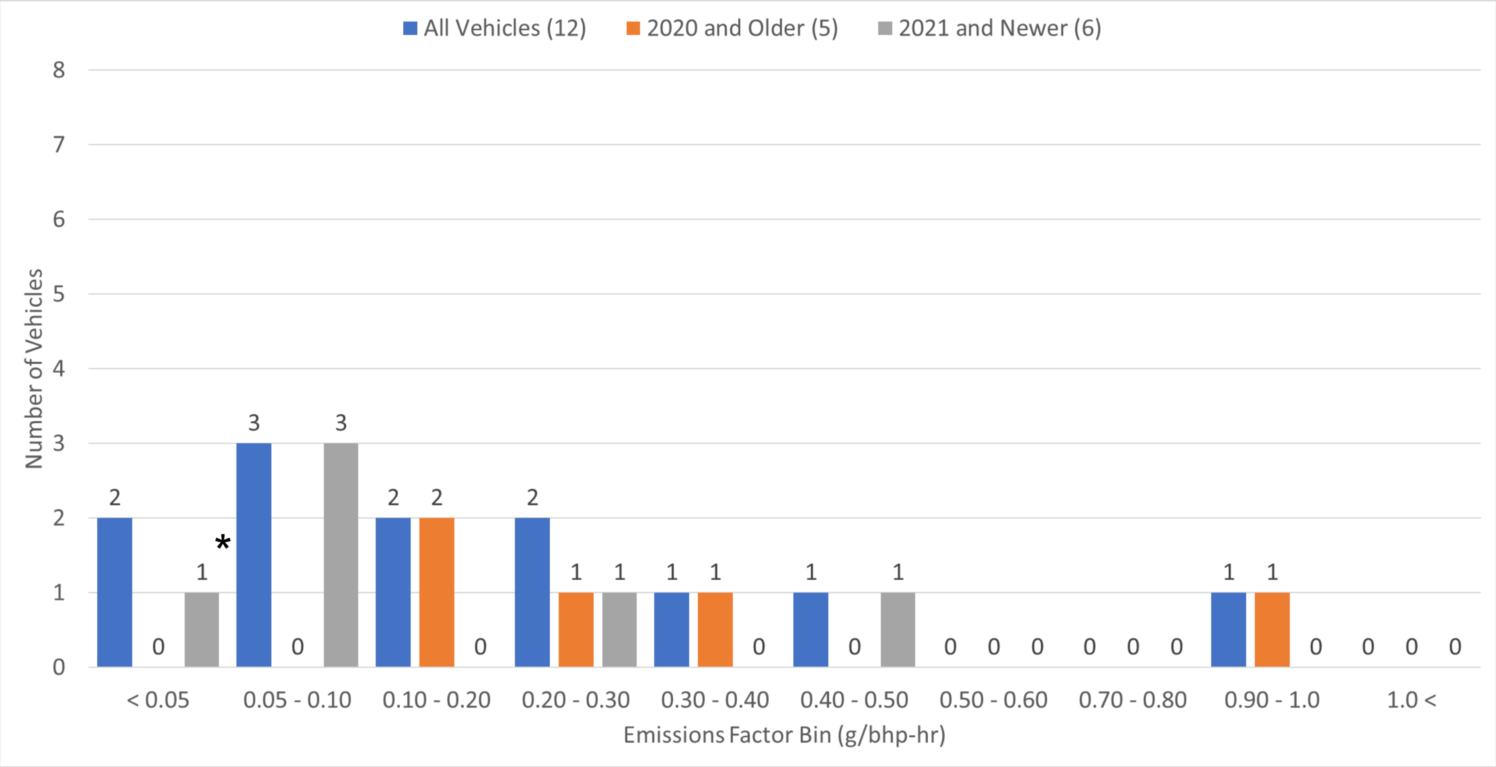
- To the extent that ultralow NOx CNG vehicles expand into the fleet, control of NH_3 emissions would likely need to be addressed more aggressively



Average NH_3 (g/bhp-hr)

Preliminary Diesel Vehicle Emissions Histogram

- Initial data is suggesting lower emission rates than found in “200 vehicle study, with some vehicles showing higher emissions than others.

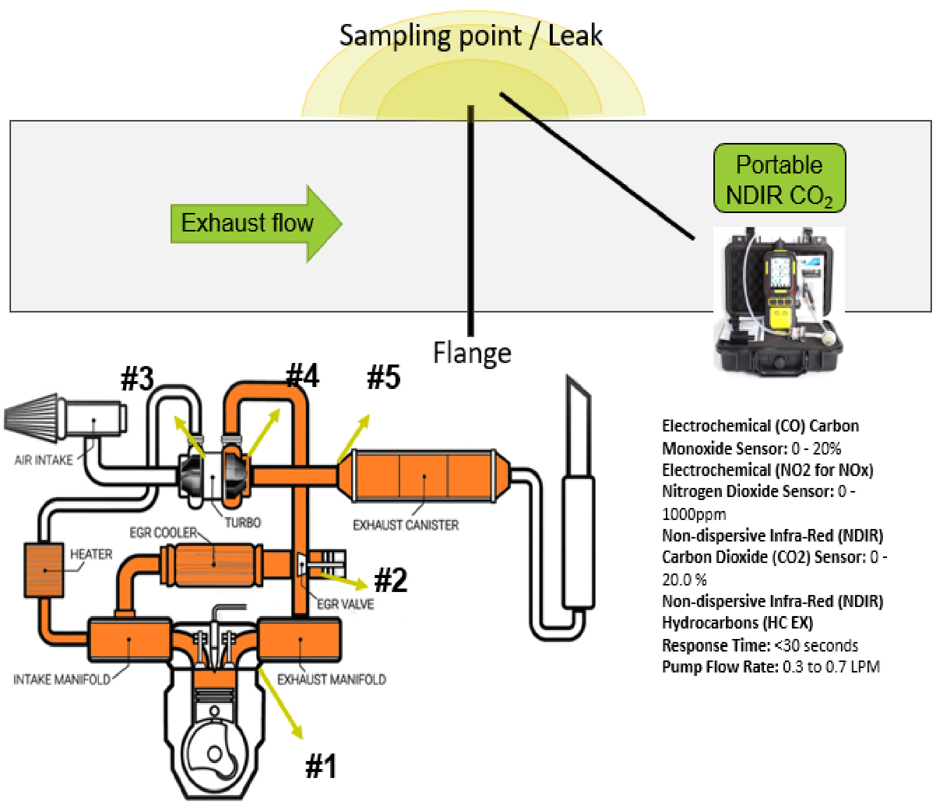


Sum NOx g all trips
Sum Work all trips

*The vehicle missing from this section is from the OEM fleet. We have not been given this information

