CALIFORNIA
ENERGY COMMISSION

CALIFORNIA
NATURAL
RESOURCES
AGENCY

Energy Research and Development Division

FINAL PROJECT REPORT

In-Use Emissions Testing and Activity Profiles for On-Road Heavy-Duty Vehicles

Summary of 200 Heavy-Duty Vehicle Emissions Testing Program from the University of California, Riverside and West Virginia University

March 2023 | CEC-500-2023-002

PREPARED BY:

Primary Authors:
Jonathan Leonard[1], Patrick Couch[1], Thomas D. Durbin, Ph.D., Kent Johnson, Ph.D. et al [2], Arvind Thiruvengadam, Ph.D., Marc Besch, Ph.D.et al[3], Sam Cao, Ph.D. et al

[1]Gladstein, Neandross & Associates (Main Report)
2525 Ocean Park Blvd., Suite 200
Santa Monica, CA 90405
310-314-1934
www.gladstein.org

[2]**Appendix A** (UCR-CE-CERT Final Report to SCAQMD)
UC Riverside, College of Engineering Center for Environmental Research & Technology
1084 Columbia Ave
Riverside, CA 92507
951-781-5791
www.cert.ucr.edu/emissions-and-fuels

[3]**Appendix B** (WVU Final Report to SCAQMD)
West Virginia University Center for Alternative Fuels, Engines & Emissions
1306 Evansdale Drive | PO Box 6106
Morgantown, WV 26506
304-241-1273
www.cafee.wvu.edu/

Contract Numbers: 500-15-002 (CEC), 5660048487 (SCG), 16RD012 (CARB)

PREPARED FOR:
California Energy Commission
South Coast Air Quality Management District
California Air Resources Board
Southern California Gas Company

Peter Chen
Project Manager

Reynaldo Gonzalez
Office Manager
ENERGY SYSTEMS RESEARCH BRANCH

Jonah Steinbuck, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

In addition to Commission Agreement Manager Peter Chen and the respective authors for Appendix A and Appendix B from the two universities, the project team members from GNA wish to gratefully acknowledge the assistance and/or support given by the following individuals/organizations:

- Sam Cao, Fan Xu, Dana Foist, South Coast Air Quality Management District
- Chris Ruehl, Yi Tan, Seungju Yoon, Sara Forestieri, Lei Zhou, California Air Resources Board
- Michael Lee, Matt Gregori, Alan Leung and Jeffery Chase, Southern California Gas Company
- Filiz Kazan, Arvind Thiruvengadam and Marc Besch, West Virginia University
- Adewale Oshinuga, Wale Associates Corporation
- Tom Durbin, Hanwei Zhu, Chengguo Li, University of California, Riverside

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. ,This program promotes greater reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture, and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Transportation.

In-Use Emissions Testing and Fuel Usage Profiles for On-Road Heavy-Duty Vehicles: Summary of 200 Heavy-Duty Vehicle Emissions Testing Program from the University of California, Riverside and West Virginia University is the final report for the On-Road, In-Use Emissions and Fuel Usage Assessment project (500-15-002). This summary report was prepared by Gladstein, Neandross & Associates, with strong support from multiple parties (see Acknowledgements); technical conduct was prepared by the two noted universities. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California's on-road heavy-duty vehicles are major sources of harmful air pollutants, especially nitrogen oxides (NOx) which contribute to formation of ground level ozone and fine particulate matter. The South Coast Air Basin, which is in "extreme nonattainment" for national ozone standards, depends on systematic and rapid NOx emission reductions from heavy-duty vehicles. While new on-road heavy-duty vehicle models meet stringent emissions standards and even-tougher standards are coming by 2024, "in-use" vehicles can sometimes emit NOx and other pollutants at higher-than-design levels. This hinders progress toward attainment and understates emission inventories.

In this comprehensive, multi-year, four-phase program, the University of California, Riverside and West Virginia University collaborated with four industry and government agency co-sponsors to test more than 200 heavy-duty vehicles, making it one of the world's largest efforts to test in-use heavy-duty vehicle tailpipe emissions.

The program's goals were to better characterize emissions of heavy-duty vehicles using conventional and alternative powertrains under real-world operating conditions, and to further understand causes for higher emissions, especially for NOx. The program provided insights for development and implementation of advanced technologies and expedited reductions needed for attainment of air quality standards.

Measured emission levels varied widely across different duty cycles, test methods, engine/fuel technologies, and vocations. Heavy-duty vehicles tested ranged from model year 2001 to 2019, and most exhibited elevated in-use emissions under operational conditions differ than certification cycle. New heavy-duty vehicle emission regulations have both included additional measures that address the gap between certification and in-use, and over various duty cycles. This extensive test program has also successfully provided new data to improve air quality modeling and planning. Program findings are informing follow-up work, policy decisions, and program development.

Key words: Emissions testing, heavy-duty vehicles, in-use emissions, certification levels, not-to-exceed (NTE), portable activity measurement systems (PAMS), portable emissions measurement systems (PEMS), chassis dynamometer emissions testing, EMFAC2021, natural gas, low oxides of nitrogen (NOx) engines, optional low NOx standard (OLNS), 0.02 g/bhp-hr, near-zero emission (NZE).

Please use the following citation for this report:

Leonard, Jonathan; Couch, Patrick; Durbin, Thomas; Besch, Marc; Cao, Tanfeng; 2022. "*In-Use Emissions Testing and Activity Profiles for On-Road Heavy-Duty Engines: Summary of 200 Heavy-Duty Vehicle Emissions Testing Program from the University of California, Riverside and West Virginia University*." California Energy Commission. Publication Number: CEC-500-2023-002.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

On-road heavy-duty vehicles (HDVs), primarily consisting of freight trucks, transit buses, delivery vehicles, school buses, and refuse trucks, are major sources of criteria pollutant and greenhouse gas emissions California and in the South Coast Air Basin. The South Coast Air Basin is one of only two air basins in the U.S. categorized as being in "extreme nonattainment" of health-based national ambient air quality standards for ozone. Mobile sources, with HDVs being the top emitter, emit approximately 80 percent of the South Coast Air Basin's inventory for oxides of nitrogen (NOx), which is the primary precursor of ground level ozone. Rapid NOx emission reduction from HDVs is, therefore, a critical step towards achieving ozone standards.

Over the last 30 years, major progress has been made to reduce HDV emissions of NOx, as well as particulate matter, resulting in improved ambient air quality in the South Coast Air Basin and throughout California. New emission standards for on-road HDVs that took effect for model years 2007 and 2010 led to widespread implementation of vehicles equipped with diesel particle filters to control particulate matter emissions, and selective catalytic reduction to control NOx emissions. As these two exhaust aftertreatment technologies have become almost fully implemented into California's in-use HDV fleet, they have provided major particulate matter and NOx reductions from diesel-fueled trucks, buses and other mobile sources. With the implementation of even-more-stringent emissions standards under the California Air Resources Board Heavy-Duty Omnibus Regulation starting in 2024, it is expected that in-use emissions from HDVs will continue to decline.

Additionally, particulate matter and NOx emissions from HDVs, especially in the South Coast Air Basin, have been reduced through commercial introduction and fleet adoption of vehicles powered by natural gas engines, including those that meet the California Air Resources Board's lowest-tier "optional low-NOx standard."

Major ambient air quality improvements have been realized as diesel HDVs with advanced exhaust aftertreatment systems and those powered by alternative fuel platforms have been integrated into California's HDV fleet. Notwithstanding these major gains, previous in-use HDV emission testing programs have shown that both MY 2010+ diesel HDVs as well as natura gas HDVs can emit NOx, and sometimes particulate matter, significantly higher levels than certification standards under real-world driving conditions. Therefore, there is a need to build on previous studies with additional data from extensive real-world activity data collection as well as including engines certified to the optional low-NOx standard.

To improve understanding of this phenomenon and expand the knowledge of how in-use HDVs emit in real-world, the California Energy Commission, California Air Resources Board, the South Coast Air Quality Management District, and the Southern California Gas Company cosponsored this 200 Heavy-Duty Vehicle In-Use Emissions Testing Program (Program)and chose University of California at Riverside (UCR) and West Virginia University to conduct testing and analysis under the Program, resulting in one of the world's largest emissions testing programs for HDVs to date.

Project Purpose

The Program's goals were to collect robust and empirical information that could better characterize and help understand the real-world vehicle activity data and emissions profiles of HDVs powered by common diesel engine types and technologies and advanced/alternative fuel technologies, and to further understand causes for higher-than-design levels of emissions, especially for NOx. Working both separately and jointly, the University of California, Riverside and West Virginia University research teams collected and analyzed test data on an unprecedented scale for a wide range of HDV types and applications that are commonly found in the HDV fleets of Southern California.

The Program aimed to assess the emissions reduction efficacy of HDV technologies (engines, drivetrains, fuels, and aftertreatment systems) under commonly encountered driving and operational conditions in the South Coast Air Basin. Applications of results will help to reduce emissions from in-use HDV fleets and provide recommendation on new non-zero-emission HDVs added into the fleet are powered by the lowest-emitting fuel-technology types throughout their useful lives.

Additionally, the vehicle emission measurements collected under this Program can provide important new data to improve air quality planning. Specifically, results and data from both test teams will inform the ongoing development of reliable, accurate emissions inventories derived from real-world studies. This is a critical part of the world-leading efforts in California and the South Coast Air Basin to systematically improve ambient air quality and achieve a wide array of other state and local environmental goals.

Project Approach

The Program used a phased approach to collect vehicle operating data across a large pool of test HDVs using portable instruments with a smaller subset of tests HDVs for emissions measurements and other types of testing using more reliable and accurate laboratory-grade instruments. Specifically, the HDV testing was conducted in the following four sequential phases:

1) On-road data gathering with portable activity measurement systems (PAMS).
2) On-road emissions testing with portable emissions measurement systems (PEMS).
3) In laboratory (stationary) emissions testing with a chassis dynamometer.
4) On-road emissions testing with mobile emissions laboratory trailer.

Each phase of testing used a subset of the vehicles tested in the prior phase. The phased testing started with a broad characterization of the vehicle activity patterns using PAMS (phase 1) and in-use emissions trends using PEMS (phase 2). PAMS and PEMS data were then used to develop test cycles for chassis dynamometer testing (phase 3), and test routes for the in-use testing with the mobile laboratory (phase 4). These last two phases involving subsets of the total HDVs and provided more detailed emissions characterizations.

Collectively, the two university research teams performed 227 tests for in-use data collection with PAMS, 100 in-use emissions tests with PEMS, 55 chassis dynamometer tests, and 10 real-world on-road emission tests using mobile emissions laboratories.

The test matrix included vehicles from five vocations, which are transit buses, school buses, refuse trucks, delivery trucks, and goods movement trucks. The vehicle fuel technologies included natural gas, propane, conventional and renewable diesel fuels, and dual fuels. The vehicles were categorized into six groups as follows:

1) Natural gas engines certified at or below 0.2 grams per brake horsepower-hour NOx (0.2 grams natural gas).
2) Natural gas engines certified at or below 0.02 grams per brake horsepower-hour NOx (0.02 grams natural gas).
3) MY 2010+ SCR-equipped diesel engines certified at or below 0.2 grams per brake horsepower-hour NOx (0.2 grams diesel).
4) Diesel engines with no selective catalytic reduction systems.
5) Dual fuel engines.
6) Alternative fuel engines, including propane, diesel-electric hybrid, battery electric, and hydrogen fuel cell vehicles.

The activity and emissions results were analyzed to develop emission profiles for HDVs for different vocations, technology types, and driving conditions for NOx and other emissions species. The emissions testing data were also analyzed to evaluate aftertreatment deterioration impacts, technology issues and benefits, and provide comparisons with California Air Resources Board's emission inventory models.

Project Results

Portable Activity Measurement Systems Cycle Development Results

To comparatively assess emissions from different HDV fuel-technology types while being operated over representative driving cycles, data collected during PAMS testing was used to develop test cycles needed for phase 3 (chassis dynamometer testing) and phase 4 (real-world testing using mobile emissions laboratories on the roads of Southern California).

PAMS data collected by the two university teams represent real-world activity characteristics of the HDVs through the 227 tests. The PAMS activity data collected for each vocation were compared with the corresponding existing vocational chassis dynamometer test cycles for various statistical parameters. After initial cycle comparisons, summary cycle statistics such as average speeds, idle periods, and average load/power were compared. Differences were observed between known standard test cycles and PAMS data for three HDV vocations: school buses, goods movement trucks, and delivery trucks. To test these HDV types under more representative conditions, new chassis dynamometer test cycles specific to these three categories were developed using a Markov-Chain Drive Cycle Generation Tool developed by West Virginia University. A varying grade feature was also added to the curbside pick-up portion of the standard refuse cycle to simulate the hydraulic actuators that enable curbside refuse pick-up and compaction.

The PAMS profile data collected for the goods movement trucks were shared with California Air Resources Board staff to help inform and improve HDV activity patterns. Per California Air Resources Board's technical documentation for EMission FACtors (EMFAC) 2021, when compared to EMFAC2017, the new data show that the majority of the HDV categories have a “higher percentage of vehicle miles traveled at higher speeds, higher starts per day and longer soak time, and less extended idling time.” The California Air Resources Board also observed that HDV activity has “no significant difference between fuel types.” Whenever applicable, the new PAMS data was also applied to other regions in California.

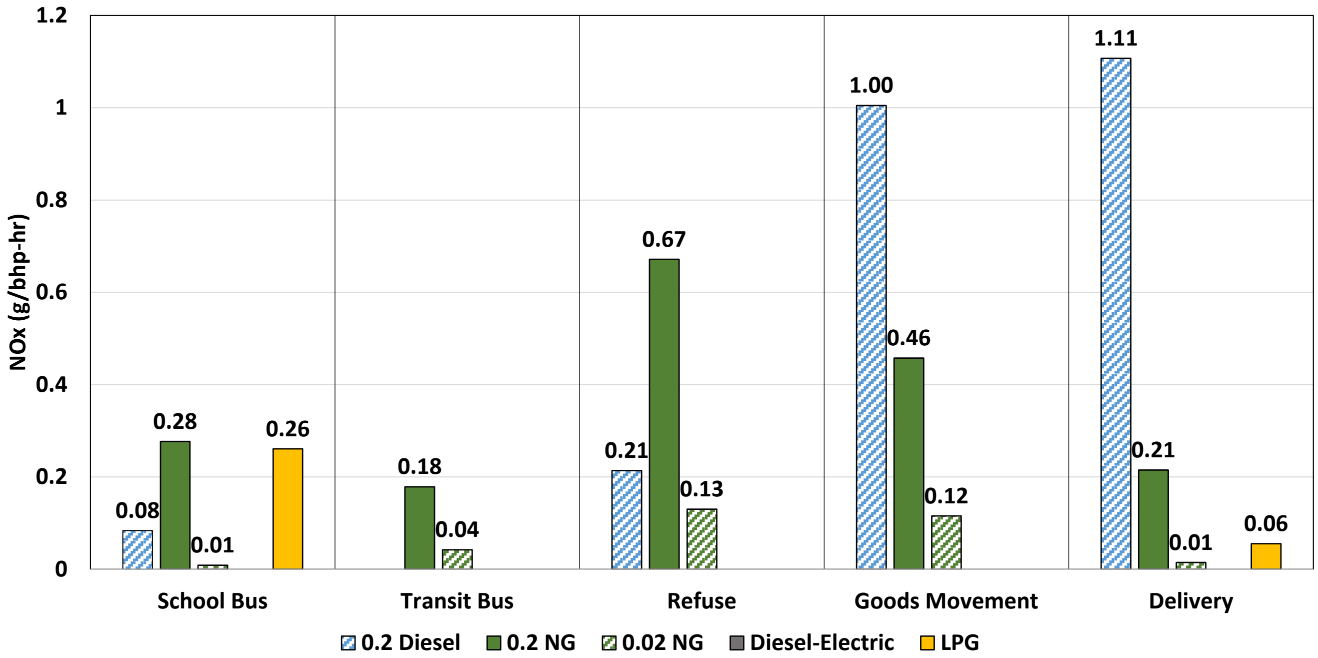
Four real-world driving routes, representative of typical goods movement trucking operations in Southern California (including grocery distribution, drayage operations, regional delivery, and longer-haul waste transport), were developed based on PAMS activity data collected from trucks operated in Southern California fleets.

Portable Emissions Measurement Testing Results and Discussion

A subset of 100 HDVs from the vehicle test matrix of the PAMS test phase were selected for PEMS testing based on availability, vehicle type, and considerations for the later test phases. The PEMS testing results were considered “daily” averaged emissions where the HDV was put into revenue service as intended.

In general, PEMS testing incorporated a diverse set of HDVs, fleet operators, and operating conditions/duty-cycles. The PEMS results showed high variability in NOx emission levels between vocations and technology categories. Figure ES-1 summarizes the daily averaged NOx emission rates of each vocation and technology category.

Figure ES-1 Brake-Specific PEMS NOx Daily Averaged Emission Rates



***NG = natural gas. LPG = liquefied petroleum gas or propane.**

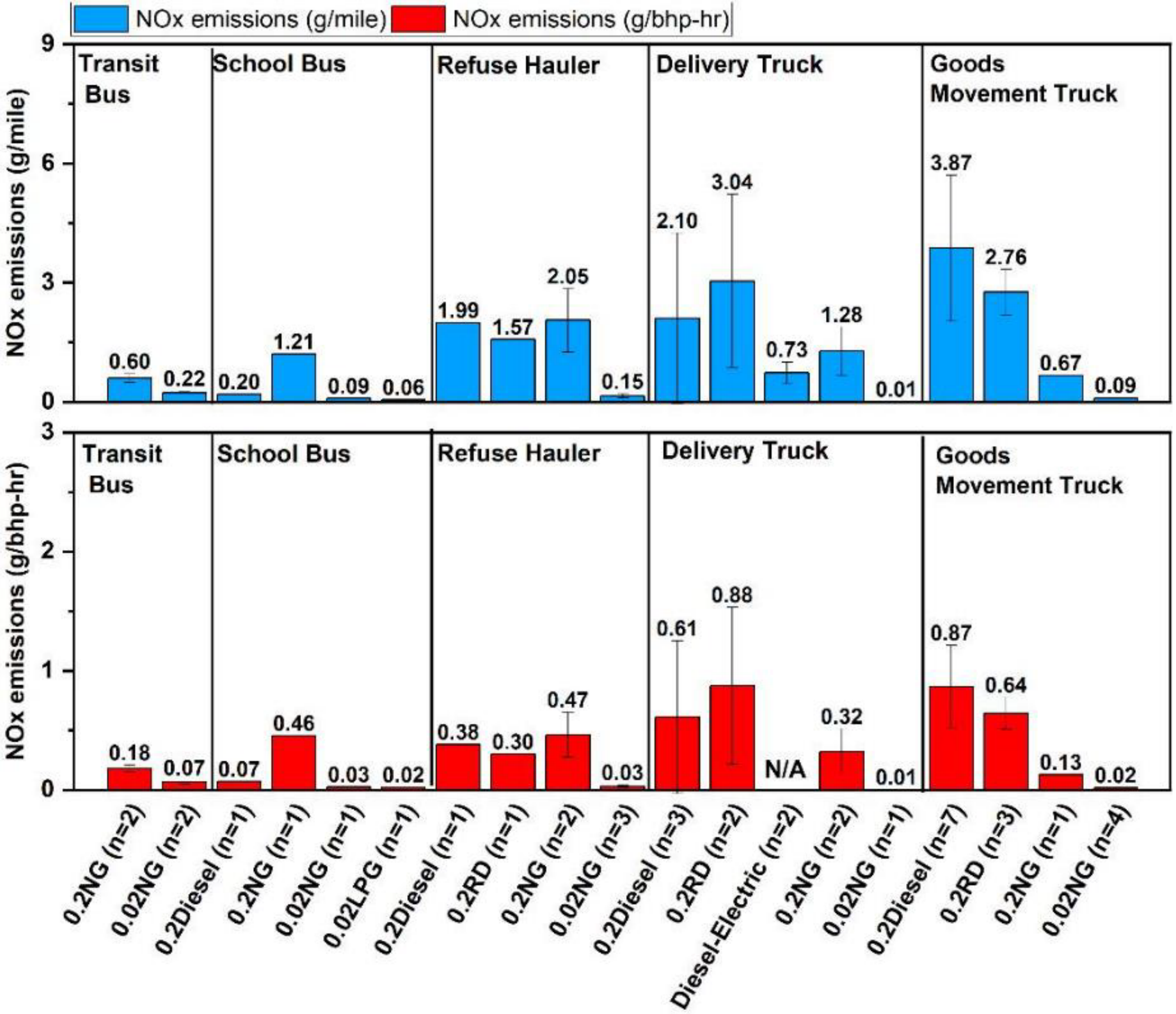
Sources: UCR and WVU

The California Air Resources Board staff analyzed the PEMS data for the natural gas vehicles to inform updates the natural gas emission rate assumptions in EMFAC2021. Prior to this study, EMFAC only modeled natural gas emissions from refuse trucks and transit buses due to the lack of natural gas data for other truck categories. This provided a more accurate picture of emissions from natural gas trucks and buses operating in California.