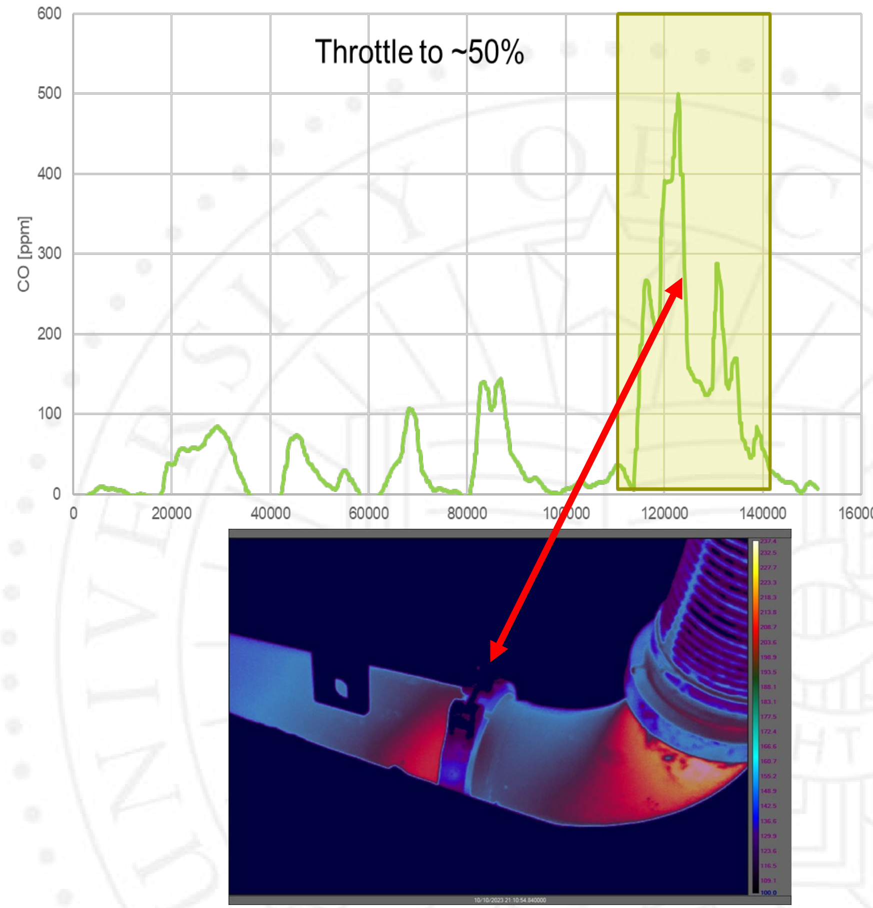
Monitoring for Leaks

- The potential for exhaust leaks prior to the aftertreatment system could add significantly to in-use emission rates
- CE-CERT is currently working on a CARB-funded project to evaluate the potential extent on more than 300 heavy-duty vehicles



Electrochemical (CO) Carbon Monoxide Sensor: 0 - 20%
Electrochemical (NO2 for NOx) Nitrogen Dioxide Sensor: 0 - 1000ppm
Non-dispersive Infra-Red (NDIR) Carbon Dioxide (CO2) Sensor: 0 - 20.0 %
Non-dispersive Infra-Red (NDIR) Hydrocarbons (HC EX)
Response Time: <30 seconds
Pump Flow Rate: 0.3 to 0.7 LPM

Figure 1 Illustration of sampling system methodology



Inspection and Maintenance Programs can play a big role in keeping emissions low

- **High emitters in-use will remain a key consideration for ICEs**
- **The CARB Clean Truck Check program is expected to be one of the most impactful programs approved in decades.**
- **Projected emissions reductions include:**
  - Reductions of 8.6 tons per day (tpd) NO_x and 0.09 tpd PM emissions in San Joaquin Valley (SJV) in 2024.
  - Reductions of statewide NO_x emissions by 81.3 tpd and PM emissions by 0.7 tpd in 2037.
- **Benefits of these PM and NO_x emissions reductions include**
  - Roughly 7,500 avoided premature deaths
  - 6,000 avoided hospitalizations statewide
  - Equivalent monetized health benefits of $75.8 billion for 2023-2050 period.
- **Clean Truck Check would reduce NOx from HDVs >14,000 lbs.**
  - Reductions of 50% in 2031, increasing to a 56% reduction by 2037 compared to baseline.

Inspection and Maintenance Programs can play a big role in keeping emissions low

- Trucks “caught” having high emissions will have to be brought to inspection locations to be evaluated
- UC Riverside CE-CERT involved in the CARBTest “referee” part of this of the program to CE-CERT in part because of our reputation as being an honest broker

Takeaways

- Climate change will likely remain one of the most significant challenges facing the world for the foreseeable future.
- An "All hands on deck" will be needed in the drive to a sustainable transportation future.
- Conventionally-fueled technology vehicles will play a important part in the intermediate term in achieving environmental metrics.
  - Some early data show trends towards lower in-use emissions with later generation vehicles, with some vehicles still having higher emissions.
  - If the vehicles can maintain ultralow emissions during operation, fleet turnover could provide 95% of emissions reductions from 2025 to 2040.
  - This could be coupled with greater renewable fuels use for reducing GHGs.
- Ensuring conventionally fueled vehicles can maintain low or ultralow emissions levels will likely be the key to ensuring continued progress towards achieving future air quality goals.
- Emissions monitoring and inspection will continue to play an important role as we continue our journey to a fully sustainable transportation sector.

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journal homepage: www.elsevier.com/locate/scitotenv

Short Communication

The impacts of improving heavy-duty internal combustion engine technology on reducing NOx emissions inventories going into the future

Troy Hurren [a,b], Thomas D. Durbin [a,b], Kent C. Johnson [a,b], Georgios Karavalakis [a,b,*]

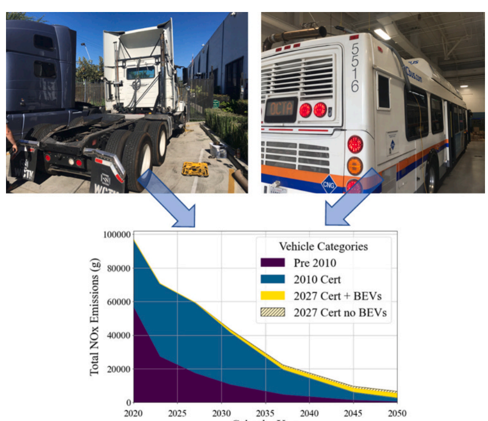
[a] *University of California, Bourns College of Engineering, Center for Environmental Research and Technology (CE-CERT), 1084 Columbia Avenue, Riverside, CA 92507, USA*

[b] *Department of Chemical and Environmental Engineering, Bourns College of Engineering, University of California, Riverside, CA 92521, USA*

HIGHLIGHTS

- Data from 63 heavy-duty vehicles was analyzed using the EPA 2 bin method.
- Existing diesel and natural gas engine technologies can meet future EPA in-use NOx standards.
- NOx emissions trended lower for the 2017–2020 and >2020 diesel vehicles compared to the <2017 vehicles.
- Natural gas engines certified to 0.02 g/bhp-h NOx comfortably meet the 2027 and 2035 NOx standards.
- Using the EPA future standard, NOx can be reduced by 92 % in California by 2050 according to EMFAC.

GRAPHICAL ABSTRACT



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Editor: Pavlos Kassomenos

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Natural gas vehicles
In-use emissions
Emissions inventories

ABSTRACT

In an effort to reduce nitrogen oxide (NOx) emissions and other pollutants from heavy-duty vehicles (HDVs), regulators have been implementing more stringent regulations that have included a combination of significantly more stringent emissions standards with the introduction of battery electric vehicles (BEVs). This study analyzed in-use NOx emissions data from 63 HDVs across various vocations, model years, and engine technologies/fuels to assess which current technologies offer a realistic path toward reducing NOx emissions without significantly burdening fleet operators or electrical infrastructure. All 63 HDVs were equipped with portable emissions measurement systems when they were tested for in-use NOx emissions during their routine operation on California roadways. The data was analyzed using the moving average window method proposed by the Environmental Protection Agency (EPA) in which the in-use emissions are broken up into two bins dependent on the engine load: ≤6 % (idle) and >6 % of maximum rated power. It was found that diesel engines manufactured after 2020 and natural gas engines certified to the 0.02 g/bhp-h NOx standard met the 2027 and 2035 EPA in-use NOx standards for both bins even though the future standards do not apply to these older engines. In addition, over an

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https://doi.org/10.1016/j.scitotenv.2025.179781
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80 % reduction in average NOx emissions is seen in both bins and fuels as modern NOx and greenhouse gas standards were implemented in 2017. With the implementation of ultralow NOx diesel technology engines, capable of meeting 0.035 g/bhp-h NOx limits, it was found that reductions in the NOx emissions inventories from 90.0 to 91.9 % could be achieved by 2050, depending on the deployment of BEVs. In conclusion, current and upcoming engine technologies can serve as benchmark powertrain solutions for emissions inventory reductions in the near and intermediate terms solutions even to the extent that the transition to battery electric HDVs becomes more gradual.

1. Introduction

Heavy-duty vehicles (HDVs) play a vital role in the economy through the movement and distribution of goods. HDVs make up about 10 % of the vehicles on the road but carry >70 % of freight in the United States (U.S.), both by weight and value, with approximately 2.9 million tractor-trailers (Askin et al., 2015). Different vocational HDVs include refuse trucks and transit buses, with approximately 180,000 refuse trucks and about one million buses across the U.S., respectively. The majority of HDVs are powered by diesel-powered compression ignition engines, followed by natural gas engines (Engine Technology Forum, 2023; Askin et al., 2015). HDVs of different vocations are known to contribute to the creation of pollutant emissions and greenhouse gas (GHG) emissions (Teixeira et al., 2020; Anenberg et al., 2017; Quiros et al., 2017). At a global scale, HDVs account for over 40 % of nitrogen oxide (NOx) emissions, over 60 % of particulate matter (PM), >20 % of black carbon emissions, and about 29.4 % of carbon dioxide (CO_2) emissions (Posada et al., 2015). The impact of HDVs on urban air quality is especially important in regions such as the South Coast Air Basin of California, where HDVs represent about 32 % of the NOx emissions inventory (SCAQMD, 2022). Studies have shown the emissions of HDVs and freight movement disproportionally affect disadvantaged communities and poorer areas that may be adjacent to freight corridors, warehouses, and distribution centers (Su et al., 2024; Zalzal and Hatzopoulou, 2022; Ma et al., 2025).

Controlling emissions from HDVs has long been a key goal for both regulatory agencies and the industry. Over the past decades, revolutionary developments have been made to enhance engine efficiency, improve aftertreatment systems, and transition to cleaner fuels. Current heavy-duty diesel vehicles, that are designed to meet a 0.2 g per brake horsepower-hour (g/bhp-h) emissions standards put in place in 2010, are equipped with selective catalytic reduction (SCR) to control NOx emissions, diesel particulate filters (DPF) to control PM emissions, and diesel oxidation catalysts (DOC) to control carbon monoxide (CO) and total hydrocarbon (THC) emissions (Preble et al., 2019; Preble et al., 2018). Many newer diesel engines are also equipped with ammonia oxidation catalysts to reduce ammonia that slips through the SCR system (Zhang et al., 2024). SCR technology has continued to evolve and improve, to the point that engines manufactured beyond 2027 will be required to meet a 0.035 g/bhp-h NOx emissions standard, 10 times lower than the current NOx emissions certification limit (EPA, 2023a). Natural gas engines equipped with three-way catalysts (TWCs) that can meet the 0.02 g/bhp-h level are also readily available for heavy-duty applications and have been deployed in significant numbers for refuse hauler and transit bus applications, and are also available for class 8 trucks, delivery trucks, and other applications (Bae et al., 2024; Smith et al., 2017; Zhu et al., 2024a; McCaffery et al., 2021). Electrification of HDVs has been recognized as a prominent path to reducing harmful pollutants and GHG emissions at the tailpipe (Fleming et al., 2021; Giuliano et al., 2021). Battery electric vehicles (BEV) are also now more readily available for heavy-duty applications, and are now extensively incorporated in regulations both in California, the U.S., and elsewhere (CARB, 2021a; Inflation Reductions Act of 2022; European Commission, 2019).

While these new technologies show promise in reducing emissions and are targeted for rapid integration into the fleet going into the 2030s (Giuliano et al., 2021), 2010-certified heavy-duty diesel engines will still make a significant contribution to the overall fleet for at least the next decade and a half. This is even true based on a "hyper ambitious zero-emission vehicle penetration" scenario using EMission FACtors (EMFAC) modeling from the California Air Resources Board (CARB), which shows that 2010-certified engines will remain a substantial fraction of the in-use fleet throughout the 2030s, and will have a presence going into the 2040s (CARB, 2021b; CARB, 2020). The results for California provide a best-case scenario for fleet turnover given the aggressive targets for BEV deployment under CARB's advanced clean truck (ACT) and advanced clean fleet (ACF) rules, which have been recently withdrawn. This contribution is expected to be even higher in regions outside of California, where the turnover of 2010-certified diesel engines will likely be more gradual. It is also important to note that newer technology vehicles will either be BEVs or, after 2027, diesel engines with ultralow NOx levels. As a result, the contribution of the 2010+ certification engines to urban air quality will likely be considerably greater than it is on a purely population basis.