Chassis Dynamometer Testing Results and Discussion

A total of 52 unique HDVs were tested on a chassis dynamometer over the Urban Dynamometer Driving Schedule and their respective vocational cycles. As shown in Figure ES-2, the cycle-averaged results were similar across different HDV categories; this is a markedly different result than the “daily” averages presented in the PEMS section. The Urban Dynamometer Driving Schedule cycle, although not identical, closely resembles the Federal Test Procedure certification test cycle, over which an HDV engine’s emissions certification value is derived. Therefore, Urban Dynamometer Driving Schedule data provides a reasonable comparison point to understand NOx emissions in this context.

Figure ES-2 Cycle Averaged Chassis Dynamometer NOx Emission Rates over the Urban Dynamometer Driving Schedule



***NG = natural gas. LPG = liquefied petroleum gas or propane. RD = renewable diesel. n = sample size number.**

Sources: UCR and WVU

For vocations with well-established diesel baselines, such as delivery and goods movement categories, the natural gas HDVs showed significantly lower NOx emissions. The reductions were 26 to 78 percent lower for 0.2 gram natural gas HDVs and 97 to 99 percent lower for 0.02 gram natural gas HDVs relative to the diesel baselines. Renewable diesel results in general showed a 0-20 percent reduction in NOx emissions relative to conventional diesel.

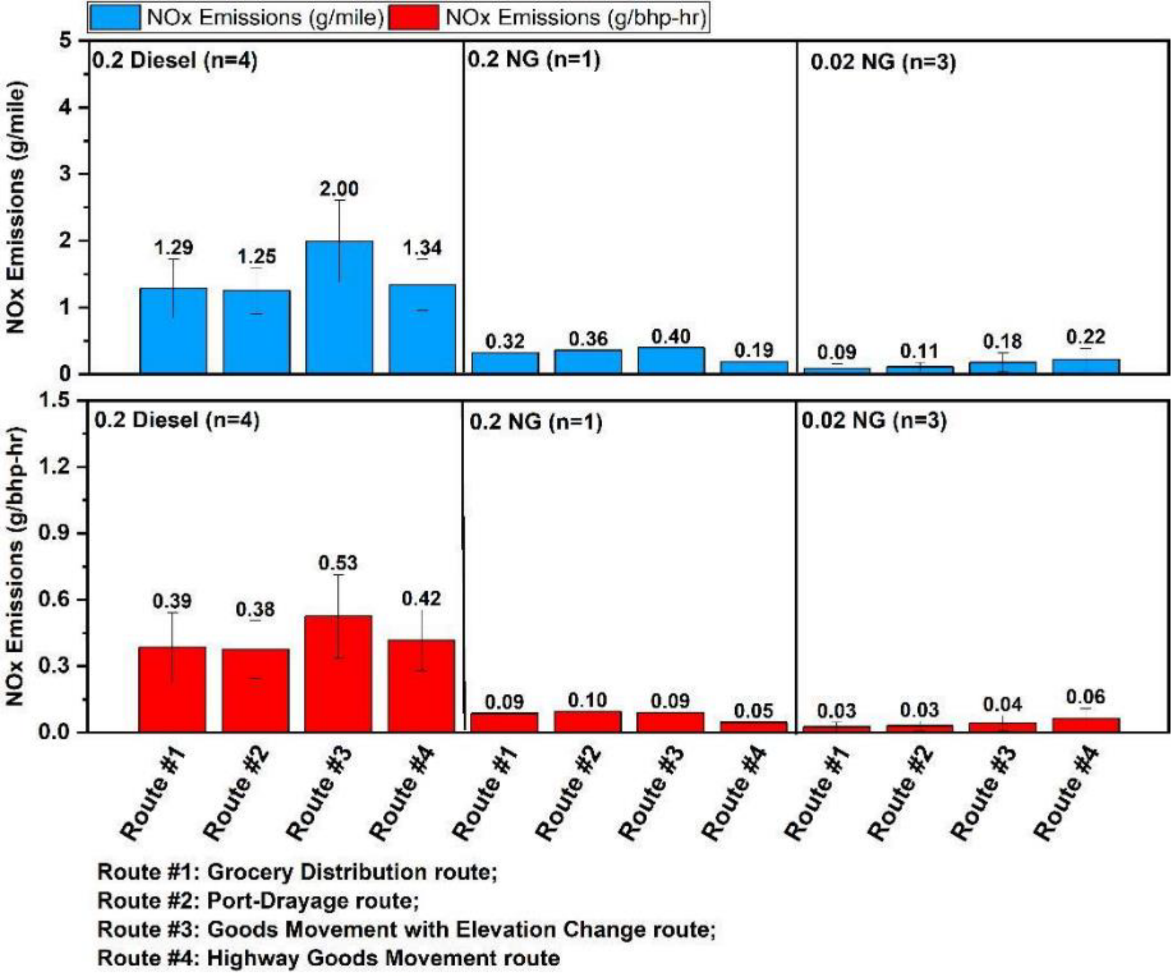
Over the course of the testing, it was observed that a subset of natural gas HDVs exhibited elevated NOx emissions during idle and deemed to be data outliers. For the natural gas vehicles equipped with an 8.9-liter engine (both 0.2 gram and 0.02 gram) with this issue, the root cause was determined to be an "artifact" where ambient air was leaking into the exhaust prior to the aftertreatment system, which was caused by a vacuum generated by the constant volume sampler measurement system (which is not part of real-world operation). As a result of this finding, the affected outlier data (9 vehicles) were removed from the data comparison. The other outliers, including the natural gas vehicles equipped with a 12-liter engine, were not affected by this "artifact" and were included as part of the data comparison.

The diesel hybrid electric delivery vehicles showed approximately 65 percent lower average NOx emission rates in grams per mile than the conventional diesel delivery trucks, but not as low as the 0.02 gram natural gas delivery vehicles. Vocational cycles were also tested to better assess HDV emissions under typical duty cycles. Although the vocational cycles' emissions trends were similar to the Urban Dynamometer Driving Schedule, the absolute cycle-averaged NOx level showed some differences.

Results and Discussion for On-Road Testing with Mobile Labs

A total of 10 HDVs were tested over on-road routes in Southern California. The HDVs in this phase were exclusively Class 8 goods movement trucks capable of legally towing the specially designed mobile emissions laboratories weighing about 62,000 to 65,000 pounds. The tests were done on four driving routes developed using PAMS data to represent typical goods movement operations in Southern California. Compared to the emissions data presented in PEMS and chassis dynamometer testing, the NOx and fuel economy were averaged over the entire-test route. Distance- and work-specific NOx emission results are summarized in Figure ES-3.

Figure ES-3 - Route Averaged Emission Rates by Fuel Types and Routes



Route #1: Grocery Distribution route;
Route #2: Port-Drayage route;
Route #3: Goods Movement with Elevation Change route;
Route #4: Highway Goods Movement route

***NG = natural gas. n = sample size number.**

Sources: UCR and WVU

In contrast to the larger variability observed for the PEMS and chassis dynamometer testing, the route-averaged NOx emissions showed more consistent trends and lower variability. In part, this can be attributed to the smaller data sample as well as the single vocation. Further, the fixed routes reduced duty-cycle variability, which had a significant impact on the daily-averaged NOx emissions in the PEMS testing. Lastly, the mobile reference lab offers better instrumentation compared to PEMS and provided a fixed curb weight throughout the route. The lower variability for the route-averaged NOx emission rates compared to the PEMS and chassis dynamometer measurements indicate that duty cycle is a large contributor to in-use emissions variations.

Emission Data Outliers

The Program observed multiple cases where HDVs emitted NOx (and other key air pollutants) at higher-than-designed levels during real-world operation. The two test teams classified the likely causes for these HDV NOx emission "outliers," which are discussed further in Appendix C into three distinct categories:

1) Systemic: Expected problems/conditions that occur with fairly constant frequency (these events could be considered as part of the typical emissions signature of a vehicle operation as they occur repeatably and in a “quasi-predictive” manner).
2) Rare/Random: Unexpected or anomalous problems and conditions that occur at low frequency (these events would not be considered representative of the typical emissions signature of a vehicle operation).
3) Duty Cycle Related: High emission events during off-cycle real-world driving not reflected in certification testing (these events could be considered as part of the typical emissions signature of a vehicle operation).

Fifteen HDVs produced “outlier” daily-averaged NOx levels during PEMS testing. Most daily-averaged in-use NOx levels were significantly above the not-to-exceed level. The causes of PEMS outliers were attributable mainly to systemic issues and duty cycle issues.

For the chassis dynamometer testing, 16 HDVs emitted outlier cycle-averaged NOx levels. Diesel HDV outliers included a combination of rare/random and systemic issues such as low selective catalytic reduction temperature, poor NOX conversion, and potential issues with selective catalytic reduction conversion efficiency. For the natural gas HDV outliers with the 8.9-liter engine, the cause of the outliers was mostly rare/random and related to a “artifact” caused by constant volume sampler measurement system interference. For the natural gas HDVs with the 12-liter engine, systemic high idle NOx emissions were identified for some vehicles, which were considered part of typical emission signature. Among all the NG vehicles tested, only one 0.2 gram natural gas HDV exhibited a systemic issue related to deterioration.

Technology/Knowledge Transfer/Market Adoption

All four co-sponsoring agencies have already conducted knowledge transfer activity for the Program. Specifically,

- The California Energy Commission leveraged activity data from this study to support development of the Medium- & Heavy-Duty Electric Vehicle Load, Operations, and Deployment Tool. The inaugural Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment report included results from the study data to help characterize load profiles and charging infrastructure needs for on-road medium and heavy-duty electric vehicles.
- The South Coast Air Quality Management District (South Coast AQMD) is using study data as a key input for its latest 2022 Air Quality Management Plan (AQMP), which is the regional blueprint for achieving air quality standards in the South Coast Air Basin.
- The California Air Resources Board (CARB) has published literature highlighting this Program, and has incorporated study data into its latest EMFAC2021 model. In parallel, CARB has also initiated efforts to further test and study in-use natural gas HDVs using 0.02 gram certified engines.
- Southern California Gas Company has conducted various follow-up activities, including participating in a maintenance cost study funded jointly with the U.S. Department of Energy and the South Coast AQMD.

The two universities that performed the testing and analysis have also engaged in (and continue to engage in) activities to transfer knowledge gained through the Program. As one key example, University of California, Riverside presented a summary of the Program results at the Coordinating Research Council's 32nd annual Real World Emissions Workshop (San Diego, March 2022). Additionally, along with West Virginia University, team members have disseminated Program results through various other key venues that are specifically focused on reducing in-use mobile source emissions and development of emissions factors, and are in the process of publishing a number of journal articles on various parts of the study.

Benefits to California

This study builds on the CEC's and CARB's past efforts to reduce NOx and greenhouse gas emissions by investigating in-use emission levels of natural gas HDVs in the context of the 0.02 g/bhp-hr NOx certification standard, legacy 0.2 gram natural gas HDVs, multiple HDV vocations, and other fuel types. By identifying technology impacts and shortfalls potentially causing higher than expected in-use emissions, as well as areas of exceptional in-use emissions performance, the Program is informing further technology development and research opportunities to maximize emission reduction benefits from deploying 0.02 NG HDVs.

Additionally, the comprehensive dataset (and the models leveraging the data) can help policymakers better understand real world emissions from California's in-use fleet (approximately one million medium- and heavy-duty vehicles). Decision makers can leverage the study results to determine the pathways forward for meeting transportation decarbonization and air quality goals. For the on-road fleet, most of those reductions will need to come from HDVs, including newly manufactured units as well as those already in use. To prepare these new control measures, it is critical that the agency's planners, modelers and rule-development staff have a robust, accurate, and up-to-date characterization of NOx emissions from the in-use HDV fleet, while being operated in real-world conditions.

CHAPTER 1: Introduction

1.1 Background

1.1.1 Key California Co-Sponsoring Agencies and Project Objectives

The 200 Heavy-Duty Vehicle Emissions Testing Program (Program) is co-sponsored by three key California agencies: the California Energy Commission (CEC), the California Air Resources Board (CARB), and the South Coast Air Quality Management District (South Coast AQMD). The Southern California Gas Company (SoCalGas) is a fourth Program co-sponsor. Two academic institutions, the University of California at Riverside (UCR) and West Virginia University (WVU), carried out the work in a combined effort to design and implement one of the world's largest emissions testing programs for heavy-duty vehicles (HDVs). Collectively, UCR and WVU tested more than 200 HDVs between 2017 and 2022 under real-world operating conditions in the South Coast Air Basin (SCAB), one of only two air basins in the United States categorized as being in "extreme nonattainment" for federal ambient ozone standards. This 200 HDV Testing Program was managed by the South Coast AQMD, the local air quality regulatory agency for the SCAB.

The Program and its findings are instrumental in the ongoing and future work to reduce transportation-related petroleum consumption and harmful emissions from HDVs. Table 1 summarizes the synergistic roles, missions and specific objectives of the four co-sponsoring organizations for the 200 HDV Testing Program:

Table 1. Summary of Organizations Co-Sponsoring 200 HDV Testing Program

Agency	Role / Jurisdiction	Primary Mission	Primary Interests in Co-Sponsoring the 200 HDV Testing Program
California Energy Commission (CEC)	California's primary energy policy and planning agency	Strategically invest funds to catalyze change and accelerate achievement of energy policy goals.	• Better characterize and understand activity profiles of in-use HDVs to inform infrastructure planning • Reduce GHG and air pollutant emissions from HDVs • Support CARB and South Coast AQMD missions
California Air Resources Board (CARB)	California's primary air pollution policy, planning, and regulatory agency	Protect public from harmful effects of air pollution and lead state's actions to fight climate change.	• Reduce in-use HDV emissions • Better characterize and understand emission profiles of in-use HDVs; improve modeling tools • Support and inform wide array of existing, planned and potential regulatory initiatives for on-road HDVs/engines • Support CEC and South Coast AQMD missions
South Coast Air Quality Management District (SCAQMD)	Regulatory agency responsible for air quality in the four-county SCAB; lead agency	Clean air and protect health of all residents in the SCAB through practical and innovative strategies.	• Help ensure SCAB HDV fleet gets progressively lower emitting for criteria pollutants, to meet health-based ambient air quality standards • Support regulatory initiatives (e.g., indirect source rules) for on-road HDVs and heavy-duty engines; support CEC and CARB missions • Identify real-world technology emissions and cost benefit and short falls, provide recommendations and migration strategies for future SCAB/Statewide fleet planning, support the goals outlined in the Air Quality Management Plan (AQMP) and the Clean Fuels Program Fund
Southern California Gas Company (SoCalGas)	Nation's largest natural gas distribution utility	Deliver energy to 24,000 square miles, including SCAB	• Support adoption of low-emission renewable natural gas technologies to meet the air quality standards of agencies • Support needs for deployment including natural gas refueling infrastructure

Source: South Coast AQMD

1.1.2 On-Road HDVs: Harmful Emissions and High Petroleum Consumption

On-road HDVs, primarily consisting of freight trucks, transit buses, school buses, and refuse trucks, annually consume approximately 3.3 billion gallons of diesel fuel in California, of which about 75 percent is petroleum based, and emit approximately 32.5 million metric tons of carbon dioxide equivalent (MMT CO_2e) per year, or 7.8 percent of the state-wide greenhouse gas (GHG) emissions.[1,2] These HDVs are the state's largest on-road mobile (vehicular) source of nitrogen oxide (NOx) emissions. NOx is the primary precursor to the formation of ozone (photochemical smog), which can cause irritation and damage to lung tissue, and worsen asthma and chronic illnesses.[3] It also leads to the formation of harmful secondary organic aerosols.

---

[1] California Energy Commission, "Final 2020 Integrated Energy Policy Report Update, Volume I," March 23, 2021, https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2020-integrated-energy-policy-report-update.

[2] California Air Resources Board, 2000–2019 GHG Emissions Trends Report Data, https://ww2.arb.ca.gov/ghg-inventory-data.

[3] U.S. EPA (2019b). Policy Assessment for the Review of the National Ambient Air Quality Standards for Particulate Matter, External Review Draft.