Given the importance of the contribution of 2010 certification diesel engines to the emissions inventory going into the future, it is important to have a good understanding of their contribution to the emissions inventory. While there have been extensive studies of 2010-certified diesel engines, much of this work has focused on 2010–2016 model year vehicles (Quiros et al., 2016; McCaffery et al., 2021; Jiang et al., 2018; Misra et al., 2013; Dixit et al., 2017; Yu et al., 2021). These represent first generation and early second generation SCR systems, which are relatively early versions of the SCR technology. Since that time, engine manufacturers have continued to develop and refine their engine technologies, as well as SCR, including improvements required to meet progressively more stringent GHG standards in 2017 and 2021. Although studies on these newer technology SCR-equipped HDVs are important to understanding how rapidly the emissions inventory for HDVs will decline going into the future, there is limited data available on engines manufactured after 2017.

This study aims to evaluate the potential for emissions reductions for newer technology diesel and natural gas engines and the impacts that such engines could have on the emissions inventory. This includes an evaluation of more recent data of 2017 and newer emissions data that demonstrate that existing diesel and natural gas technologies equipped with SCR and TWC systems, respectively, can meet future Environmental Protection Agency (EPA) in-use NOx emissions standards using real-world in-use emissions data and the EPA's new two-bin moving average window (MAW) methodology, and that these vehicles show a declining trend in NOx emissions relative to early generation SCR-equipped engines. The importance of improvements in emissions control systems for internal combustion engines in reducing emissions inventories was evaluated with CARB's EMFAC data to predict future HDV emission trends. Such analysis is particularly important in the light of recent pullbacks and scrutiny of regulations designed to promote a more rapid transition to electric (zero-emission) propulsion technologies in the heavy-duty sector. The results in general suggest the significant improvements in emissions inventories can still be achieved with improved internal combustion engine technologies, and in particular with ultralow NOx engines going into the future. These results can provide important information for policy development in the changing landscape of regulations of heavy-duty engines and vehicles.

2. Experimental

2.1. Vehicle selection and testing

A total of 63 HDVs were analyzed for this study. This included vehicles from a wide range of applications and technologies, including HDVs from five different vocations: refuse, school and transit buses, delivery, and goods movements. The technologies/fuels selected for this study include diesel vehicles with 2010 and newer model year engines that are equipped with DPFs and SCR systems certified to a 0.2 g/bhp-h NOx emission limit, a diesel hybrid electric vehicle, compressed natural gas (CNG) and liquefied petroleum gas (LPG) vehicles certified to the 0.2 g/bhp-hp NOx emission limit, and CNG and LPG vehicles certified to 0.02 g/bhp-h NOx emission limit. The 2010+ diesel vehicles also included a range of different model years, which allowed the improvement in the SCR technology over time to be evaluated. Specifically, the fleet was divided into three distinct model year groups, each representing a different phase of GHG regulations. All model year engines manufactured before 2017 are considered pre-phase 1 U.S. EPA GHG engines, any built from 2017 to 2020 are phase 1 GHG engines (EPA, 2011), and any built after 2020 are considered phase 2 GHG engines (EPA, 2016). Although the separation is based on GHG standards, it is understood that improvements in SCR technology have also occurred on an ongoing basis over the same time periods. Table 1 presents a breakdown of the number of vehicles in each technology category that are included in the analysis.

The emissions data obtained from these HDVs was collected over a series of in-use emissions measurement programs. The majority of the emissions data (50 of the 63 vehicles) were obtained from a study by McCaffery et al. (2021) and the engine model year, vocation, and fuel/technology details of these 50 vehicles, as well as the measurement techniques have been published in that study. Emissions measurements were made with portable emissions measurement systems (PEMS) over a normal day of use for the vehicle in its typical fleet operations. Each vocational vehicle carried out its typical activity, such as refuse vehicles picking up trash, transit and school buses picking up and dropping off passengers, and goods movement and delivery vehicles picking up and dropping off loads. Another 6 vehicles were from a study by Ma et al. (2024) that included 6 goods movement vehicles operating in the San Joaquin Valley region of California. These data were also obtained from PEMS measurements over normal daily operations. Zhu et al. (2024a, 2024b) provided data for 5 goods movement vehicles when operated on various routes in the South Coast Air Basin that were designed based on the activity patterns of various goods movement fleets. Emissions measurements were obtained from CE-CERT's Mobile Emissions Laboratory (MEL) using laboratory-grade equipment. The remaining 2 vehicles were diesel goods movement vehicles of model years 2019 and 2021 tested using the MEL (Ma et al., 2025).

2.2. Data analysis

The data was analyzed using the moving average window (MAW) method, which the EPA will implement for in-use compliance testing starting in 2027 (EPA, 2023b). This method is replacing the not-to-exceed (NTE) testing procedure, which had exclusion criteria for low-load engine operating modes where the SCR system is typically below the light-off regime (Demirgok et al., 2021). A study by Pondicherry et al. (2021) highlights the importance of replacing the NTE method with a form of a MAW method for in-use certification procedures to better capture the entire operating range of in-fleet operation, and not only operating modes that are favorable to NOx reduction aftertreatment systems. The method is based on 2 bins as shown in Table 2 based on the engine load. Engine load is calculated using the normalized CO_2 rate from the certification test cycles. Each bin consists of 300 s worth of data collected at 1 Hz. The average CO_2 emission rate (g/ghp-h) is divided by the engine Federal test Procedure (FTP) CO_2 certification level (FCL) (g/bhp-h) and the maximum horsepower (hp) output of the engine. This fraction/percentage is then used to determine which bin the window is categorized in. After bins have been assigned for each 300 s operating window, a sum-over-sum (SOS) approach is used to determine whether a vehicle passes the emissions criteria for each bin. For bin 1, the SOS emissions are reported in g/h. The SOS emissions for bin 2 are reported in g/bhp-h.

It should be noted that not all vehicles tested in this study had an FCL and/or maximum power output rating. For those vehicles, the maximum CO_2 emission rate and power output measured during the testing period were used for the FCL and/or maximum horsepower. More details on the equations used to calculate these values can be found in the Supplementary Material (SM). The NOx data for each vehicle was categorized using the EPA binning method described with Equation SM1 and then analyzed using Equations SM2 and SM3, which are all included in the SM section. The vehicle was considered to have passed the NOx emissions criteria if the SOS NOx emissions for each bin met or were below the NOx limits set by the EPA. These standards are categorized by two different times in which they will take effect: 2027 and 2035, as shown in Table 2. Bin 1 standards are set to conform with the Clean Idle standard with a conformity factor of 1.0. Bin 2 standards are set to conform to the Light Load Cycle (LLC) and the heavy-duty Supplemental Emissions Test (SET) with a compliance margin factor of 1.5. Table 2 lists the NOx SOS standards for each year using the MAW method prescribed by EPA.

3. Results and discussion

Fig. 1 shows the SOS NOx emissions grouped by technology/fuel for bin 1 and bin 2 on a g/h and g/bhp-h basis, respectively. The data in each category are shown as a box and whisker plot for categories with 5 or more vehicles, or individual dots for categories that have fewer than 5 data points. For example, there were only three transit buses with natural gas engines certified to 0.2 g/bhp-h NOx, so the vehicles in this category are represented by dots in Fig. 1. For the box and whisker plots, the line represents the mean value, the box represents the first and third

Table 2
EPA proposed engine load parameters for 2 moving average window (MAW) bins and their respective pass criteria for 2027 and 2035 EPA NOx standards.

Bin	Percent engine load	2027 SOS NOx Standard	2035 SOS NOx Standard
1	≤6 %	10 (g/h)	10 (g/h)
2	>6 %	73 (mg/bhp-h)	58 (mg/bhp-h)

Table 1
Matrix of vehicle vocations and technologies.

Vocation	Diesel MY <2017	Diesel MY 2017–2020	Diesel MY>2020	Diesel-Battery Hybrid Electric	NG 0.2 NOx	NG 0.02 NOx	LPG	Total
School Bus	1				4		1	6
Transit Bus					3	3		6
Refuse Hauler					6	1		7
Goods Transport	16	2	1		5	10		34
Delivery Vehicle	4			2	2		2	10
Total	21	2	1	2	20	14	3	63

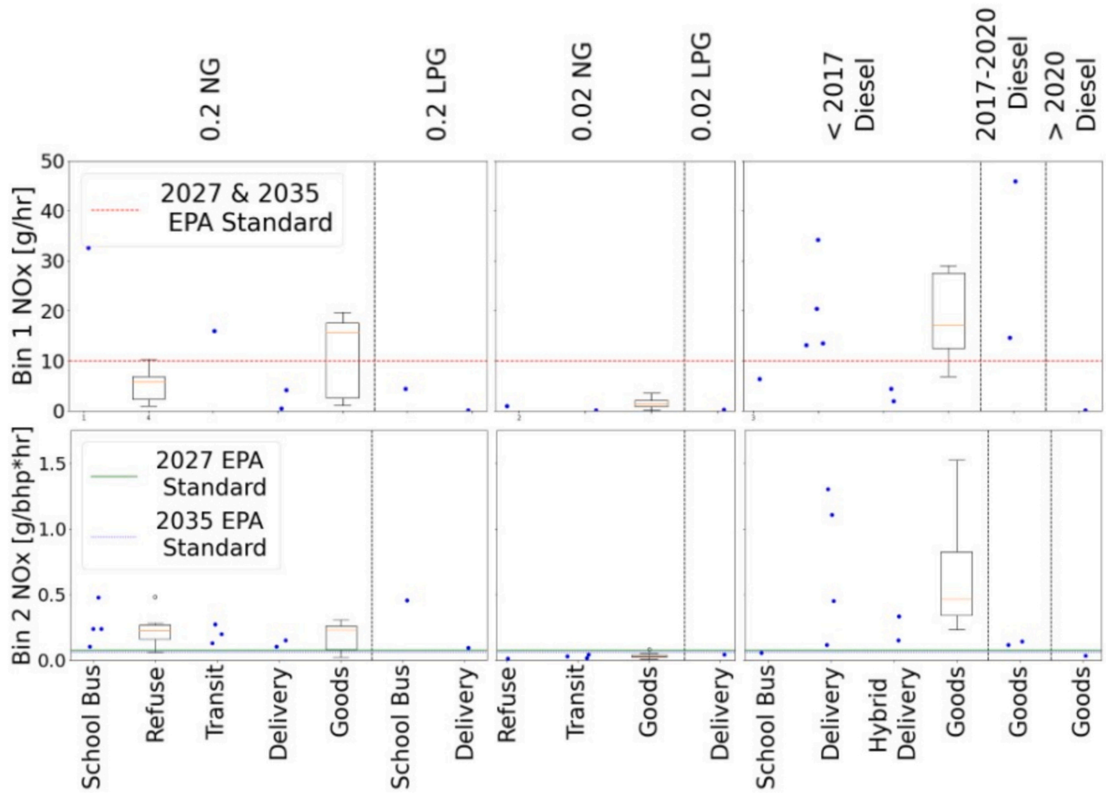

Fig. 1. Bin 1 and bin 2 of all different vocational HDVs grouped by technology/fuel/certification years.

quartiles, and the whiskers represent the minimum and maximum values with outliers represented by white dots with a black outline. Because a minimum window of 300 s is required to categorize the real-time engine load as either bin 1 or bin 2, as seen in Equation SM1 (SM), some vehicles did not meet the requirements for having data for each bin. For example, a total of seven school buses were tested, but only three of them had operations where at least one period met the minimum requirement of 300 consecutive seconds of engine load below the 6 % maximum power rating threshold for valid bin 1 NOx emissions. However, all seven school buses had valid bin 2 NOx emissions data.

The 2027 and 2035 EPA in-use NOx standards are also shown in Fig. 1. For bin 1, the standard for both years is 10 g/h, which is represented by the dashed line in the bin 1 plots. For bin 2, the standard of 73 mg/bhp-h for 2027 is represented by the solid line and 58 mg/bhp-h for 2035 is represented by the dotted line. Any dots or box and whisker plots that appear below these lines are vehicles that are already capable of meeting the 2027 and/or 2035 EPA in-use NOx standards. It should be noted that the vehicles tested in this program were not designed to meet the 2027 and 2035 EPA NOx standards, and hence the observation of emissions above the future limits does not indicate a failure from a regulatory perspective. Instead, comparisons with these criteria highlight the technological progress that has been made with existing engines ahead of the introduction of the regulations.