Heavy-heavy-duty diesel trucks (HHDDTs) with a gross vehicle weight rating (GVWR) greater than 33,000 pounds (lbs), are especially large fuel consumers and contributors to the statewide NOx inventory. As shown in Figure 1, in 2022 HHDDTs emitted an estimated 36.2 percent (142 tons per day) of the statewide NOx inventory from on-road mobile sources.[4] They contribute nearly 20 percent of the total NOx from all mobile sources, including ships and trains.[5] On-road diesel HHDDTs and other diesel HDVs are also major emitters of toxic diesel particulate matter (PM), which is California's leading airborne cause of cancer.[6] For low-income and disadvantaged communities that experience disproportionate levels of negative health impacts from air pollution, actions to reduce fossil fuel combustion and move to cleaner technologies are critical.[7]

For California to meet health-based ambient air quality standards for ozone, the state must rapidly reduce NOx emissions from on-road HDVs over the next decade. Regionally in the SCAB, mobile sources emit more than 80 percent of the NOx inventory. For SCAB to achieve federal and state health-based ozone standards, NOx emissions must be reduced by 45 percent in 2023 from the expected baseline 2012 NOx inventory, and another 55 percent by 2031.[8]

Figure 1: Statewide NOx Emission Contributions by On-Road Vehicle Type

---

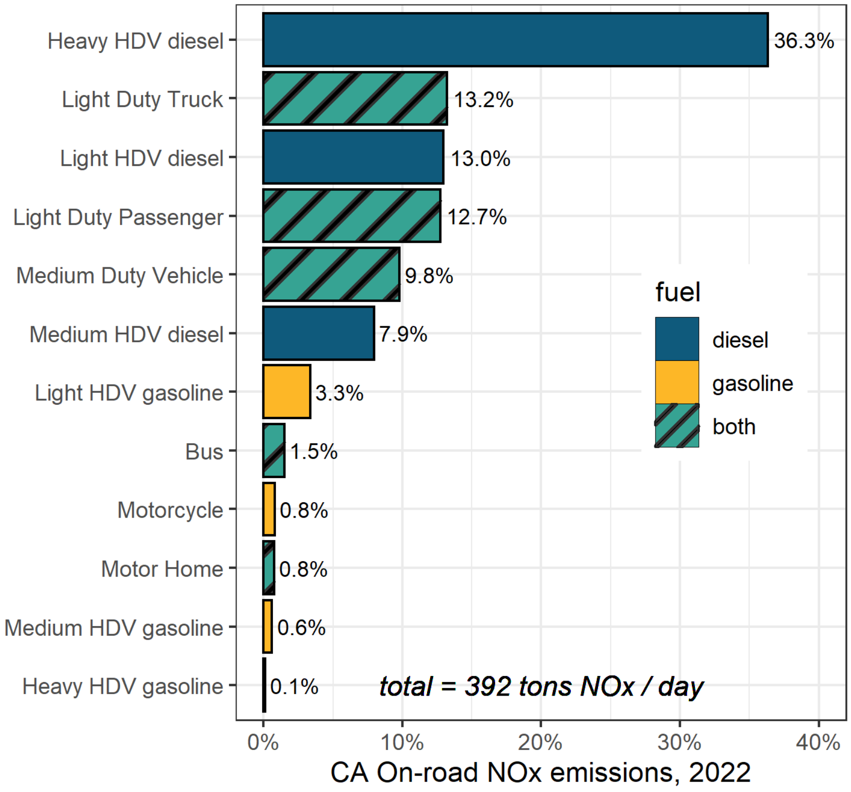
[4] California Air Resources Board, mobile source NOx inventory graph provided to GNA in August 2022.

[5] California Air Resources Board, "Mobile Source Emissions: 2017 Estimated Annual Average Emissions Statewide," https://ww2.arb.ca.gov/applications/mobile-source-emissions.

[6] California Air Resources Board, "Facts about the Low NOx Heavy-Duty Omnibus Regulation," https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/hd-low-nox-omnibus-regulation-fact-sheet.

[7] American Lung Association. (2020). State of the Air; Union of Concerned Scientists, U. (2019). Inequitable Exposure to Air Pollution from Vehicles in California (2019); Cushing et al. (2015). Racial/ethnic disparities in cumulative environmental health impacts in California: evidence from a statewide environmental justice screening tool (CalEnviroScreen 1.1). American journal of public health, 105(11), 2341-2348.

[8] South Coast Air Quality Management District, "Final 2016 Air Quality Management Plan," March, 2017. http://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2016-air-quality-management-plan/final-2016-aqmp/final2016aqmp.pdf.



This graph shows that heavy HDVs powered by diesel engines currently contribute an estimated 36.3 percent (142 tons per day) of the total NOx emitted by on-road vehicles in California (392 tons per day).

Source: California Air Resources Board, August 2022

As CARB has stated, "All forms of cleaner heavy-duty trucks and buses will be critical to achieving ambient air quality standards, near-term (air toxics) risk reduction goals, and climate goals." CARB recently adopted several regulations to help ensure that the on-road heavy-duty sector becomes progressively lower emitting, and eventually zero emitting. For example, the new Heavy-Duty Omnibus Regulation establishes more stringent NOx emission certification levels, an additional certification test cycle, and revised in-use testing protocols. The regulation also contains a suite of requirements for "longer useful life emission compliance, longer warranty periods, and more stringent in-use performance standards, all of which will improve the real-world emissions performance of heavy-duty vehicles."[9]

1.1.3 Emission Reductions from California's In-Use HDV Fleet

Major progress has been made over the last 16 years to reduce NOx and PM emissions from HDVs. In particular, the U.S. Environmental Protection Agency (EPA) and CARB have promulgated progressively more stringent emissions standards for new engines powering on-road HDVs, combined with new standards for transportation fuels. These measures have enabled widespread deployment of HDVs equipped with diesel particulate filters (since 2007) and selective catalytic reduction (SCR) (since 2010). Along with the retirement of older HDVs

---

[9] California Air Resources Board, "2020 Mobile Source Strategy," September 28, 2021, https://ww2.arb.ca.gov/resources/documents/2020-mobile-source-strategy.

without diesel particulate filters and SCR systems from natural attrition, these measures have contributed to major reductions in PM and NOx emissions from the collective in-use HDV fleet[10, 11, 12].

While air quality benefits have been realized from the deep penetration of HDVs with these exhaust aftertreatment systems into California’s fleet, in-use emission testing programs have also shown that these new generation HDVs can emit NOx (and sometimes PM) at significantly higher levels than certification standards during urban driving conditions or suburban driving conditions, where the speeds are less than 25 miles per hour [mph] or between 25 and 50 mph, respectively. For example, studies performed or commissioned by CARB have observed higher NOx emissions for SCR-equipped diesel vehicles when operating under low-load conditions, due to “insufficient SCR performance” that can be attributed to some combination of “low operation temperature, catalyst malfunction, and insufficient dosing of diesel exhaust fluid.”[13]

This issue of unexpectedly high in-use emissions is not necessarily limited to compression-ignition diesel-fueled HDVs. Spark-ignited heavy-duty engines fueled by natural gas (NG) and propane, including those certified to CARB’s Optional Low-NOx Standard of 0.02 grams per brake horsepower-hour (g/bhp-hr), also have potential to emit above certification standards under conditions different than the certification cycles.

Studies like the 200 HDV Testing Program are critical to assess the effectiveness of HDV emissions-control technologies (engines, drivetrains, fuels and aftertreatment systems) in real-world use to help reduce emissions from in-use fleets−while also helping to ensure that only new HDVs with the lowest-emitting HDV technologies (over full useful lives) are added into the fleet. These studies are also essential to improve emission inventories used for air quality modeling and planning, and to develop effective mobile source control strategies.

In summary, by providing better knowledge and understanding about how to reduce in-use HDV emissions, the 200 HDV Testing Program strongly supports California’s world-leading efforts to improve air quality and achieve National Ambient Air Quality Standards (NAAQS), as

---

[10] Haugen, Molly J. and Bishop, Gary A: Long-Term Fuel-Specific NOx and Particle Emission Trends for In-Use Heavy-Duty Vehicles in California, ES&T (2018)

[11] Chelsea V. Preble, Robert A. Harley, and Thomas W. Kirchstetter: Control Technology-Driven Changes to In-Use Heavy-Duty Diesel Truck Emissions of Nitrogenous Species and Related Environmental Impacts, ES&T (2019)

[12] Ruehl, C; Misra, C; Yoon, S; Smith, J; Burnitzki, M; Hu, S; Collins, J; Tan, Y; Huai, T; Herner, J: Evaluation of Heavy-Duty Vehicle Emission Controls with a Decade of California Real-World Observations, JAWMA (2021).

[13] Yi Tan, Paul Henderick, Seungju Yoon, Jorn Herner, Thomas Montes, Kanok Boriboonsomsin, Kent Johnson, George Scora, Daniel Sandez, and Thomas D. Durbin, “On-Board Sensor-Based NOx Emissions from Heavy-Duty Diesel Vehicles”, Environmental Science & Technology 2019 53 (9), 5504-5511 DOI: 10.1021/acs.est.8b07048

outlined for the SCAB in the South Coast AQMD's Air Quality Management Plan,[14] and reducing greenhouse gas emissions.

1.2 Objectives of the 200 HDV Testing Program

The 200 HDV Testing Program conducted jointly by UCR and WVU was designed to gather robust, empirical information that better characterizes and helps improve the understanding of real-world vehicle activity data, emission measurements and fuel usage profiles of HDVs powered by diesel engine technologies, as well as advanced/alternative-fuel technologies. The data and information collected by the Program will be/are used to:

- Identify conditions where HDVs (across a wide range of types and applications) are producing higher-than-expected emissions, and develop strategies to mitigate the problem.
- Improve accuracy of the emission inventory by developing more profiles (activity and emissions) for different vocations and technology types.
- Revised emission rates and activity profiles to inform updates of models, such as CARB's 2021 EMission FACtors (EMFAC) [15], for emission rates and activity profiles.
- Develop and/or enforce regulatory solutions that help mitigate high in-use HDV emissions.

1.3 Research Teams and University Reports

The two academic institutions performing the testing and analyses for this Program operate at nationally recognized facilities specifically designed to conduct complex, multi-faceted HDV emissions testing. The UCR team for the Program was composed of faculty staff and researchers from UCR's College of Engineering Center for Environmental Research & Technology. The WVU team included faculty staff and researchers from WVU's Center for Alternative Fuels, Engines and Emissions. Investigators and contributors of each team are provided in Table 2.

Each research team prepared separate final reports to describe testing protocols, equipment, findings, and analytics for their respective parts of the Program, as listed in Table 2.

---

[14] South Coast AQMD, 2022 Air Quality Management Plan, http://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan

[15] According to CARB, EMFAC2021 is the latest emission inventory model it uses "to assess emissions from on-road motor vehicles including cars, trucks, and buses in California, and to support CARB's planning and policy development." It reflects CARB's current understanding of statewide and regional vehicle activities, emissions, and recently adopted regulations such as Advanced Clean Trucks (ACT) and Heavy Duty Omnibus regulations. More details are summarized in CARB's EMFAC2021 Technical Documentation released in April 2021.

Table 2: Summary of University Test Programs and Final Reports

University	Final Report Title	Principal Investigators / Contributors	Contract
University of California, Riverside (UCR) College of Engineering Center for Environmental Research & Technology	In-Use Emissions Testing and Fuel Usage Profile of On-Road Heavy-Duty Engines **(Appendix A)**	Thomas D. Durbin, Kent C. Johnson, Georgios Karavalakis, Kanok Boriboomsomsin, George Scora, Mark Villela, Chengguo Li, Daniel Sandez, Cavan McCaffery, Hanwei Zhu, Tianbo Tang, and Susumo Sato	SCAQMD #C17286
West Virginia University Center for Alternative Fuels, Engines and Emissions	In-Use Emissions Testing and Fuel Usage Profile of On-Road Heavy-Duty Vehicles **(Appendix B)**	Arvind Thiruvengadam, Marc C. Besch, Filiz Kazan, Berk Demirgok, Jason England, Aaron Leasor, Jordan Leatherman, Chakradhar Reddy, Cem Baki	SCAQMD #C17245

Source: South Coast AQMD

Figure 2 shows the two chassis dynamometer testing laboratories. For this program, WVU conducted much of its testing while located at the UCR test facility in Riverside next to UCR's chassis dynamometer facility for resource sharing and collaboration.

Figure 2: UCR and WVU Chassis Dynamometer Laboratories

This shows WVU's portable chassis dynamometer testing facility (in the foreground while set-up at UCR), and UCR's permanent chassis dynamometer testing facility (in the background, under the cover).

Sources: South Coast AQMD and UCR

This summary report compliments and supplements the two referenced university reports. It uses terms more suited to the general public to present key aspects of the combined testing program conducted by the two universities, including testing methodologies, testing facilities, vehicles tested and results. Additional technical aspects of the 200 HDV Testing Program (e.g., test design, test methodologies and equipment, 1065/1066 verifications results, activity data analysis, cycle development, in-depth data analysis as well as detailed unregulated emissions such as ammonia, toxics, particle number, etc.) are presented in the university reports in Appendices A and B.

CHAPTER 2:
Project Design and Methodologies

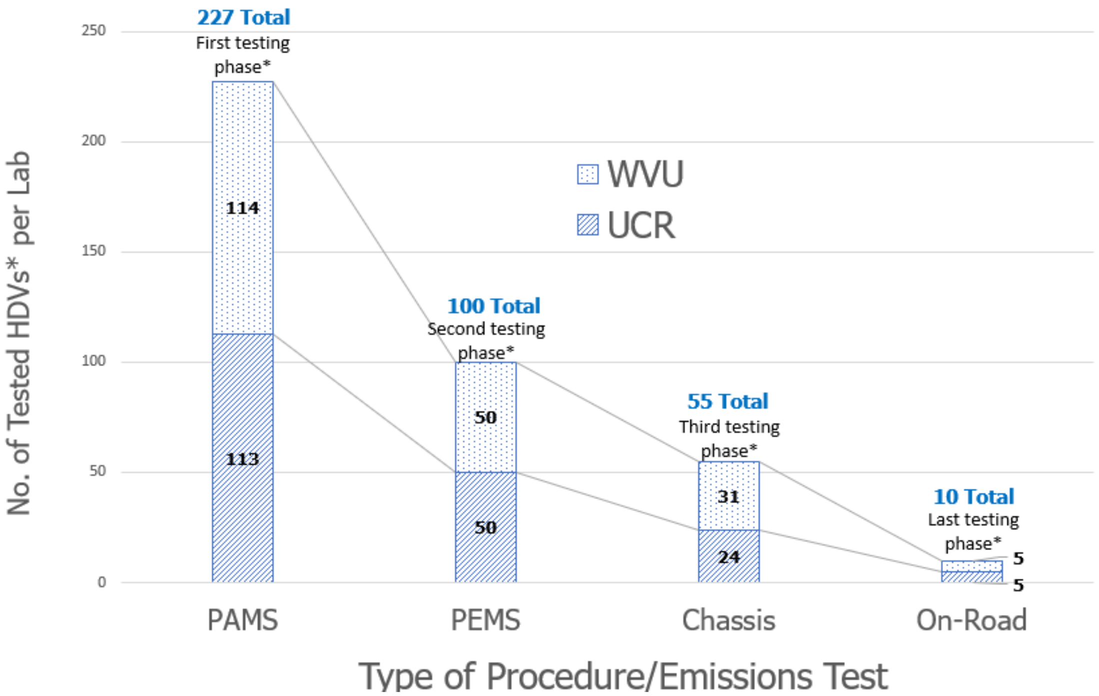
2.1 Overview of Testing Phases

The Program was designed to procure a large number of representative in-use HDVs, and test them using two distinct methodologies / settings: 1) in real-world conditions, on the roads of Southern California; and 2) in the relatively controlled laboratory environment, using prescribed driving cycles designed to simulate in-use driving conditions. Using both of these two methodologies, the HDV testing was conducted in four sequential testing phases:

- Phase 1: Real-world duty cycle characterization with portable activity measurement systems (PAMS).
- Phase 2: Real-world emissions testing with portable emissions measurement systems (PEMS).
- Phase 3: Laboratory emissions testing on chassis dynamometers.
- Phase 4: Real-world emission testing while towing mobile laboratories (Class 8 tractors only).

As shown in Figure 3, each subsequent phase of testing used a subset of the vehicles tested in the prior test phase, whenever feasible.

Figure 3: Phased Approach for HDV Testing

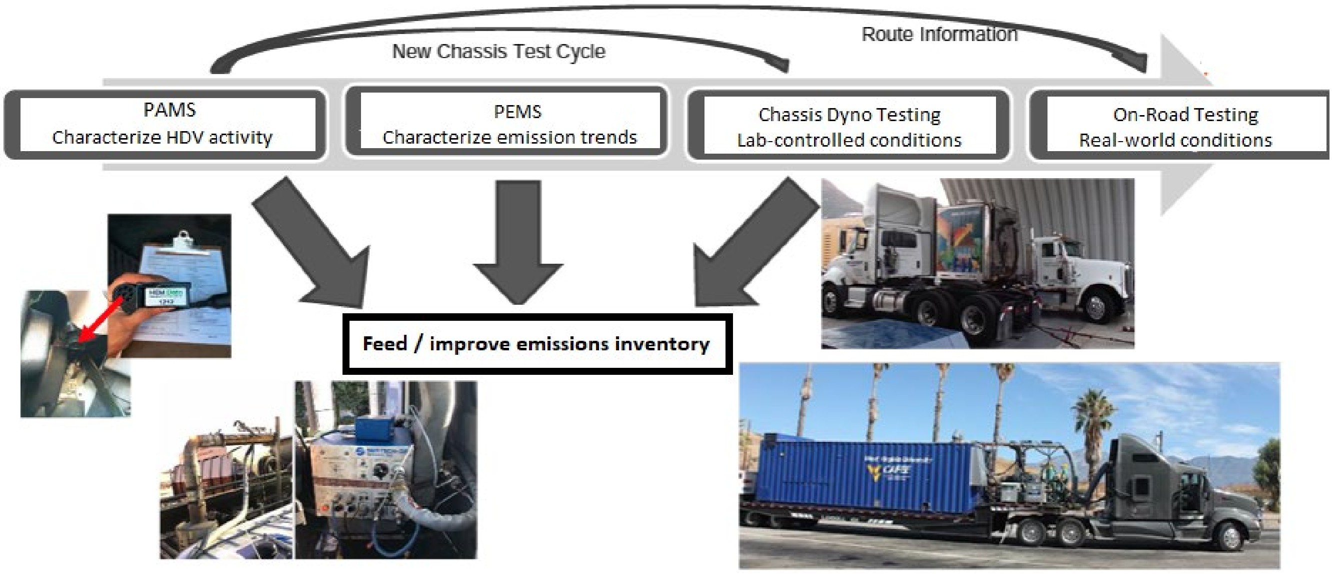


This depicts the number of tested HDVs per lab for each of the four phases; each subsequent phase tested a subset of HDVs from the previous phase. Because 1) some HDVs were tested by both laboratories, and 2) 10 HDVs were tested first on baseline diesel and then on renewable diesel, the number of total tests for each phase is higher than the total HDVs tested.

Sources: UCR and WVU

The schematic in Figure 4 depicts the progression of data collection and testing design throughout the four phases. In the initial phase, UCR and WVU developed the matrix of 227 HDVs and characterized their activity patterns using PAMS data loggers. This was followed with in-use emissions trend analyses using PEMS data in the second phase. The two university teams together conducted PEMS tests for 97 individual HDVs (3 of them were tested by both teams). The information from the first two phases was used to develop test cycles and test routes for the last two phases. In the third phase, more-detailed emissions data from 55 HDVs (3 were tested by both teams) were collected in a highly controlled laboratory setting using chassis dynamometers. In the fourth and final phase, a subset of 10 HDVs (# double tested) from the chassis dynamometer testing were driven on the road and measured for their emissions using the mobile emission laboratories that were also used for the emissions measurements in the earlier chassis dynamometer phase. This phased approach allowed the HDVs being tested in the later phases to reference the previous phases, hence broadening the impact of the emissions testing with a relatively larger set of activity data.

Figure 4: Four Sequential Phases of Testing



This figure helps understand how the phase 1 PAMS activity testing on 200+ HDVs helped to inform design of the last two testing phases, by providing data for creation of test cycles (chassis dynamometer testing) and real-world driving routes (on-road testing).

Source: South Coast AQMD

2.2 Vehicle Selection Methodology and Test Matrices

Key considerations for vehicle selection in each phase included the need to test a mix of

- Technologies and vocations representative of the HDV fleet currently operating in the SCAB.
- Advanced technologies that could potentially become a more-significant fraction of the future HDV fleet.
- At least two vehicles within each technology/vocation category, where possible.

The mix of technologies currently represented in the SCAB was determined by examining vehicle population data provided by CARB staff for calendar year 2017. Availability was another key factor in the selection of HDVs for testing. HDVs used for testing in the latter phases, for example, needed to be pulled from regular service and, thus, posed a potential hardship on the HDV fleet from which it was procured.

The HDV test matrix included transit buses, school buses, refuse trucks, delivery trucks, and goods movement applications. The test vehicles were powered by engines fueled with various alternative fuels (natural gas, propane, electric, and hybrid), conventional and alternative diesel fuels, and a combination of diesel and natural gas (dual) fuels. The engines were categorized into six groups including:

1) Natural gas engines certified at or below 0.2 g/bhp-hr NOx (0.2g NG).
2) Natural gas engines certified at or below 0.02 g/bhp-hr NOx (0.02g NG).
3) MY 2010+ SCR-equipped diesel engines certified at or below 0.2 g/bhp-hr NOx (0.2g Diesel).

4) Diesel engines with no SCR systems (Non-SCR Diesel).
5) Dual fuel engines (dual fuel).
6) Alternative fuel engines, including propane, diesel-electric hybrid, battery electric, and hydrogen (H_2) fuel cell vehicles.

WVU tested 114 HDVs, and UCR tested 113 HDVs. Six HDVs were cross tested by both universities. In total, 227 HDVs were tested. Table 3 summarizes the number of HDVs by fuel/technology type, and the relative percentages each type contributed to the overall HDV test fleet. Table 4 presents the average gross vehicle weight ratings (GVWR) and average model years by vehicle vocations.

Table 3: Summary of HDV Test HDVs by Vocation and Technology

Vehicle Types	Delivery Truck	Refuse Hauler	Transit Bus	Goods Movement Truck	School Bus	Total	Percentage
# of Diesel (NO SCR)	2	-	-	5	2	9	4.0%
# of 0.2 g Diesel	19	3	-	44	6	72	31.7%
# of 0.2g NG	15	20	9	22	21	87	38.3%
# of 0.02g NG	-	9	6	18	-	33	14.5%
# of Dual Fuel (HPDI)	-	-	-	4	-	4	1.8%
# of 0.2 g Propane	4	-	-	-	1	5	2.2%
# of 0.02g Propane	1	-	-	-	1	2	0.9%
# of Diesel Electric Hybrid (HEV)	6	-	-	-	-	6	2.6%
# of Battery Electric	-	-	4	4	-	8	3.5%
# of H_2 Fuel Cell	-	-	1	-	-	1	0.4%
Total Test HDVs	**47**	**32**	**20**	**97**	**31**	**227**	**100%**

Source: South Coast AQMD

Table 4: Average GVWR and Model Year by Vehicle Vocation

	Delivery Truck	Refuse Hauler	Transit Bus	Goods Movement Truck	School Bus
Average GVWR (lbs)	35,500	60,000	45,000	50,000	34,000
Average Model Year	2015	2014	2015	2014	2014

Source: South Coast AQMD

2.3 PAMS Test Methodologies and Data Analysis

2.3.1 PAMS Test Procedures and Equipment

All recruited test vehicles were instrumented with the PAMS (that is, data loggers) to monitor daily vehicle activities. The data loggers were attached directly into the HDV's J1939 connectors and continuously gathered and stored vehicle activity data for at least one week or one month depending on the HDV vocation. Transit buses, school buses, and refuse haulers were monitored for a period of at least one week because they are typically operated on regular return-to-base routes. Goods movement and delivery vehicles were monitored for at least one month because they are often operated over varying routes (depending on their daily schedule). Each data logger collected publicly available data through the controller area network (CAN) bus as well as tracked each HDV's position and operational route through a global positioning system (GPS).

UCR used HEM Data/IOS-X PAMS devices (data loggers, see Figure 5) to collect vehicle activity data on 113 HDVs. This data logger has provisions for both cellular transmission and local storage of vehicle activity data. Each unit was configured to store data locally to flash memory media, instead of transmitting data cellularly, and can store data up to 32 gigabytes of data, which is sufficient to store up to six months of activity data. The units are designed to start and stop automatically upon key-on and key-off events. Full details about UCR's PAMS data logging methodology and equipment can be found in Appendix A (UCR final report).

Figure 5: HEM Data Logger Used in UCR's PAMS Testing

Source: UCR

WVU used an in-house telemetry-based platform for PAMS testing (see Figure 6). The data logger, designated "AirCom" by WVU, captured data fields that include GPS, traffic information, ambient/meteorological conditions, ambient air quality conditions, on-board diagnostics, and other publicly available CAN and GPS data. AirCom also served as the data acquisition, storage, and transmission unit.

Figure 6: AirCom Data Logger Used for WVU's PAMS Testing

Source: WVU

2.3.2 PAMS Data Analysis

The activity data collection during PAMS testing was an important part of this study to characterize and better understand the difference between the operational duty cycles of the various HDV vocations. This included developing basic activity statistics for the different vocations, including average speed, idle percentage, average vehicle miles traveled (VMT), average power, fuel consumption and others. The activity data was used to develop new, improve, or retain existing vocation-based heavy-duty drive cycles for each vocation. These cycles were used subsequently in the chassis dynamometer testing phase. The activity data was also used to develop representative routes for the on-road testing. More importantly, this activity data was used to improve EMFAC2021's characterization of truck activity. Note that this data was also used to update activity in other regions where the data is lacking.

Additionally, the PAMS data was used to identify HDVs with major active malfunctions or other obvious mechanical issues that could prevent testing completion of later phases. For example, HDVs with an illuminated malfunction indicator lamp (MIL) or check engine light were eliminated from the candidacy for the subsequent PEMS testing phase. Specific parameters for which each HDV was inspected for included the following:

- Drivability and safety.
- Status of Engine Control Unit, On-Board Diagnostic system codes, and/or MIL.
- Level of smoke from the exhaust.
- Evidence of tampering or damage to the exhaust/emission control systems.
- Evidence of mis-fueling.

2.4 PEMS Equipment, Procedures and Data Analysis

2.4.1 PEMS Testing Background

PEMS are widely used by manufacturers, regulators, and research laboratories to measure in-use HDV emissions. More than a decade ago, the U.S. EPA promulgated requirements for each heavy-duty engine manufacturer to use PEMS to monitor in-use exhaust emissions from its engines with Not-to-Exceed (NTE) exhaust emission standards according to the provisions in Title 40 Code of Federal Regulations (CFR), Part 1065.

The Program focused the PEMS testing on gas-phase pollutants, because it was logistically challenging and resource-intensive to measure PM with PEMS. PM measurements were conducted during subsequent chassis dynamometer and on-road mobile lab testing phases, where the expected low emissions could be more readily characterized.

2.4.2 PEMS Equipment and Procedures

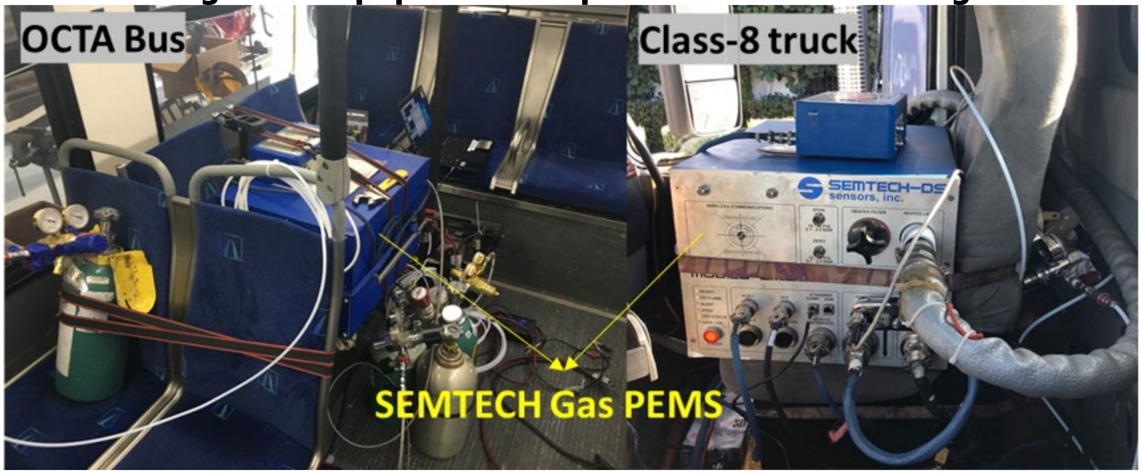
Both university teams used the Semtech®-DS gas-phase analyzer for the PEMS testing, which complies with the previously mentioned CFR requirements. This system measures tailpipe emissions of carbon monoxide (CO), CO_2, total hydrocarbon (THC), and NOx. Exhaust oxygen levels (O_2), GPS location, and publicly available truck activity data are also collected by the PEMS. NOx emissions were measured using a non-dispersive ultraviolet analyzer, THC using a heated flame ionization detector, and CO and CO_2 using a non-dispersive infrared analyzer. THC emissions are collected through a line heated to 190°C, consistent with the conditions for regulatory measurements.

PEMS measurements were taken while the test HDVs were undergoing typical daily revenue operation for their specific application whenever possible, to ensure the measurements were representative of typical in-use operation.

Both university teams used exhaust flow meters manufactured by Sensors, Inc. for the PEMS testing. Exhaust flow rates were multiplied by the time-aligned emissions concentration levels measured by the analyzers to derive emission rates in grams per second. These readings were converted to distance-specific (grams per mile) and/or work-specific (grams per bhp-hr) emission metrics.

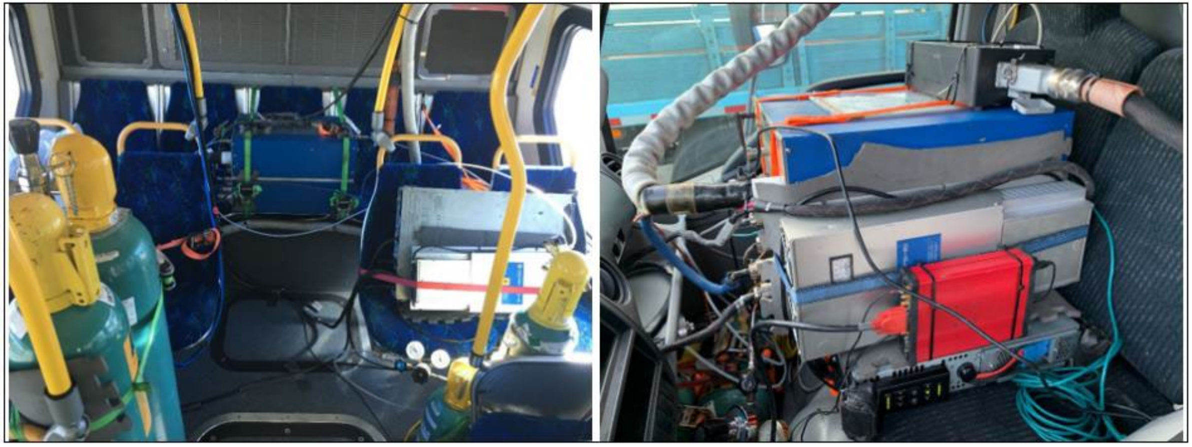
WVU data was collected and stored continuously every one tenth second (10 Hertz) while UCR reported data every second (1 Hertz). Electrical power for both team's PEMS instruments was provided through a standalone gasoline-fueled generator that was installed in each tested HDV. The PEMS were typically situated inside the vehicle, although the configurations varied between different vehicles/fleets. The interior installation ensured the PEMS were isolated from the interference of the external environment for data accuracy and avoiding equipment breakdown. The setup of the PEMS equipment is shown in Figures 7 and 8 for UCR and WVU, respectively.

Figure 7: Equipment Setup of UCR's PEMS Testing



Source: UCR

Figure 8: Equipment Setup of WVU's PEMS Testing



Source: WVU

The UCR team installed the PEMS on a total of 50 HDVs from its PAMS vehicle pool, including 6 transit buses, 7 school buses, 7 refuse haulers, 10 delivery vehicles, and 20 goods movement trucks. The WVU team installed the PEMS on a total of 50 HDVs from its PAMS vehicle pool, including 4 transit buses, 6 school buses, 8 refuse haulers, 10 delivery vehicles, and 22 goods movement trucks.

2.4.3 PEMS Data Analysis

PEMS test data were analyzed and used to calculate emissions rates for the HDVs. Emission rates were expressed in distance-specific (g/mile), work-based (g/bhp-hr), fuel-consumption-specific (g/gallon or g/kg of fuel), and time-specific (g/second, g/hour, g/day, or g/shift) metrics averaged over the entire day of testing regardless of the actual duty cycles.

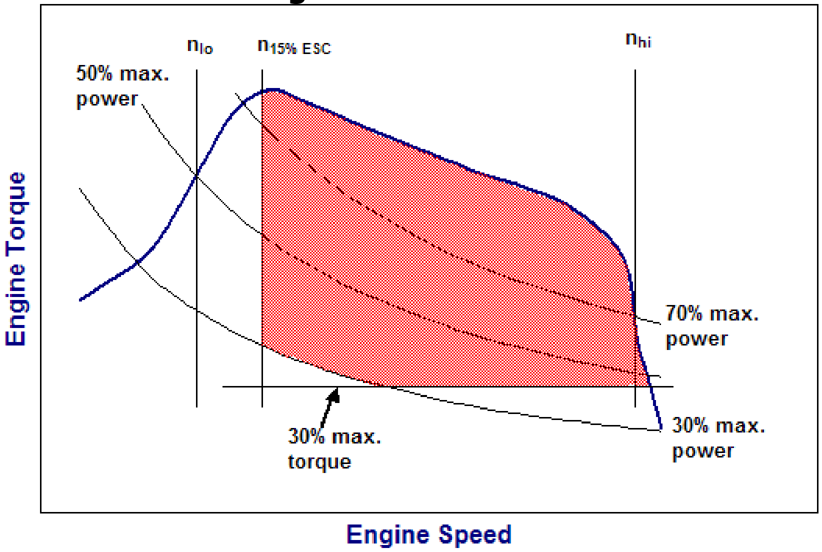
The PEMS testing was used to identify operational modes and/or conditions that contribute disproportionately to in-use HDV NOx emissions during on-road operation. Past studies have shown that low-load, low speed operation makes up the vast majority of vehicle activities in urban areas like SCAB. Emissions data from in-use HDVs are more variable when compared with emissions certification data collected for heavy-duty engines over the Federal Test

Procedure (FTP) since duty cycles experienced by HDVs under in-use testing conditions differ from how engines are tested under the FTP. The daily averaged PEMS data from this study provides a rough range of estimates that characterize how the various HDV fuel-technology types can perform in the real-world, but can also be analyzed further to assess performance over wide variety of duty cycles.

2.4.4 Not-to-Exceed (NTE) Testing

The NTE test procedure was jointly adopted by U.S. EPA and CARB for the Heavy-Duty In-Use Testing (HDIUT) program. Compliance of an HDV's engine is based on the time-weighted NOx emissions during NTE events over the course of a typical operational day. The NTE test procedure requires that in-use emissions are measured while heavy-duty diesel engines are "operating within a broad range of speed and load points" under conditions that "can reasonably be expected to be encountered in normal vehicle operation and use."[16] U.S. EPA and CARB define the NTE "control area"–based on a given engine's peak torque and rated power -- as the basis for comparing specific NTE emission limits.

Figure 9: NTE Zone



Source: DieselNet, NTE (Not-To-Exceed) Testing, https://dieselnet.com/standards/cycles/nte.php

The NTE regulation also provides multiple exclusions based on engine operational conditions, such as intake manifold temperature, engine coolant temperature, and altitude, as well as conditions when the outlet temperature of the SCR NOx-aftertreatment system is below 250 degrees Celsius for engines certified to the U.S. EPA 2010 emissions standards. To assess compliance, emissions are quantified over a period of a minimum of 30 seconds, then compared to NTE emissions standards that are a function of the certification standard, an in-use compliance multiplier, and a measurement allowance margin. Additional details about this

---

[16] Code of Federal Regulations (CFR) Title 40, Volume 20, Part 86.1370–2007, https://www.govinfo.gov/app/details/CFR-2012-title40-vol20/CFR-2012-title40-vol20-sec86-1370-2007.

procedure are available in the UCR and WVU final reports (Appendix A and Appendix B, respectively) and in the applicable Code of Federal Regulations (CFR) Section 86.1370-2007.[17]

This study conducted NTE analyses for all PEMS-tested HDVs. Per procedure requirements, each HDV was tested during typical daily operation to evaluate the percentage of HDV operation that occurred within an NTE zone, and the portion of total NOx emitted during those NTE events. It is noteworthy that for compliance purposes under the HDIUT program, NTE analysis is only applicable to diesel vehicles. However, for comparison purposes, an NTE analysis was also conducted on PEMS-tested natural gas vehicles.

Notably, certification values from engine testing over the FTP wereused as the basis for developing the NTE limits for different engine families that were applicable to in-use operating conditions within the NTE operating zone. However, as many studies, including this one, have noted, the percentage of time within NTE zone was very limited. Therefore, both CARB and EPA are transitioning from the single-level NTE metric to the two/three-level "two/three-bin moving average window" (2/3B-MAW) metric. The 2/3B-MAW will capture all duty cycles and will have a separate limit for each bin. The newly adopted 2/3B-MAW analysis was not in the original scope of this study but will be assessed as part of future work.

2.5 Chassis Dynamometer and Test Procedures

The chassis dynamometer testing is also a widely used in-vehicle testing method using dynamometer rollers and laboratory grade equipment that is similar to the engine dynamometer certification testing. The test cycles are repeatable, so emissions and fuel economy can be compared among different vehicles.

A total of 52 unique HDVs were tested at the two universities' heavy-duty vehicle emission laboratories using two different kinds of chassis dynamometers.

The chassis dynamometer test facilities at the two universities' laboratories were designed to meet all applicable requirements codified under CFR 40, Part 1065 and Part 1066. The chassis dynamometers at the two laboratories performed the following essential testing functions:

1) Accurately applying varying road loads.
2) Simulating the HDV's inertia mass that must be accelerated and decelerated.
3) Providing a speed-versus-time "trace" for the HDV driver to follow for a given test cycle.
4) Providing speed-dependent air flow to cool the front of the HDV being tested.

The HDV was tested while a trained laboratory technician drove it in a normal fashion by operating the accelerator pedal, transmission gear, and brake. Both university teams used mobile trailers to house the testing equipment, including the constant volume sampler (CVS), exhaust analyzers, and other measurement/analysis instrumentation, which are called Mobile Emissions Laboratory by UCR, and Transportable Emissions Measurement System by WVU.

There are two key differences between the two chassis dynamometer laboratories. First, UCR's facility was permanently installed in an outdoor area while the WVU's facility was

---

[17] Ibid.