3.1. Diesel vehicles

Comparisons of the different technologies/fuels in Fig. 1 show that diesel engines manufactured before 2017 are on average the highest emitters of NOx for both bins. This finding corresponds with observations made by McCaffery et al. (2021), where all diesel HDVs tested were manufactured before 2017 and had on average the highest NOx emissions across all vocations and engine technologies. The emission factors for these older vehicles are also consistent with results from a wider range of studies that were utilized in the development of the EMFAC2017 and EMFAC2021 models, which included results from CARB surveillance testing (CARB, 2018; CARB, 2021c). However, for all diesel vehicles, there is a trend of lower NOx emissions for the 2017–2020 and >2020 diesel vehicles compared to the <2017 vehicles. For goods movement vehicles with 2017 to 2020 and 2021+ model year diesel engines, respectively, emissions were lower by an average of 46 % and 99 % for bin 1 and 78 % and 96 % for bin 2 compared to pre-2017 diesel vehicles. This represents total reductions of over 99 % and 96 % for bin 1 and bin 2, respectively, for engines manufactured under pre-phase 1 GHG regulations compared to engines manufactured under the current phase 2 GHG regulations.

Although the data for 2017 and newer vehicles are more limited, it is noteworthy that even some later-generation diesel vehicles certified to the 2010 0.2 g/bhp-h NOx standard are already demonstrating the potential to meet the 2027 and 2035 NOx standards for both bins. A study by Li and Lin (2021) on a 2019 model year heavy-duty goods movement vehicle certified to the China VI standard also reported NOx emission rates of 1.4 g/mile, which were similar to the rates found in the current study. This represents about a 60 % reduction as compared to the vehicles older than 2017 tested in our work. In another study, Lyu et al. (2023) found that even after 200,000 km of on-road driving, the real-world NOx emission factor for a 2021 heavy-duty vehicle meeting the China VI certification level was 1.6 g/mile, which is nearly half the value of the standard. This suggests that technological improvements in the SCR and associated emissions control systems are more broadly available on a global scale. More recently, Durbin et al. (2025) reported preliminary data from NOx sensors installed on diesel HDVs operating under real-world conditions, showing that the majority of vehicles newer than model year 2020 (10 of 11) had average emissions no more than twice the 0.02 g/bhp-h level.

The diesel hybrid electric vehicles showed on average NOx emissions nearly 70 % below the bin 1 certification levels for 2027 and 2035. However, they did not meet either future NOx standards for bin 2 exceeding them by 3 and 4 times on average for 2027 and 2035, respectively. Both diesel hybrid electric vehicles were delivery trucks characterized by frequent stop-and-go operations, which caused engine-off moments that resulted in lower exhaust gas temperatures. These thermal conditions for the SCR system were not favorable for efficient NOx reductions for these vehicles. Several other studies have also reported reduced SCR efficiencies and elevated NOx emissions during in-use operating conditions with a lot of stop-and-go driving for vocational vehicles (Quiros et al., 2016; McCaffery et al., 2021; Pondicherry et al., 2021).

3.2. Natural gas vehicles

While NOx emissions from diesel HDVs have steadily declined with newer model years and new GHG standards, natural gas vehicles exhibit a more distinct trend, marked by a significant step change in emissions following the implementation of engines capable of meeting the stricter 0.02 g/bhp-h NOx standards starting in 2016, setting them apart from their diesel counterparts. Most notably, nearly all 0.02 certified vehicles across all vocations met the 2027 and 2035 EPA NOx standards whereas only two 0.2 certified natural gas vehicles met at least one of the future standards. For the goods movement vehicles, NOx emissions were reduced by an average of 90 % and 80 % for bin 1 and bin 2, respectively, between these two technology categories. Similar reductions of approximately 80 % were observed in the study by McCaffery et al. (2021). In a recent study, Durbin et al. (2025) reported initial results from monitoring a larger sample of 0.02 natural gas vehicles with a NOx-sensor system installed on these vehicles operating under real-world conditions. They showed that the majority of vehicles (75 of 85) had average emissions no more than twice the 0.02 g/bhp-h level, with a smaller subset of 10 with higher emissions, including 4 with emissions >0.10 g/bhp-h. The average brake-specific NOx for all goods movement natural gas vehicles certified to 0.02 g/bhp-h tested in this work was also 95 % lower than the average value of the pre-2017 diesel vehicles of the same vocation. The 0.02 g natural gas vehicles also had average NOx emissions that were 74 % lower than the diesel vehicles manufactured between 2017 and 2020. The brake-specific NOx emissions for the single diesel vehicle manufactured after 2020 in this study were nearly identical to the average NOx emissions of all ten natural gas goods movement vehicles, suggesting that diesel vehicles also have the capability of performing at low NOx levels. The LPG vehicles showed trends similar to those for the natural gas vehicles between the different NOx certification levels, with the 0.02 LPG vehicles showing reductions of 55 % compared to the 0.2 LPG vehicles for bin 2.

NOx emission factors on a per mile basis across the technologies and model years are provided in Fig. 2. The natural gas vehicles certified to 0.02 g/bhp-h NOx levels showed NOx emissions from <0.1 to up to 0.6 g/mile of NOx across all vocations, whereas the 0.2 certified natural gas vehicles showed more variability and higher average NOx emissions. Diesel goods movement vehicles produced between 2017 and 2020 showed NOx emissions of <0.6 g/mile and diesel goods vehicles produced before 2017 ranged from ~0.5 to 7 g/mile. The single vehicle newer than 2020 showed NOx emissions of approximately 0.13 g/mile.

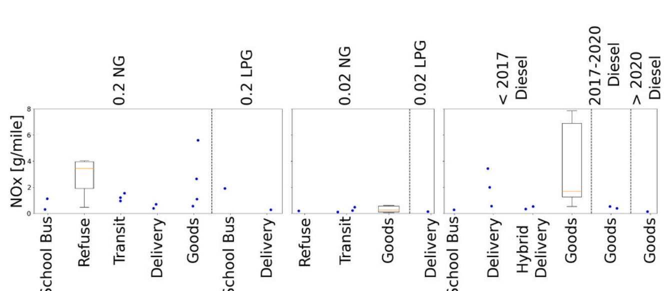

Fig. 2. NOx emissions expressed in g/mile grouped by technology/fuel/certification years.

3.3. Emissions inventory

CARB's EMFAC online tool, which uses the exact same emissions as those provided in the EMFAC2021 software model, was used to assess the impacts that technology improvements for HDVs will have on emissions inventories (CARB, 2021b). Using the CARB EMFAC model, emissions inventories for different scenarios of vehicle technology apportionments can be projected up to the year 2050. Fig. 3 shows the default population distribution of class 3 through class 8 HDVs, including motor homes and buses, according to certification year and technology up to the year 2050 as predicted by the EMFAC model. The results reported here show that by the year 2027, the newly certified internal combustion engine (ICE)-powered HDVs and BEVs will begin displacing some of the older, higher polluting vehicles. The figure also shows an overall increase of approximately 25 % in the number of HDVs (ICE-powered and BEVs) between 2020 and 2050. In the scenario presented in Fig. 3, heavy-duty BEVs are expected to make up approximately 40 % of the total HDV distribution by 2050, and HDVs equipped with ICEs certified to 2027 or higher are expected to make up most of the remaining 60 %, with some residual contribution from 2010 to 2027 MY ICE-powered HDVs.

For the population distribution shown in Fig. 3, different emissions inventories were developed. Two scenarios are shown in Fig. 4 and Fig. 5. The emissions inventory shown in Fig. 4 is based on the default NOx emission rates as provided in the current EMFAC2021 version. The corresponding base average NOx emission rates for each model year category, as used in the model, are shown in Table 3. Under this scenario, total NOx emissions by 2050 are estimated to decrease by nearly 50 %, with 2027 and newer certification vehicles representing over 95 % of the total NOx emissions in 2050. While the default scenario shown in Fig. 4 shows that emissions inventories will decrease over time, the emission rates used in the EMFAC2021 model do not reflect the more recent adoption of more stringent NOx emission standards beginning with the 2027 and 2035 model years.

For the second emissions inventory estimate presented in Fig. 5, the default emission factors for the 2027 and newer trucks were modified to reflect the lower certification limits for the 2027 and 2035 model years. These standards were implemented after an extensive technology development program of ultra-low NOx engines was conducted at the Southwest Research Institute Laboratory, and by the engine manufacturers to achieve NOx emissions <0.02 g/bhp-h over the heavy-duty FTP cycle, as well as the requirements over other cycles and durability targets (Sharp et al., 2017; Rao et al., 2020). It should be noted that many major engine manufacturers have already introduced engines designed to meet these requirements or with emissions approaching these levels

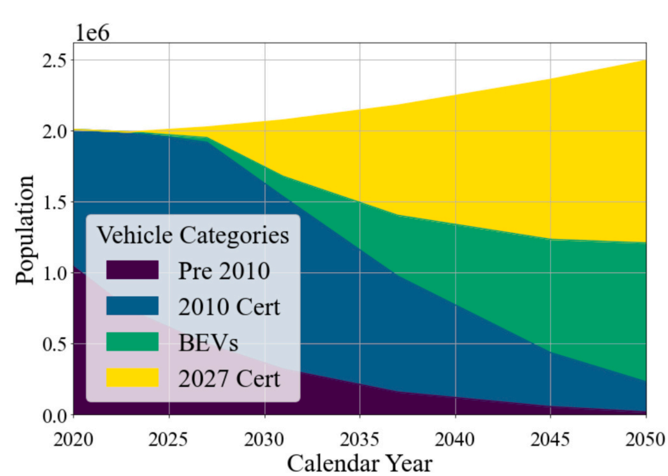

Fig. 3. EMFAC heavy-duty vehicle distribution according to vehicle technology and certification up to year 2050.

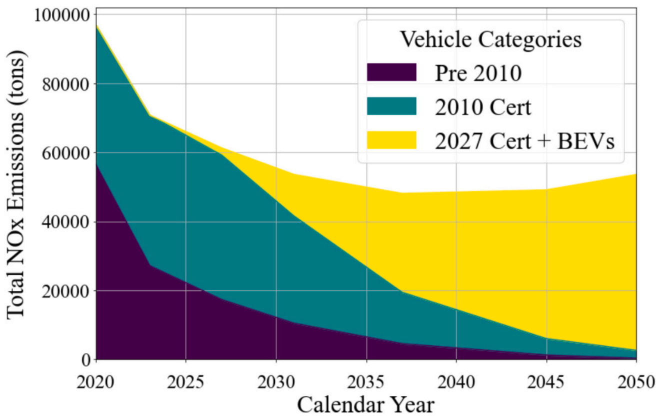

Fig. 4. Total NOx emissions from heavy-duty vehicles according to EMFAC emission rates.

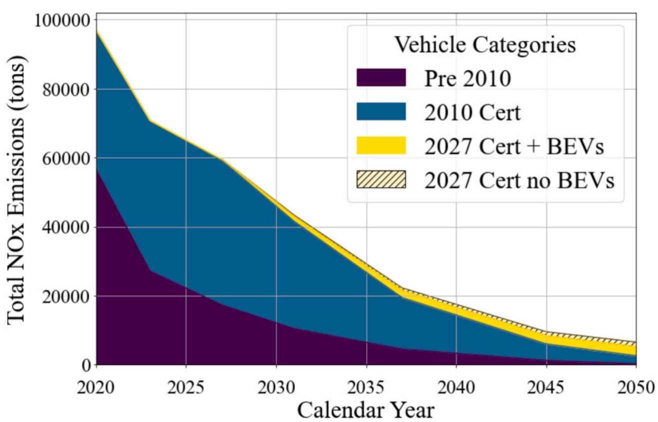

Fig. 5. Total NOx emissions from heavy-duty vehicles according to 2027 and 2035 certification NOx emission rates.

Table 3
EMFAC2021 specific NOx default data.

Model year category	NOx (g/mile)
Pre 2010	4.3
2010–2017	1.9
2017–2020	1.0
2021–2026	0.77
2027–2035	0.48
2035–2050	0.44

(Joshi, 2025), so the feasibility of the technology has been demonstrated. To convert the brake-specific certification values (in g/bhp-h) to vehicle-specific values (in g/mile), an energy use estimate of 4 bhp-h/mile was applied, which represents the upper limit of the range of values found in the literature, which in turn provides for a more conservative estimate of how high the emissions rates might be on a g/mile basis. EPA estimates for most vehicle types fall below this value, with a range from 1.1 bhp-h/mile for Class 2B diesel vehicles to 3.3 bhp-h/mile for Class 8B vehicles, with only diesel transit buses reaching as high as 4.7 bhp-h/mile (EPA, 2002). CARB uses similar conversation factors for calculations relating to various incentive programs, with estimated energy use values ranging from 1.8 to 4.0 bhp-h/mile, with transit buses again at the upper end (CARB, 2008). A study by Zhang et al. (2021) also reported an average conversion factor of approximately 3 to 4 bhp-h/mile under test cycles designed to be representative of typical vocational heavy-duty vehicle operating conditions as well as extreme cycles. Our internal evaluations of such factors over a wide range of vehicles fall within a similar range. It should be noted that to the extent that the conversion factor is <4 bhp-h/mile, the resulting emissions inventories would be even lower and show a greater reduction in NOx emissions.