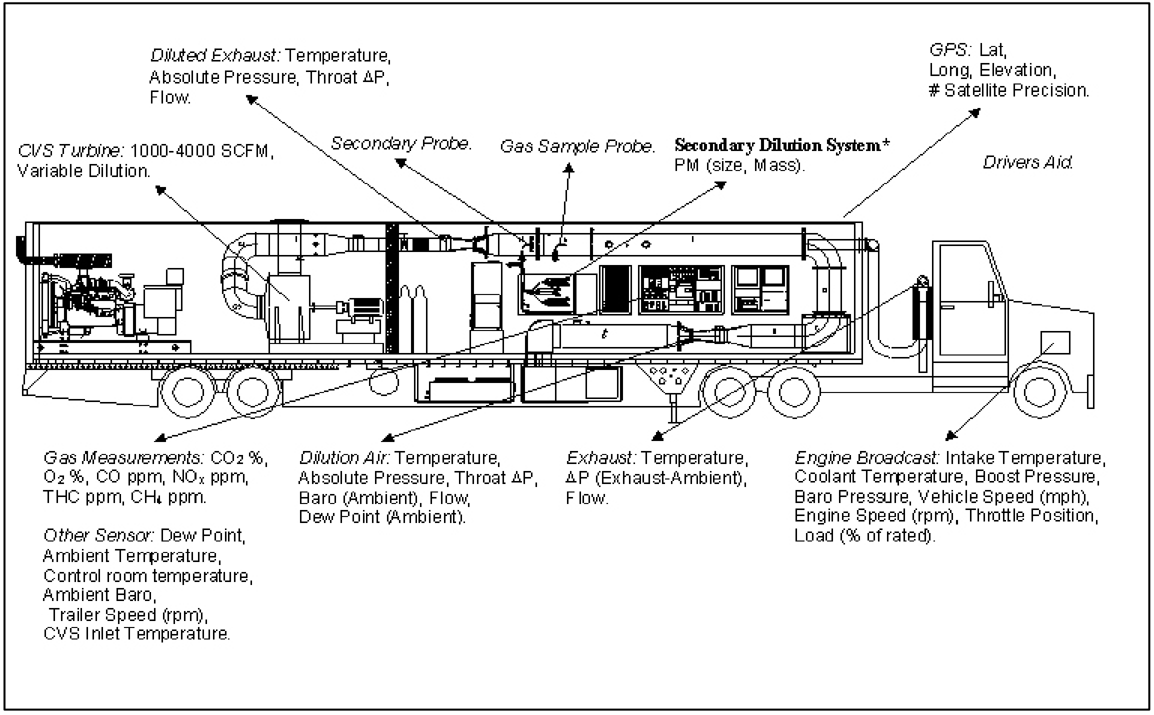
transportable. Second, the two chassis dynamometers used different mechanisms to interface with the HDV being tested. Specifically, for the UCR system, the tested HDV's driveline (rear) tires rested upon the chassis dynamometer's double roller system. The HDV was "driven" according to a prescribed test cycle, while the HDV was stationary. The tires turned the dynamometer rolls, which were attached to a system that simulated the HDVs inertia mass and applied varying resistance to simulate total road load (road surface friction, wind resistance, etc.). The WVU chassis dynamometer performed the same basic functions, but in contrast to the UCR's system, there was no tire-to-roller interface between the HDV and dynamometer. Instead, the HDV's drive axle was directly coupled to the dynamometer, which was done by removing the HDV's wheel/tires on the drive axle of the driveline and attaching the exposed drive axle to the dynamometer's drive shaft, using hub adapters.

Figure 9 shows four different HDV types installed on UCR's chassis dynamometer: a school bus (top left), a Class 8 goods movement tractor (top right), a delivery truck (bottom left), and a refuse hauler (bottom right). Figure 10 illustrates the key systems that of UCR's mobile emissions laboratory.

Figure 10: Various HDV Types Installed on UCR's Chassis Dynamometer

Source: UCR

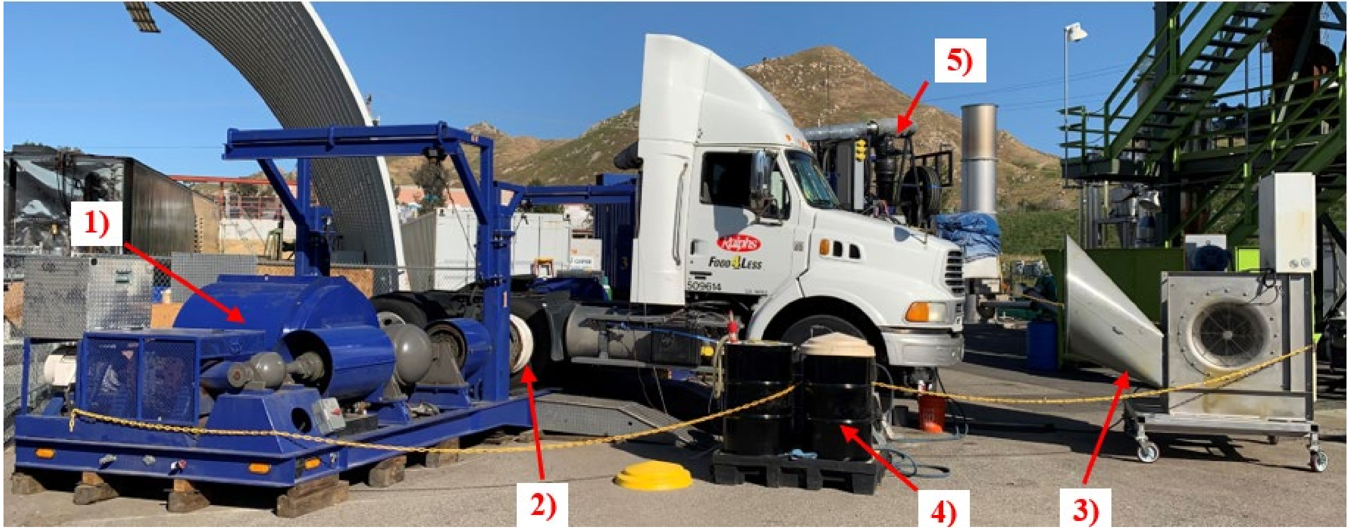
Figure 11. Main Systems of UCR's Mobile Emission Lab (MEL)



Source: UCR

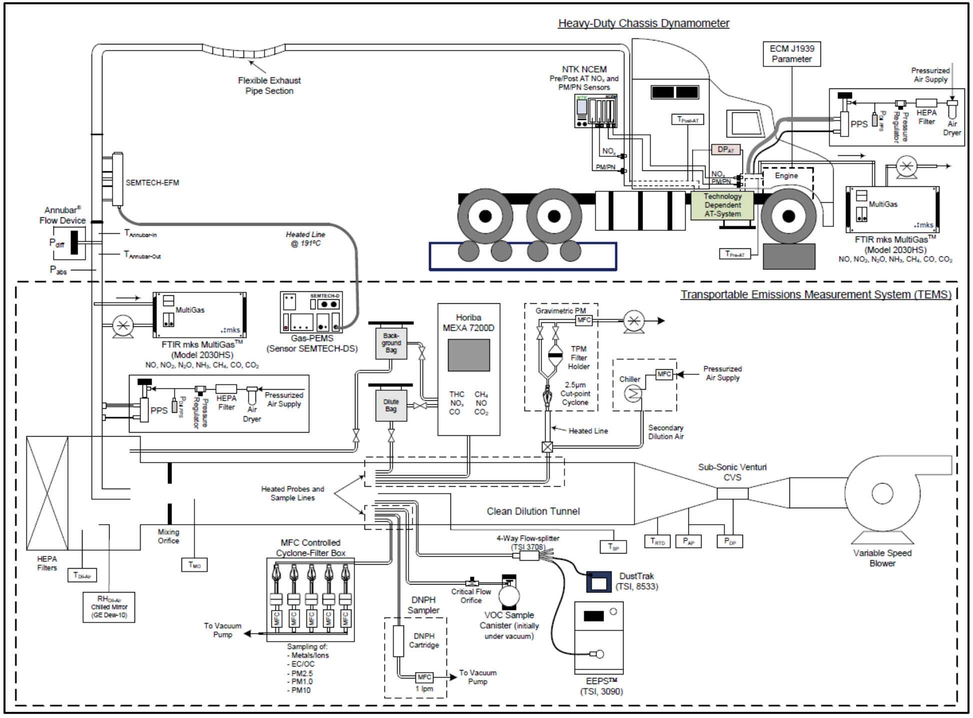
Figure 11 shows the full WVU's chassis dynamometer with 5 subsystems: 1) flywheel assembly; 2) hub adaptors, coupled with the dynamometer drive shaft; 3) air fan proportional to simulated vehicle speed; 4) fuel island with gravimetric diesel fuel measurement; 5) exhaust transfer line to the constant volume sampler (CVS) and analytical lab systems. Figure 12 illustrates the key systems of WVU's transportable emissions measurement system.

Figure 12: WVU Heavy-Duty Transportable Chassis Dynamometer



Source: WVU

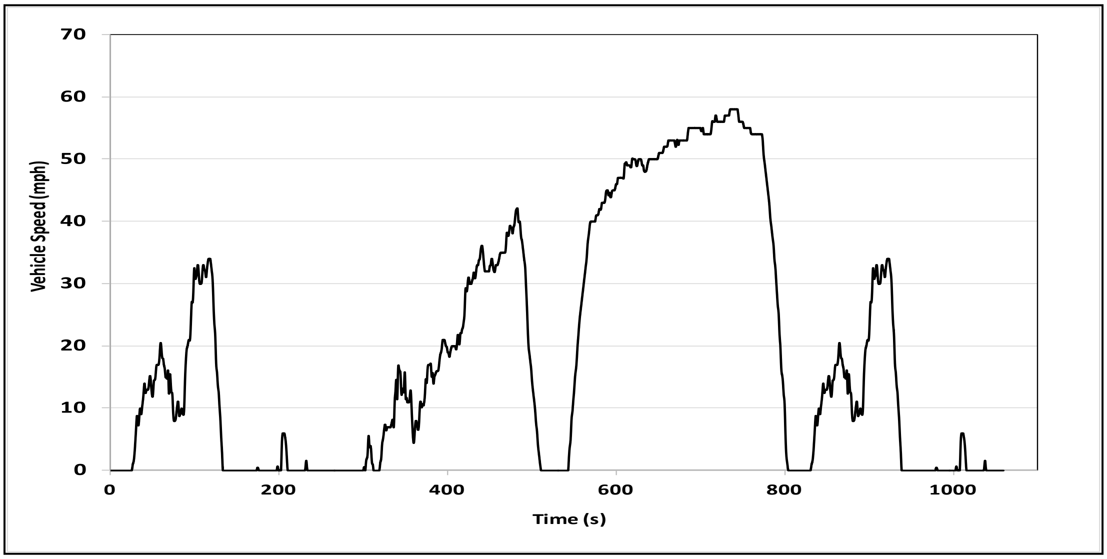
Figure 13: Schematic of WVU's Portable CVS Sampling and Gas Analyzer Systems



Source: WVU

All HDVs were tested over the Urban Dynamometer Driving Schedule (UDDS, see Figure 14), which was run as a cold start phase after the vehicle has preconditioned and soaked overnight and a hot start phase. Emission results collected under UDDS were all weighted based on 1/7 cold start and 6/7 hot start phase, which is typically done for engine certification testing using the FTP. Additional cycles were run on the different HDVs depending on their vocation category. This include some standard chassis dynamometer test cycles, including the Central Business District (CBD) cycle, the Orange County Transit Authority (OCTA) cycle, and the CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise cycle, as well as some new test cycles that were developed based on the activity data collected during the PAMS monitoring. Chapter 3 discusses the approach on developing new chassis drive cycles. Full details of the cycles used, as well as cycle development are documented in the university reports (Appendices A and B).

Figure 14: Simulated Speed vs Driving Time for UDDS Cycle



Sources: UCR and WVU

2.6 Cross-Laboratory Comparison

The complex methods, processes and equipment used to conduct HDV emissions testing entail many potential sources of variability.[18] To characterize and help minimize variability for multi-lab testing programs, one useful tool was to conduct cross-laboratory testing on the same vehicle(s). Such "round-robin" correlation testing is commonly practiced between laboratories of similar types and functions.[19] The two universities cross-tested three HDVs with PEMS, and another three HDVs with chassis dynamometer. Table 5 provides a summary of the six HDVs for cross-lab testing. The analyses were focused on the chassis dynamometer data, as the PEMS emissions data were collected during in-use operations that will inherently vary from day-to-day.

---

[18] These include the chassis dynamometer that must accurately reproduce vehicle inertia mass and road load; the exhaust sampling system designed to accurately dilute the exhaust to a constant volume; the pollutant analysis bench and instruments; the condition of the test vehicle itself; the repeatability of the test cycle; and how the vehicle was driven during the test.

[19] See for example U.S. EPA's program with CARB and Environment Canada to conduct such a round robin project for testing of off-road HDVs, https://www.epa.gov/sites/production/files/2019-09/documents/compliance-workshop-roundrobin-carb-eccc-09-2019.pdf.

Table 5: HDVs Tested by the Two Universities

Cross-Lab Test Type	Test HDV Type	Fuel / NOx Certification (g/bhp-hr)	UCR HDV Number	WVU HDV Number
PEMS	Transit Bus	NG / 0.02	18081	125
PEMS	Delivery Truck	Diesel / 0.20	18110	175
PEMS	Goods Movement Truck	NG / 0.02	18043	108
Chassis Dyno	Transit Bus	NG / 0.02	18114	223
Chassis Dyno	Delivery Truck*	Propane / 0.02	19002	210
Chassis Dyno	Goods Movement Truck	Diesel / 0.20	18072	194

***The test weights were different between UCR and WVU. Excluded for cross comparison.**

Sources: UCR and WVU

2.7 On-Road Laboratory Emission Test Procedures

The two university teams used similar methodologies and laboratory equipment to perform on-road emissions assessment on a total of ten HDVs. The HDVs were driven on Southern California roads and highways, while towing the trailer-mounted UCR MEL and the WVU TEMS emissions collection and analysis systems, respectively. This unique type of emissions testing was conducted only on Class 7 or 8 heavy-duty tractors as they could safely and legally tow the large trailers that housed the transportable emissions labs. Figure 15 shows the Class 8 tractors undergoing real-world emissions testing by UCR and WVU. WVU took the initiative and collaborated with UCR to create special “vocational” driving routes for this testing, based on their earlier PAMS and PEMS testing results. The selected test routes covered a wide array of Southern California roads with varying gradients and up and down grades. As previously mentioned, the towed trailer-mounted laboratories were the same as the ones used for stationary chassis dynamometer testing. When compared to PEMS testing, the on-road testing offers laboratory grade emission equipment, and the ability to measure a wider range of pollutants. The more repeatable, semi-fixed routes used for the on-road testing also incorporate real-world factors, such as traffic and elevation changes, that were not simulated in the chassis dynamometer testing.

Figure 15: On-Road Test Systems for UCR and WVU

Source: South Coast AQMD

CHAPTER 3:
Testing Results of the Four Phases

3.1 Results and Discussion for PAMS Data

3.1.1 Vocational Results for PAMS Testing

PAMS data collected by the two university teams characterized the real-world activity of the 217 trucks. Table 6 summarizes the real-world activity data UCR collected for each vocation with the PAMS testing, compared to the corresponding vocational test cycles that were utilized or developed for the later chassis dynamometer testing. Figure 14 provides the percentages of VMT as a function of total distance traveled for different speed ranges for each vocation based on the PAMS data UCR collected. Due to scope and page limitation of this report, the WVU PAMS analysis is not described in detail. Please reference the WVU report for details.

Table 6: Summary of PAMS Activity Data by Vocation for Vehicles Tested by UCR

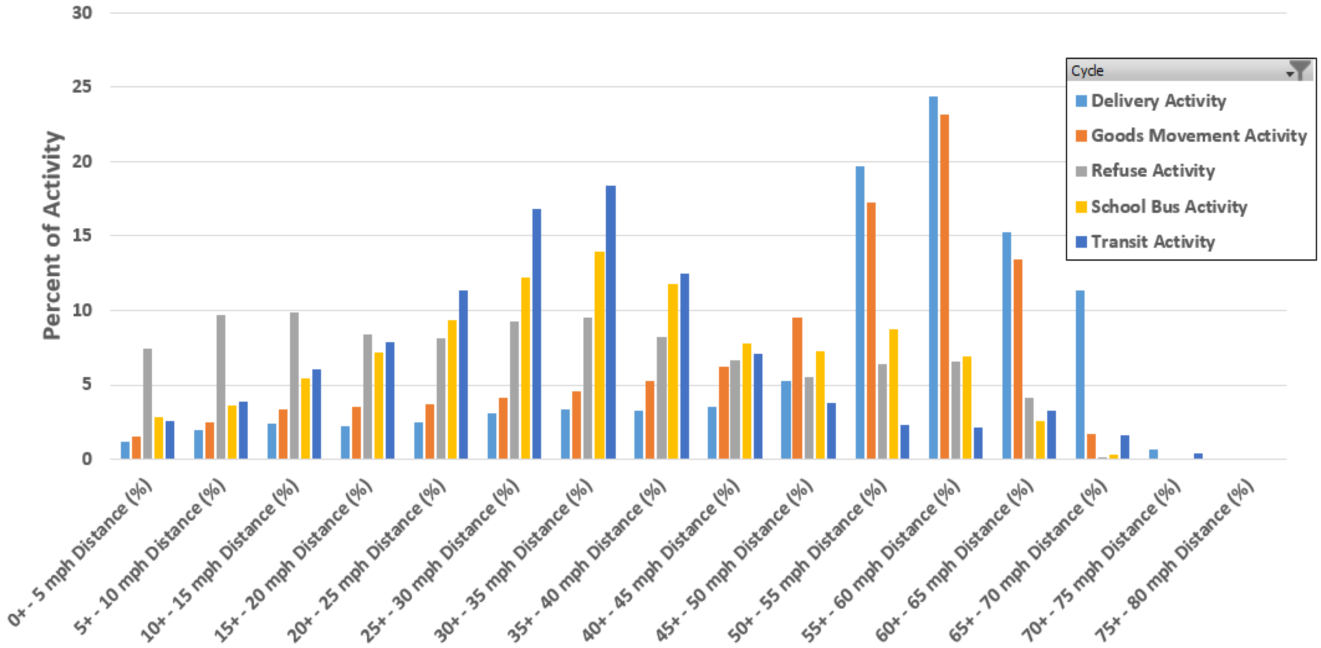
HDV Type/Vocation	PAMS vs. Chassis Dyno Cycle	Avg Non-Zero Velocity (mph)	Stdev Non-Zero Velocity (mph)	Max Acceleration (mph/s)	Idle Time %
Transit Bus	PAMS/OCTA*	16.7/15.5	15.9/9.2	8.0/3.9	30.2/21.3
School Bus	PAMS/SB	15.4/19.4	16.8/11.8	5.0/4.2	18.0/38.4
Refuse Hauler	PAMS/Refuse	9.9/10.1	13.7/11.2	5.0/4.9	19.4/5.0
Delivery Truck	PAMS/Delivery	28.2/30.2	24.9/21.6	8.0/3.2	23.7/41.7
Goods Movement	PAMS/GMC	22.5/32.8	23.0/19.8	7.7/2.8	25.9/42.2

***OCTA = Orange County Transportation Authority.**

Source: UCR

The UCR data indicate variation of activity patterns among vocations. The PAMS results in Table 6 show that delivery HDVs had the highest average speeds followed by goods movement HDVs, with 28.2 mph and 22.5 mph, respectively. When combining the speed bins in Figure 16, delivery HDVs spent 72 percent of VMT between 40 and 70 mph and goods movement HDVs spent 78 percent of VMT between 40 and 70 mph. The transit bus and school bus average speeds were moderate (16.7 mph and 15.4 mph, respectively). The refuse haulers had the lowest average speed of 9.9 mph. For the refuse haulers, the relatively low speeds were expected as their routes included curbside pick-up in residential areas. The refuse haulers were driven below 15 mph for approximately 28 percent of VMT, and at speeds below 40 mph for 72 percent of VMT. The transit buses and school buses had similar speed patterns: approximately 45 to 47 percent of the VMT at speeds between 20 and 40 mph and 67 to 76 percent of the VMT below 40 mph. The average time percentages of engine idling ranged from 18.0 to 30.2 percent, as shown in Table 6. The transit bus category had the highest idling time percentage, and the school bus and refuse hauler categories had the lowest time percentages.