Applying the lower brake-specific certification rates using the 4 bhp-h/mile conversion factor results in a base NOx emission factor of 0.14 g/mile – significantly lower than the default assumptions. This leads to a substantial reduction in the projected NOx emissions inventory. Specifically, total NOx emission reductions of 91.9 % are found between 2025 and 2050, as opposed to only 50 % reductions for the default scenario shown in Fig. 4. For the adjusted emissions inventory estimates, the 2027 and newer certified vehicles make up about 50 % of the total NOx emissions by the year 2050. Between 2025 and 2045, the results indicate that the reduction in the emissions inventory is primarily from reductions in emissions from vehicles manufactured between 2010 and 2026. This suggests that fleet turnover from 2010 to 2026 technology vehicles, coupled with the implementation of significantly tighter emissions beginning in 2027, will be the main factors in improving emissions inventories over time. To the extent that vehicle technologies could transition to completely zero emissions after 2027, this would only provide an additional 5.1 % reduction in emissions.

Furthermore, a scenario was run to evaluate what the emissions inventory reductions would be if no BEVs were to be introduced after 2025. Although the heavy-duty vehicle going into the future will likely be some combination of internal combustion engines and BEVs, following the recent withdrawal of CARB's ACF regulation (CARB, 2025a, 2025b) and the transmission of the ACT regulation waiver to Congress (U.S. EPA, 2025), the extent to which BEVs will be adopted in the near term remains more uncertain. As such, it is worthwhile to run a scenario to look at the worst-case scenario of the impacts of decreasing the deployment of heavy-duty BEVs. For this scenario, the BEVs in the population were replaced with 2027+ ultralow NOx diesel engines. The added emissions from this scenario are shown by the hashed segment in Fig. 5, which shows that the emissions reductions that can be achieved based entirely on 2027 and later diesel technology would only be two percentage points less by 2050 as compared to the mixed-technology approach. Despite the population distribution of ICE-powered HDVs and BEVs being nearly identical in 2050, the additional NOx emissions of 2027 ICE-powered HDVs no BEVs, represented by the hashed segment, are less than those represented by the 2027 + BEVs segment. This is because the NOx emissions are estimated based on total vehicle miles traveled (VMT) in the EMFAC model, which predicts BEVs to drive 52 % fewer miles than ICE-powered HDVs in 2050 (CARB, 2025a). Although there is a slight increase in the emissions inventory with the removal of the BEVs, the results still suggest that reductions of 90.0 % in the NOx emissions inventory would be possible by 2050 with the newer and upcoming internal combustion engine technologies. It is also important to note that maintaining the emissions of more conventional technology vehicles throughout their lifetime will be crucial to achieving their full reduction potential. Poorly maintained or tampered vehicles can emit significantly higher levels of pollutants compared to well-maintained ones (Fulper et al., 2025; Tian et al., 2024). Therefore, robust inspection and maintenance programs should be implemented alongside the introduction of new ultralow NOx technology vehicles (Jiang et al., 2021) and efforts should continue to detect and mitigate the impacts of tampering (Fulper et al., 2025).

4. Implications

Understanding the emissions profiles of 2010+ SCR-equipped diesel and ultralow NOx CNG and LPG vehicles is important for policy development, especially as the fleet turnover of these vehicles will be the main contributing factor in reducing emissions for the heavy-duty transportation sector. This study evaluated a comprehensive set of 2010+ technology heavy-duty vehicles to assess the impact of technological improvements from 2010 to the present on in-use NOx emissions. It also included several 2017 and newer vehicles, for which limited data is available. The results show that newer technology SCR-equipped diesel and ultralow 0.02 g/bhp-h natural gas and LPG vehicles demonstrate the potential for continued emissions reductions. With the implementation of ultralow NOx diesel technology engines, capable of meeting 0.035 g/bhp-h NOx limits, it was found that reductions in the NOx emissions inventories from 90.0 % to 91.9 % could be achieved by 2050, depending on the deployment of BEVs.

Overall, the results suggest that significant reductions in the emissions inventory of the in-use heavy-duty vehicle fleet can be achieved with improved internal combustion engines, which likely will have important implications for air quality at a regional and local level, and in environmental justice areas. Although the current study does not address the transition to zero tailpipe emissions vehicles, the results reported here can play a crucial role in shaping the ongoing discussion about the pace of this transition. As the transport industry undergoes significant transformation, it is expected that there will continue to be a need to strike a balance between the more aggressive adoption of new technologies and the economic realities that countries face. In a rapidly changing environment, where economic resources may be limited, it will be important for nations to invest strategically in the most effective technologies available to combat climate change and reduce air pollution, while also considering the feasibility of such investments. The findings of this study suggest that conventional diesel and alternative fuel vehicles, such as natural gas and LPG vehicles certified to 0.02 g/bhp-h NOx emissions, can meet the stringent NOx emissions standards set for 2027 and 2035 even under more in-use conditions. This indicates that even if the transition to fully zero-emissions HDVs occurs more gradually, newer technology conventional diesel and alternative fuel vehicles can still provide substantial and meaningful emissions reductions in the intermediate term, and in the near term as battery electric technology continues to develop.

It is suggested that heavy-duty inspection and maintenance programs and efforts for identifying and mitigating the impacts of tampering should be implemented on a more widespread scale in conjunction with the deployment of any combustion-related ultralow NOx engines to ensure the ultralow emissions levels can be maintained over the course of the vehicle's lifetime. Furthermore, replacing older, higher emitting HDVs with ultralow NOx conventional and alternative fuel vehicles operating on low carbon intensity fuels can provide additional benefits in reducing GHG emissions. In particular, renewable diesel and biodiesel provide significant reductions in carbon intensity relative to petroleum-based diesel fuel, which is particularly significant in markets such as California, where >50 % of the diesel fuel pool is from renewable sources. For natural gas vehicles, which have been available with ultralow NOx engines for more than a decade, even greater reductions can be achieved with renewable natural gas, which has a net-zero or even a net-negative carbon intensity. Furthermore, replacing older, higher-emitting HDVs with ultralow NOx natural gas alternatives - available for nearly a decade and far more economical than electric propulsion powertrains - provides an opportunity to cut GHG emissions through the use of renewable natural gas.

CRediT authorship contribution statement

Troy Hurren: Writing – original draft, Investigation, Formal analysis. **Thomas D. Durbin:** Writing – review & editing, Validation, Methodology, Data curation. **Kent C. Johnson:** Validation, Methodology, Formal analysis, Data curation. **Georgios Karavalakis:** Writing – review & editing, Supervision, Project administration, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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