Figure 16: VMT Fractions for Different Driving Speeds among Vehicle Vocations



Source: UCR

A large fraction of the PAMS activity data from the 200 HDV Testing Program was used in the development of CARB's EMFAC2021. Ultimately, 168 HDVs from this study, pooled together with 90 HDVs from a previous UCR study[20], were included in CARB's EMFAC2021. Collectively, these two data sets accounted for the majority of HDV activity updates in this latest EMFAC model. Per CARB's EMFAC2021 technical documentation, when compared to EMFAC2017, the new data show that the majority of the HDV categories have "higher percentage of VMT at higher speeds, higher starts per day and longer soak time, and less extended idling time." CARB also observed that HDV activity has "no significant difference between fuel types." Whenever applicable, the new PAMS data update was also applied to all regions in California in EMFAC2021.[21]

3.1.2 Cycle Comparisons and Development

To comparatively assess emissions from different HDV fuel technology types while being operated over representative driving cycles, it was imperative to select or develop entirely new driving cycles that best characterize typical HDV operation in Southern California, especially for each of the five HDV applications/vocations. Accurate and representative test cycles were

---

[20] Kanok Boriboonsomsin, Kent Johnson, George Scora, Daniel Sandez, Alexander Vu, Tom Durbin, and Yu (Jade) Jiang, "Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles" https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/13-301.pdf

[21] See CARB documents: 1) "EMFAC2021 Volume III Technical Document," March 31, 2021, https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf; and 2) "EMFAC202x Updates," July 30, 2020, https://ww2.arb.ca.gov/sites/default/files/2020-07/EMFAC202x_2nd_Workshop_07302020_ADA.pdf.

needed for the HDV chassis dynamometer testing phase of the Program, as well as for the real-world HDV testing on the roads of Southern California.

3.1.2.1 Chassis Dynamometer Cycle Development

The PAMS data of real-world activity data from the 227 tests in the Program was used to determine vocation-specific HDV operating characteristics with a finite number of typical statistical parameters, including vehicle speeds, idle time, engine load/power and so on. The WVU conducted comparisons for the activity parameters derived from real-world PAMS data with the respective values calculated from existing chassis dynamometer drive-cycles for different HDV vocations, similar to the comparisons presented in Table 6. These comparisons provide a basis to evaluate whether chassis dynamometer drive cycles, such as the UDDS, capture essential real-world activity patterns for a given vocational application and simulate statistically equivalent HDV operation. When comparisons show a large discrepancy, a new vocation-specific duty cycle may be needed.

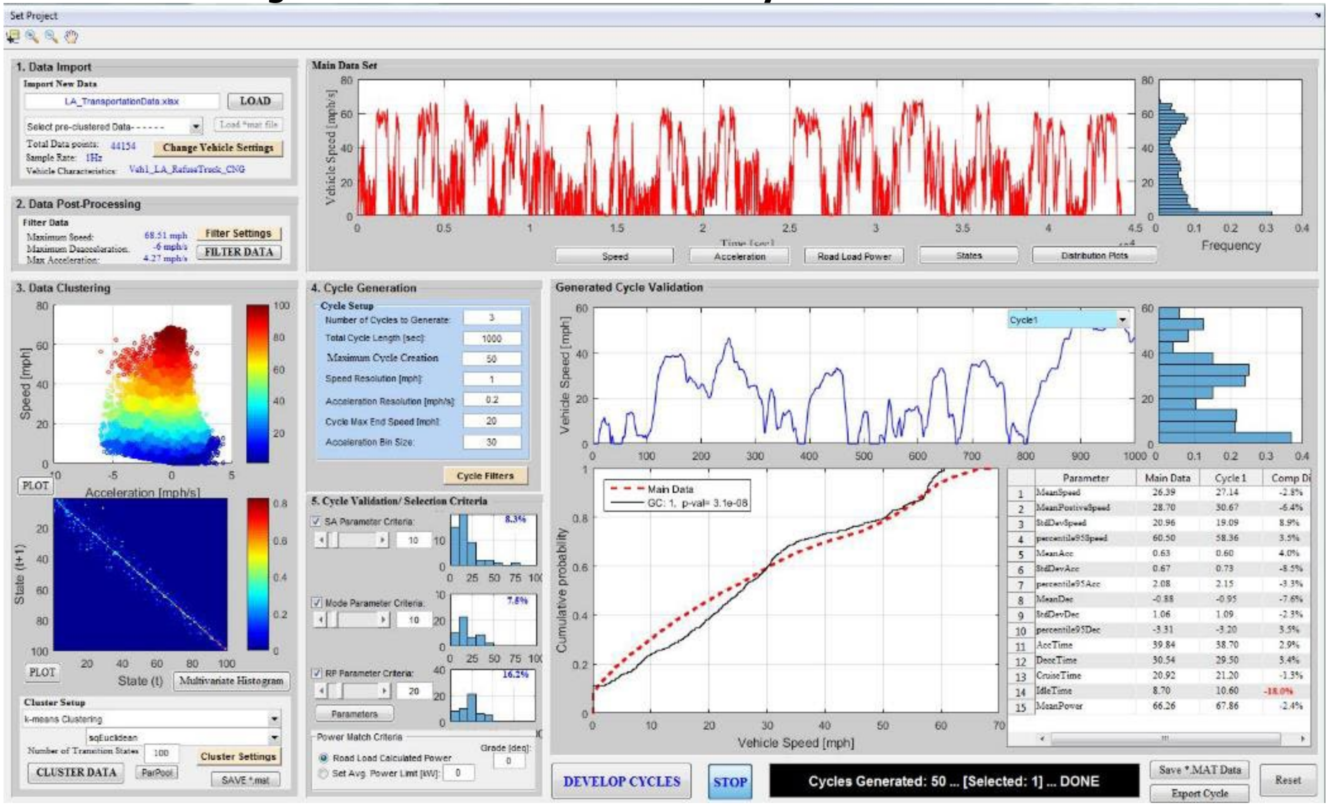
Based on the comparison for the cycle parameters, such as average speed, idle period, and average load/power, the test teams observed differences between standard test cycles (eg. UDDS) and real-world operating patterns in Southern California for three HDV types: school buses, goods movement trucks, and delivery trucks. To test these HDV types under more representative conditions, the test teams developed new chassis dynamometer test cycles specific to these three categories. In addition, PAMS activity data from refuse haulers indicated the need to modify the existing test cycle to better simulate additional work that engines of these trucks perform to power the hydraulic actuators that enable curbside refuse pick-up and compaction, which was simulated by including a varying grade to the standard refuse cycle during the curbside pick-up portion of the cycle.

The three new chassis dynamometer drive-cycles were generated with the Markov-Chain Drive Cycle Generation Tool developed by the WVU team[22] (shown in Figure 17). Combined PAMS activity data from both universities for school buses, delivery trucks, and goods movement trucks were used to calculate representative statistical parameters and to generate the new drive cycles. The specifications of these cycles are shown in Table 7.

---

[22] West Virginia University, "Development of Real World Heavy-Duty Refuse Truck Driving Cycles Using Markov Chains Method," presentation by Saroj Pradhan, Arvind Thiruvengadam, et al., 26th CRC Real World Emissions Workhop, March 15, 2016.

Figure 17: Markov-Chain Drive Cycle Generation Tool



Import New Data

LA_TransportationData.xlsx

Select pre-clustered Data- - - - - -

Total Data points: 44154

Sample Rate: 1Hz

Vehicle Characteristics: Veh1_LA_RefuseTruck_CNG

Filter Data

Maximum Speed: 68.51 mph

Maximum Deaceleration: -6 mph/s

Max Acceleration: 4.27 mph/s

Cluster Setup

k-means Clustering

sqEuclidean

Number of Transition States 100

CLUSTER DATA

ParPool

Cluster Settings

SAVE *.mat

Cycle Setup

Number of Cycles to Generate: 3

Total Cycle Length [sec]: 1000

Maximum Cycle Creation 50

Speed Resolution [mph]: 1

Acceleration Resolution [mph/s]: 0.2

Cycle Max End Speed [mph]: 20

Acceleration Bin Size: 30

☑ SA Parameter Criteria: 10

☑ Mode Parameter Criteria: 10

☑ RP Parameter Criteria: 20

Power Match Criteria

● Road Load Calculated Power

○ Set Avg. Power Limit [kW]: 0

Grade [deg]: 0

Cycles Generated: 50 ... [Selected: 1] ... DONE

	Parameter	Main Data	Cycle 1	Comp Di
1	MeanSpeed	26.39	27.14	-2.8%
2	MeanPositiveSpeed	28.70	30.67	-6.4%
3	StdDevSpeed	20.96	19.09	8.9%
4	percentile95Speed	60.50	58.36	3.5%
5	MeanAcc	0.63	0.60	4.0%
6	StdDevAcc	0.67	0.73	-8.5%
7	percentile95Acc	2.08	2.15	-3.3%
8	MeanDec	-0.88	-0.95	-7.6%
9	StdDevDec	1.06	1.09	-2.3%
10	percentile95Dec	-3.31	-3.20	3.5%
11	AccTime	39.84	38.70	2.9%
12	DeccTime	30.54	29.50	3.4%
13	CruiseTime	20.92	21.20	-1.3%
14	IdleTime	8.70	10.60	-18.0%
15	MeanPower	66.26	67.86	-2.4%

Source: WVU

Key vocation-specific factors such as vehicle speed and acceleration were considered for the development of new drive cycles (Table 7). For goods movement trucks, the gross combined vehicle weight can vary greatly, depending on the load status (e.g., bobtail, empty, half-full, full trailer), which had a significant impact on vehicle dynamics. To address this, a weight estimation algorithm was developed to simulate the actual vehicle operating weight throughout the shift-day. Delivery trucks and school buses, on the other hand, have curb weights that are typically much larger than the potential weight of the load, and the gross combined vehicle weight (cargo) changes throughout the shift-day are not as impactful on dynamic engine and vehicle operating conditions.

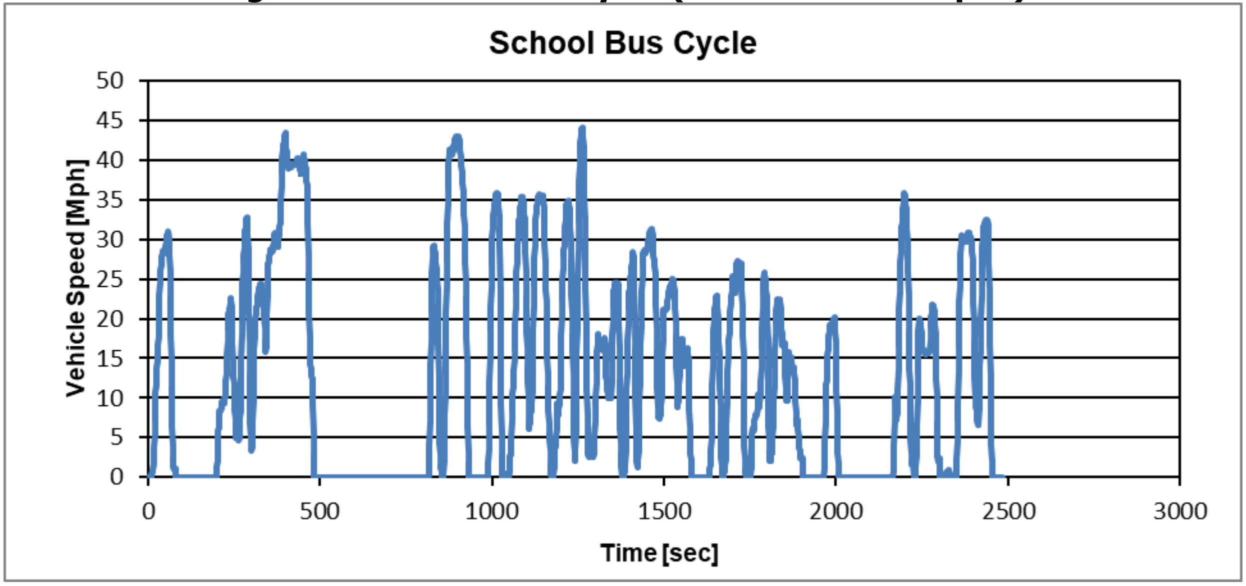
Table 7: New Chassis Dynamometer Test Cycles Developed in the Program

Cycles	Cycle Duration (s)	Distance (km)	Avg. Speed (km/h)	Max. Speed (km/h)	Idle %
Goods Movement Truck Cycle (Markov)	3600	20.1	20.1	64.1	42.18%
South-Coast School Bus Cycle (Markov)	2484	8.5	12.3	43.6	38.43%
Delivery Truck Cycle (Markov)	2587	13.0	18.1	64.4	41.73%

With these inputs and PAMS data, the Markov-Chain tool generated three candidate test cycles for further validation; they were further compared to the real-world activity to ensure there were not significant differences between the two. These final selected test cycles became the newly developed chassis dynamometer duty cycles for the given vocations, which are presented in

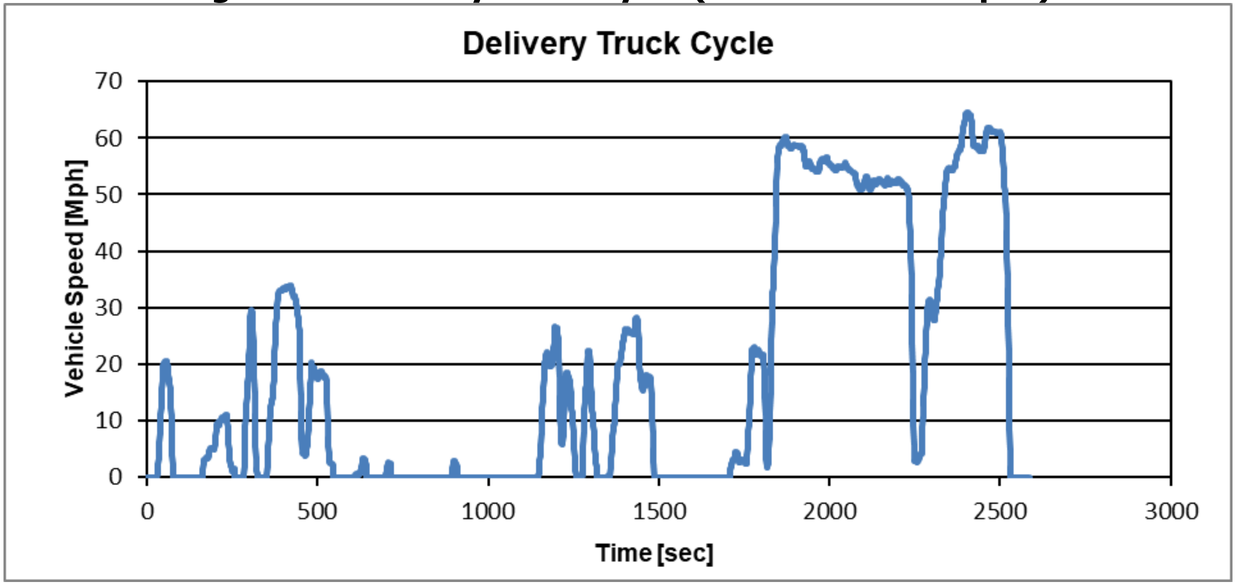
Figure 18, Figure 19, and Figure 20. The same process was followed for all three vocations. The goods movement truck cycle in particular was comprised of several different operations including 1) drayage operation, 2) garbage hauling between collecting stations and landfills, and 3) "longer haul" goods movement transport within the South Coast area.

Figure 18: School Bus Cycle (SBC-WVU developed)



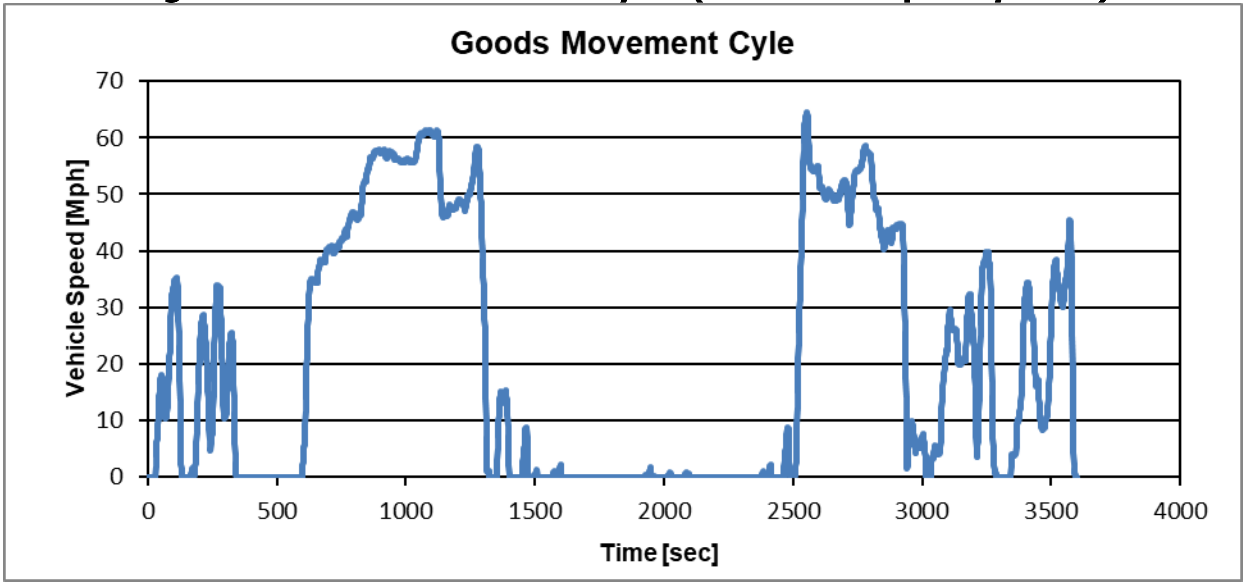
Source: WVU

Figure 19: Delivery Truck Cycle (DTC-WVU developed)



Source: WVU

Figure 20: Goods Movement Cycle (GMC-Developed by WVU)



Source: WVU

3.1.2.2 Real-World On-Road Route Development

Four real-world driving routes were developed by analyzing PAMS activity data from Class 8 tractors primarily operated in Southern California by four HDV fleets: Ralphs for grocery distribution, Total Transportation Services, Inc. (TTSI) for drayage operations, UPS for regional delivery, and CR&R Environmental Services (CR&R) for longer-haul waste transport. The main routes of these four fleets overlap with the routes of other typical Class 8 tractor fleets. Therefore, the chosen routes were representative of typical goods movement trucking operations in Southern California. In addition to the four identified routes, "loading-unloading" areas were identified to simulate truck activities at the beginning and end of goods movement trips. This simulation only represented the time of engine shutdown during the "loading-unloading" process and not the change in weight of the test vehicle.

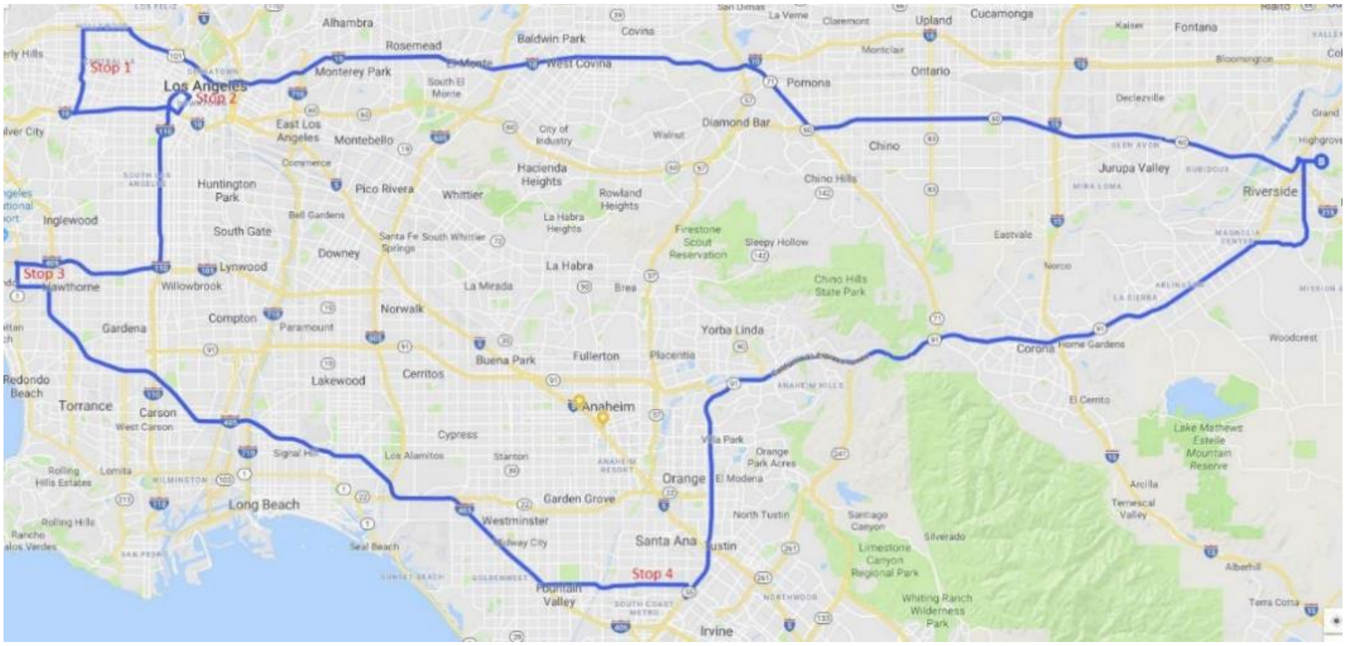
Table 8: Summary Stats for the On-Road Routes

Test Cycle	Cycle Duration (Hrs)	Distance (Miles)	Idle %	Urban <31mph	Rural (31-46 mph)	Highway (>46 mph)
Ralphs Route	7.0	183.1	20.6	44.0	10.9	24.6
TTSI Route	6.1	162.4	41.5	23.1	13.3	22.1
UPS Route	4.1	113.4	16.2	38.4	12.5	32.9
CR&R Route	4.9	179	12.7	27.5	8.6	51.3

Source: WVU

As shown in Figure 21, the Grocery Distribution Route starts in Riverside, where the truck is fully loaded, and follows typical daily operation of a Class 8 truck used by a Grocery Distribution Center in Moreno Valley. The route includes a mix of urban, rural, and highway and four stops at grocery stores where goods are unloaded at the truck docks.

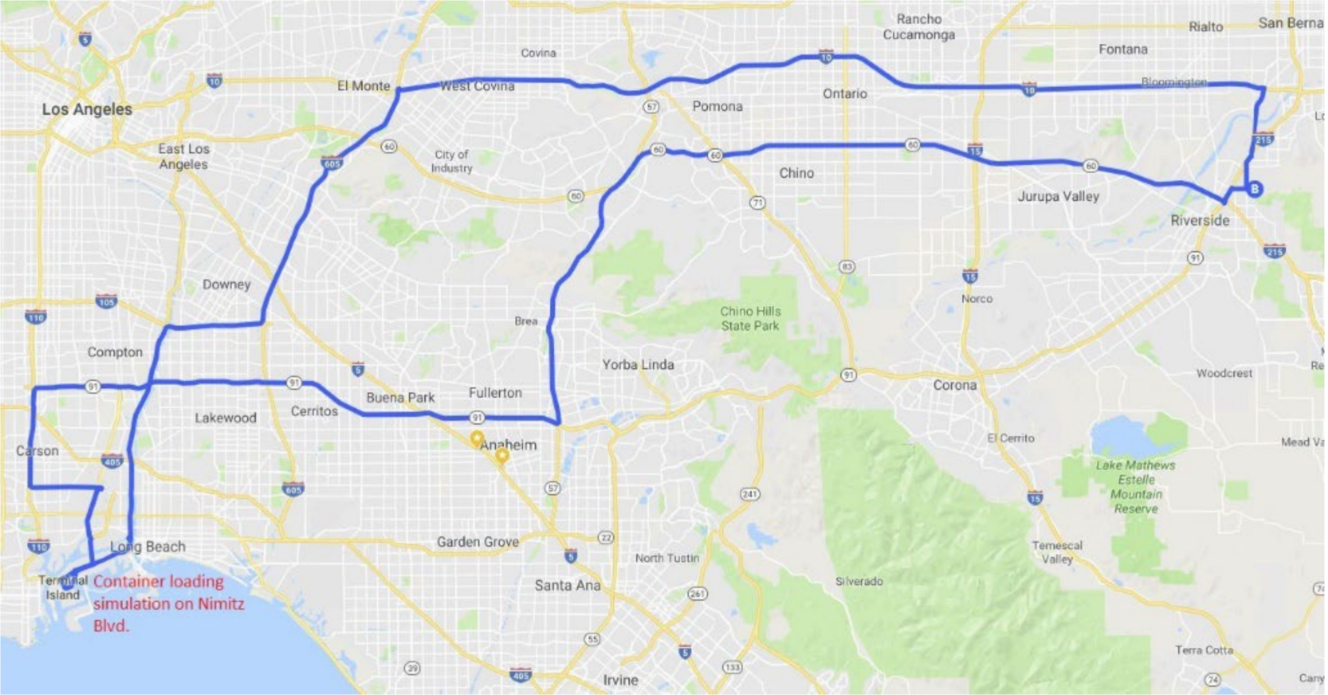
Figure 21: Grocery Distribution Route



Source: WVU

The Port Drayage Route (Figure 22) simulates typical daily operation of trucks operating between the Port of Long Beach and inland warehouses to deliver shipping containers. The route also includes urban and highway driving, and simulation of port activities (that is, extended idle and creep operation) while waiting at the port terminals to receive shipping containers.

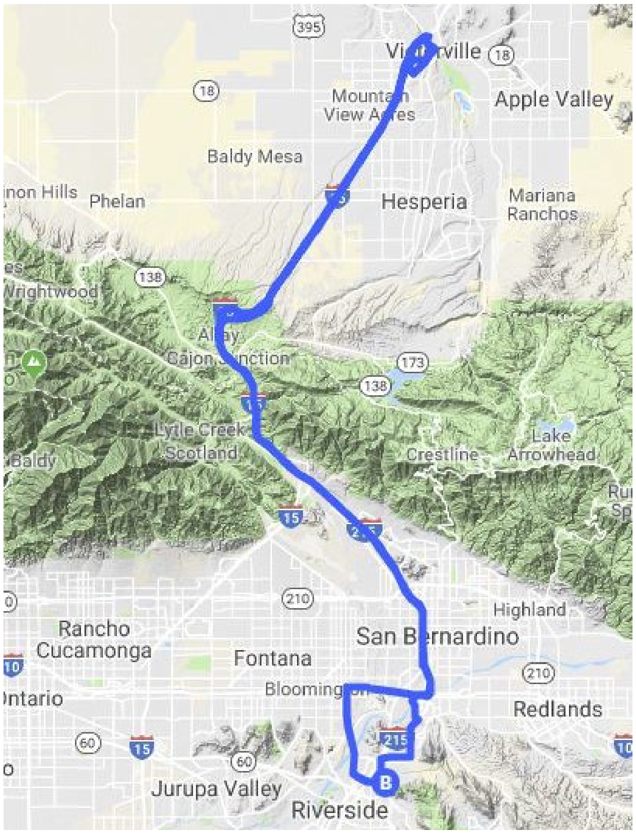
Figure 22: Port Drayage Route



Source: WVU

The Goods Movement Route (Figure 23) simulates typical operation of Class 8 delivery trucks (for example, UPS tractors) that operate on the I-15 corridor between Ontario, California and Las Vegas, Nevada through the Cajon Pass. The route comprises extended highway operation with total elevation changes of approximately 4,200 feet while ascending and descending the Cajon Pass. The beginning and end of this route includes some short rural vehicle operation activities to adequately represent the linkage between the highway and final distribution centers that the trucks drive through during regular revenue service operation.

Figure 23: Goods Movement Route



Source: WVU

The Highway Goods Movement Route (Figure 24) simulates typical operation of longer-haul Class 8 trucks, such as HDVs delivering garbage from transfer facilities to distant landfills, or moving goods between different distribution centers or production facilities. This route is primarily characterized by extended highway operation with short portions of urban operation when moving between the highway exit/entrance and the final destinations (for example, warehouses, factories, distribution centers, etc.). Accordingly, the route comprises extended highway driving between Riverside and Indio on Interstate-10 with short urban road links before the beginning and after the end of the highway operation.

Figure 24: Highway Goods Movement Route

Source: WVU

3.2 Results and Discussion for PEMS Data

3.2.1 Introduction to PEMS Testing

Using the vehicle matrix from PAMS phase, both universities identified a subset of vehicles for PEMS testing based on availability, vehicle type, and considerations for the later test phases. Table 9 summarizes the number of HDVs that each university PEMS tested by engine fuel type/NOx certification value and HDV application/type. No diesel transit buses were tested; this is because only alternative fuel buses (essentially, those using natural gas, propane, battery-electric or hydrogen fuel cell powertrains) are allowed to operate in the SCAB under South Coast AQMD's Rule 1192. Similarly, South Coast AQMD Rule 1193 precludes the use of diesel refuse haulers and school buses; however, one diesel refuse unit and one diesel school bus were obtained from outside the SCAB and tested.

Table 9: PEMS-Tested HDVs

Vehicle Types	**Transit Bus**	**School Bus**	**Refuse Hauler**	**Delivery Truck**	**Goods Movement Truck**	**Totals**
# of 0.20 g NG	5	6	10	3	7	31
# of 0.02 g NG	5	1	3	1	16	26
# of 0.20 g Diesel	0	2	2	8	17	29
# of Diesel (no SCR)	0	2	0	1	2	5
# of Diesel HEV	0	0	0	4	0	4
# of 0.02 g LPG*	0	2	0	3	0	5
Totals	10	13	15	20	42	**100**

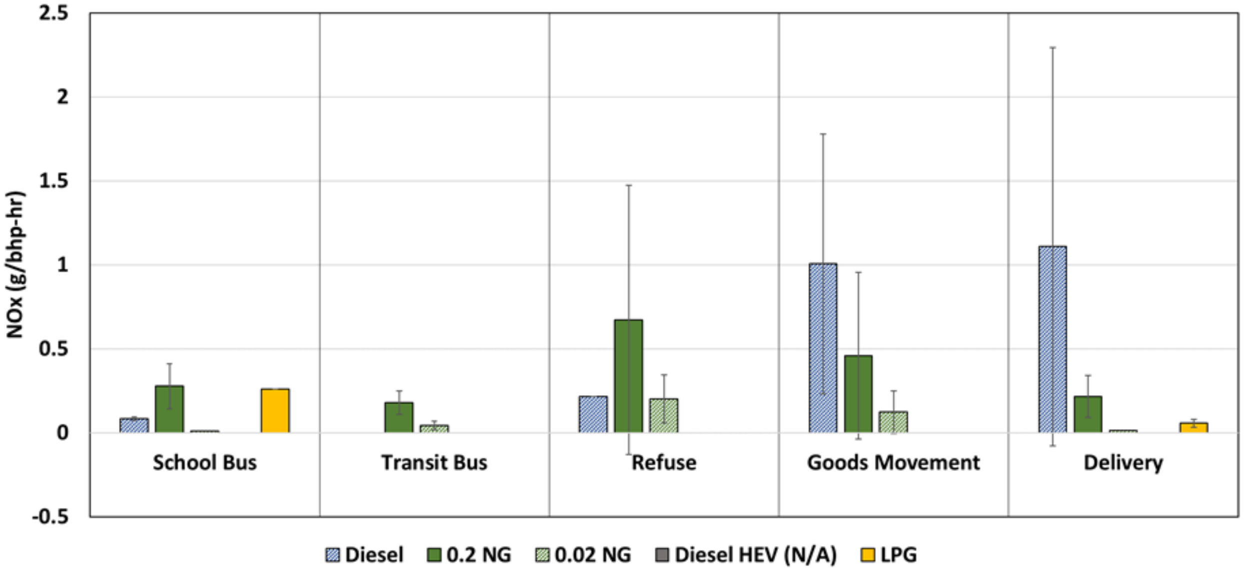
***LPG = liquefied petroleum gas.**

Sources: Information provided by UCR and WVU, April 2022

3.2.2 NOx Emissions from PEMS Testing

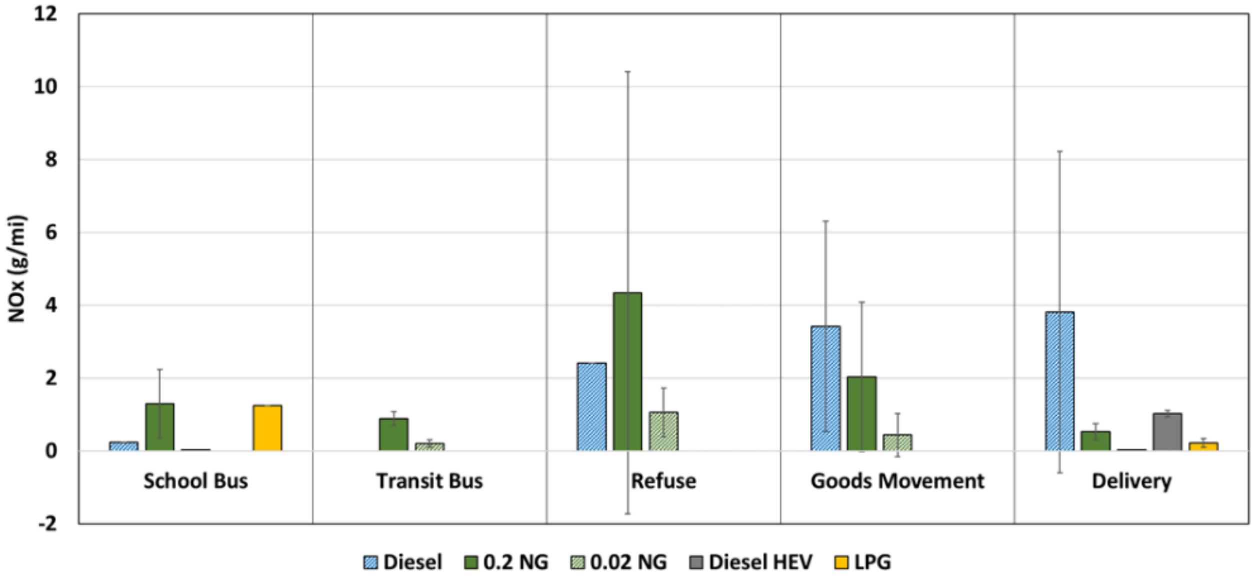
The simple "daily" averages of NOx emission rates of each combination of vocation and fuel type/emission level are illustrated in Figure 25 and Figure 26 in g/bhp-hr and g/mi units, respectively. Pre-2010 model year diesel vehicles will soon be retired from the California fleet, as the CARB Truck and Bus Regulation phases in. Further, the significantly higher NOx levels could skew the comparisons of lower NOx technologies. Thus, the five non-SCR diesel vehicles were removed from this comparison and can be found in the university reports (appendices A and B).

Figure 25: Horsepower-Based PEMS NOx Emission Rates



Source: UCR and WVU

Figure 26: Distance-Based PEMS NOx Emission Rates



Sources: UCR and WVU

The PEMS testing incorporated a wide variety of vehicles, fleet operators, and operating conditions/duty-cycles. As expected, the PEMS results showed high variability of NOx emission levels among vocations and technologies as indicated by error bars (one standard deviation). For example, after excluding the non-SCR diesel vehicles from the entire testing data, the daily averages of PEMS NOx emissions ranged from 0.009 to 3.616 g/bhp-hr. Also, as shown in Figure 25 above, the spread of NOx emission levels was much different among vocations, with the Transit Bus and school bus categories having the lower variability and the refuse truck, goods movement truck, and delivery truck categories showing higher variability for at least one technology category. The high variability is also observed within each technology category. For instance, the daily averages of PEMS NOx emissions for diesel vehicles ranged from 0.076 to 3.616 g/bhp-hr, even though all engines were certified to the same emission standard. The high variance was to be expected, since the PEMS emissions were averaged over the entire test day, regardless of the vocation and the duty cycles. This pattern was also observed in previous studies of SCR performance under in-use conditions.

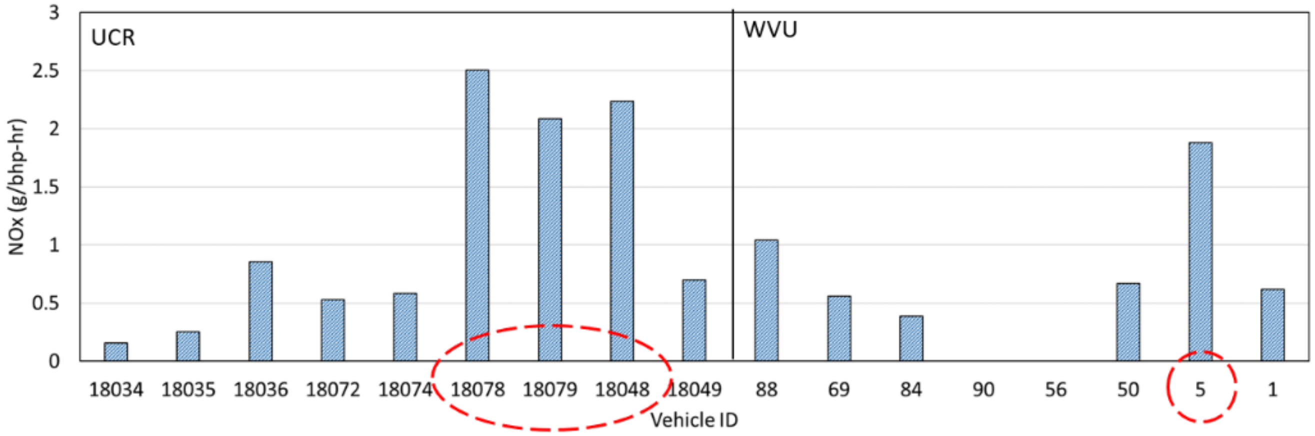
As discussed earlier, the compliance metric for the PEMS data set is the NTE method or the future 2/3B-MAW method, which are different than the "daily" averaged NOx emission data presented here. More details on NTE results can be found in the university reports. Note that Appendix C is dedicated to discussing "emission outliers" in the data, that is, emission levels (particularly for NOx) that significantly exceeded design levels. It includes analysis by the UCR-WVU test team regarding likely root causes for higher-emission events. To further look at trends in PEMS data, emission data for the individual vocations are discussed in greater detail the sections that follow.

Other analyses were performed on this PEMS data set as well. To reflect real-world emissions, CARB analyzed NG PEMS data to update the emission rates used in EMFAC2021. PEMS data from 47 out of the 120 NG vehicles tested were used in the development of EMFAC2021, which represented the data sets that were available at the time the model was being developed. CARB staff grouped the daily averaged PEMS data into 10-mph speed bins and generated speed bin-based emissions factors for updating EMFAC. More details of the CARB approach can be found in the EMFAC2021 Technical Documentation.[23] A similar binning approach can be found in the university reports (appendices A and B).

3.2.2.1 0.2g Diesel Goods Movement Trucks

Figure 27 shows the daily averages of PEMS NOx emission rates for each of the 17 0.2g diesel goods movement HDVs (Class 8 tractors). Overall, the daily emission rates ranged from 0.15 to 2.51 g/bhp-hr, with four HDV (circled in Figure 27) exhibiting relatively high NOx emission rates. The causes for the outlier were duty cycle related and ere not excluded but the daily averaged NOx emissions for the diesel goods movement truck category is 0.58 g/bhp-hr when not considering these outlier vehicles.

Figure 27: Daily Averaged PEMS NOx Emission Rates of 0.2g Diesel Goods Movement Trucks



Note: Data for Vehicles #90 and #56 are not included for illustration in the figure due to the problems with the PEMS measurement system.

Sources: UCR and WVU

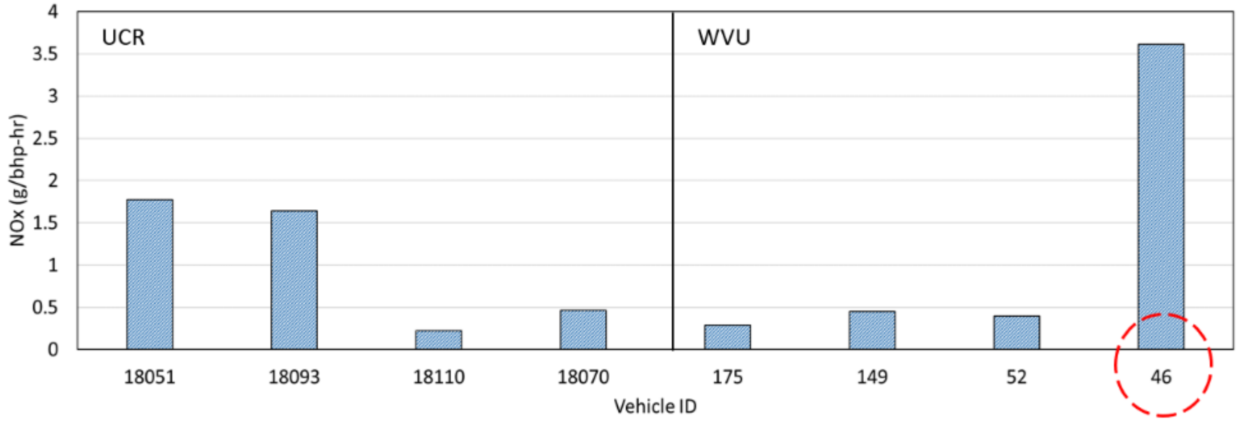
3.2.2.2 0.2g Diesel Delivery Trucks

Figure 28 shows the daily average PEMS NOx emission rates for the eight delivery trucks with 0.2g diesel engines. Five trucks had relatively low emission rates ranging from 0.22 to 0.47 g/bhp-hr, and the remaining three trucks had higher emissions, ranging from 1.64 to 3.62 g/bhp-hr. The causes for the higher NOx emissions in these cases could mostly be attributed to duty cycles that included multiple stops that resulted in low aftertreatment temperatures (see Appendix C). The averaged PEMS NOx emissions for the 0.2g Diesel Delivery Trucks were 1.11 g/bhp-hr or 0.36 g/bhp-hr, excluding the three higher-emission trucks.

---

[23] See CARB documents: 1) “EMFAC2021 Volume III Technical Document,” March 31, 2021, https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf;

Figure 28: Daily Averaged PEMS NOx Emission Rates of 0.2g Diesel Delivery Trucks

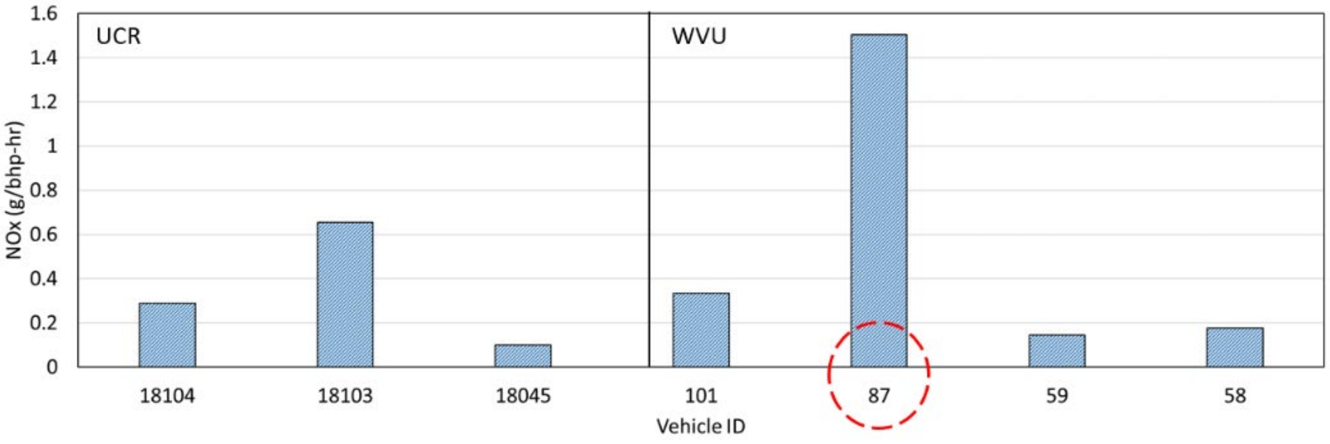


Sources: UCR and WVU

3.2.2.3 0.2g Natural Gas Goods Movement Trucks

Figure 29 shows the daily average PEMS NOx emission rates for the seven goods movement trucks (Class 7/8) with 0.2g NG engines. The emission rates ranged from 0.09 to 0.65 g/bhp-hr for all the trucks, except that Vehicle #87 had a relatively high daily averaged NOx rate of 1.50 g/bhp-hr. The higher emissions for Vehicle #87 were attributed to malfunction or deterioration of the three-way catalyst (TWC), as well as duty cycle factors (see Appendix C). When excluding Vehicle #87, the average for the remaining six 0.2g NG Goods Movement Trucks was 0.28 g/bhp-hr.

Figure 29: Daily PEMS NOx Emission Rates of Individual 0.2g NG Goods Movement Trucks

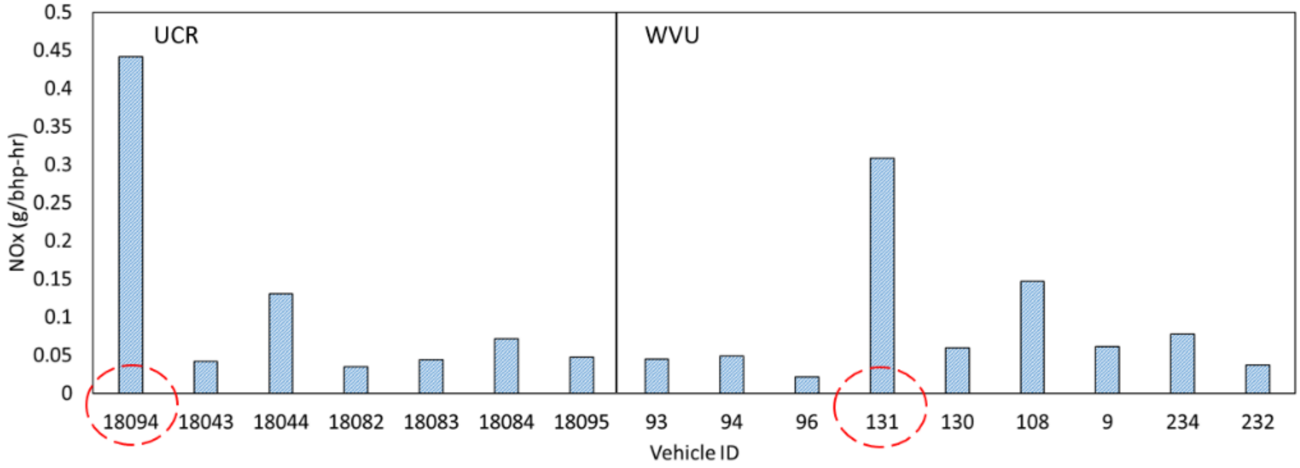


Sources: Information provided by UCR and WVU, March 2022

3.2.2.4 0.02g Natural Gas Goods Movement Trucks

Figure 30 shows the daily average PEMS NOx emission rates for the 16 goods movement trucks (Class 7/8) with 0.02g natural gas engines. The daily averaged PEMS results showed that most HDVs in this category had NOx emission rates in the range of 0.021 to 0.147 g/bhp-hr, except two trucks with relatively high emission rates of 0.446 and 0.309 g/bhp-hr. Further data analyses, as discussed in Appendix C, indicated that these two higher emission vehicles had issues with potentially deteiorated aftertreatment systems (vehicle #18094), and a longer duration extended power-take-off (PTO) event that caused three specific high NOx events (vehicle #131). The root cause of the higher NOx events is still under investigation at the time of this report. The average for the remaining 14 0.02g NG Good Movement Trucks was 0.062 g/bhp-hr. Note that the cause for higher NOx emissions for Vehicle #108 is also discussed in Appendix C.

Figure 30: Daily Averaged PEMS NOx Emission Rates of 0.02 NG Goods Movement Trucks

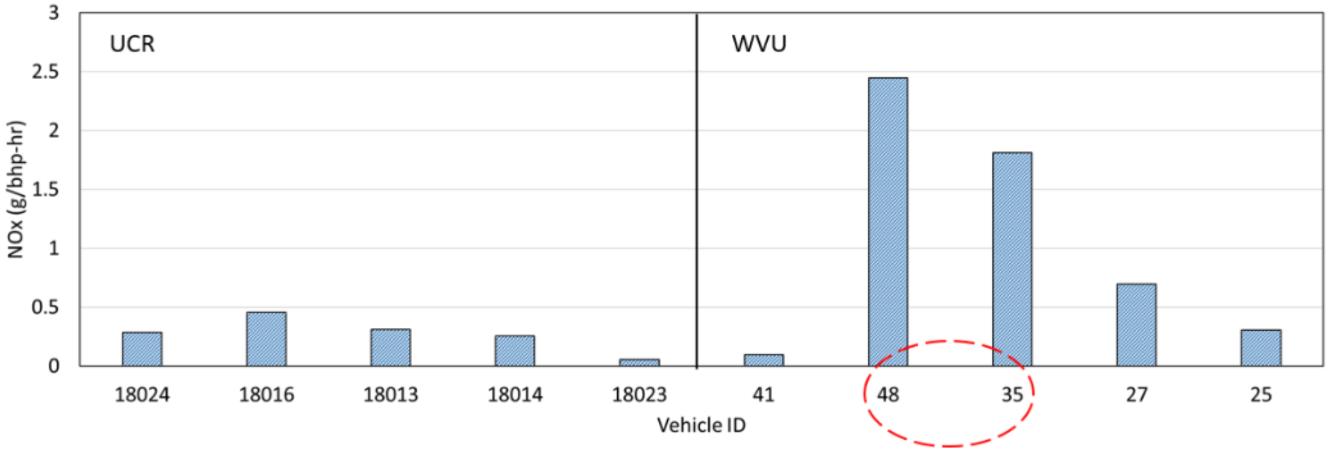


Sources: UCR and WVU

3.2.2.5 0.2g Natural Gas Refuse Trucks

Figure 31 shows the daily averaged PEMS NOx emission rates for the 10 refuse trucks with 0.2g NG engines. The trucks had NOx emission rates ranging from 0.057 to 0.697 g/bhp-hr, except for two trucks with relatively high emissions of 2.44 and 1.81 g/bhp-hr, respectively. Both Vehicles #48 and #35 were found to have deteriorated aftertreatment systems and potential mal-maintenance, as discussed further in Appendix C. The average for the remaining eight 0.2g NG refuse trucks was 0.308 g/bhp-hr.

Figure 31: Daily Average PEMS NOx Emission Rates of 0.2g Natural Gas Refuse Trucks

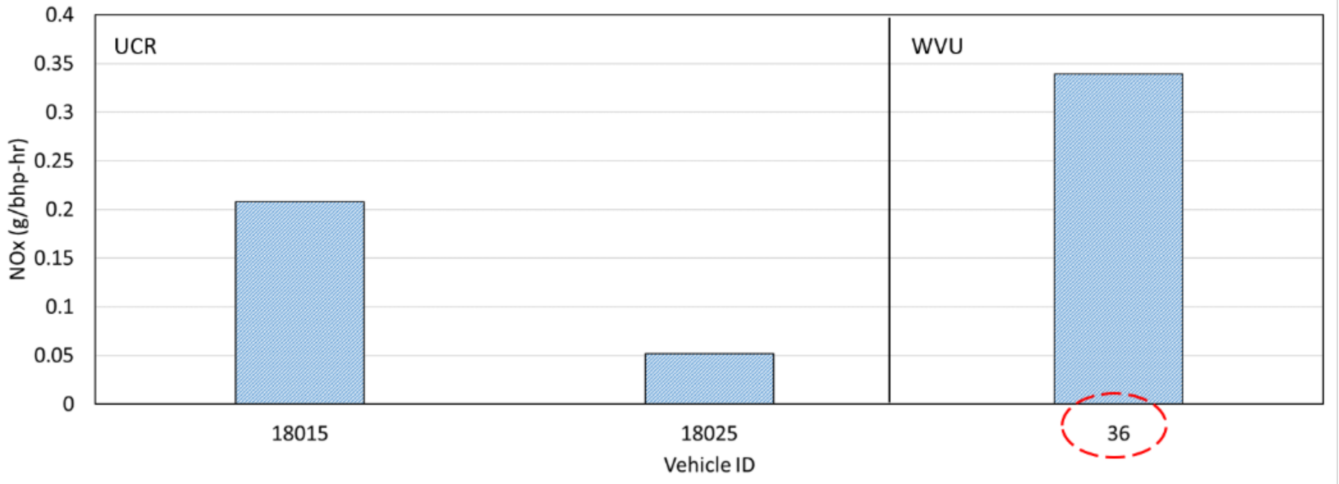


Sources: UCR and WVU

3.2.2.6 0.02g Natural Gas Refuse Trucks

Figure 32 shows the daily average PEMS NOx emission rates for the three refuse trucks with 0.02g NG engines. These vehicles had emission rates of 0.208, 0.052, and 0.340 g/bhp-hr. The highest emitting vehicle #36 showed a low fueling event, that represented approximately 3 percent of the operating time, that caused over 50 percent of the NOx emitted during that day, as discussed further in Appendix C. The average for the remaining two 0.02g NG Refuse Trucks was 0.130 g/bhp-hr.

Figure 32: Daily Average PEMS NOx Emission Rates of 0.02g Natural Gas Refuse Trucks



Sources: UCR and WVU

3.2.2.7 NOx PEMS Data Crosscheck between UCR and WVU

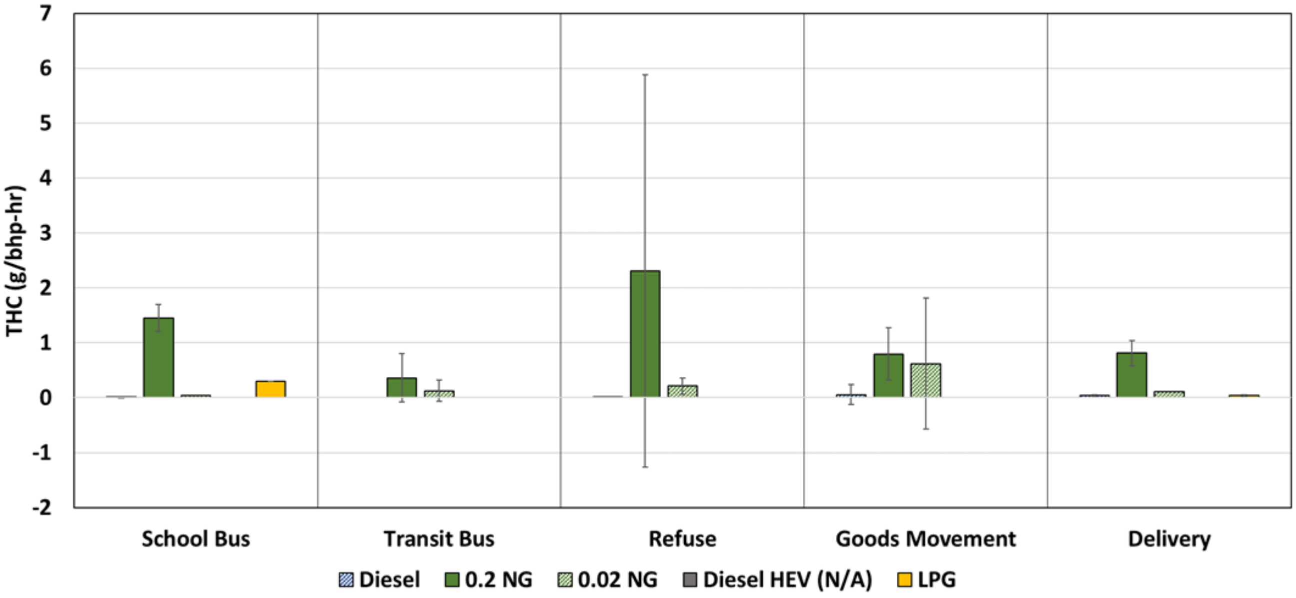
Four HDVs were PEMS tested by both UCR and WVU, as mentioned earlier. These vehicles included a 0.02g NG transit bus, a 0.2g NG school bus, a 0.2g diesel delivery truck, and a 0.02g NG goods movement truck. As expected, the daily averaged NOx levels measured with PEMS were vastly different between the two universities. The differences in routes (and days) over which the two universities tested the individual HDVs could contribute the majority of the differences in testing results. This reinforces the importance of understanding variations in HDV duty cycles associated with different vocations and applications. Additional cross-laboratory comparisons were also performed for the chassis dynamometer testing, which were conducted over the same chassis test cycle. These results are quantified and discussed in section 3.4.5.

3.2.3 THC Emissions from PEMS Testing

3.2.3.1 Results for THC

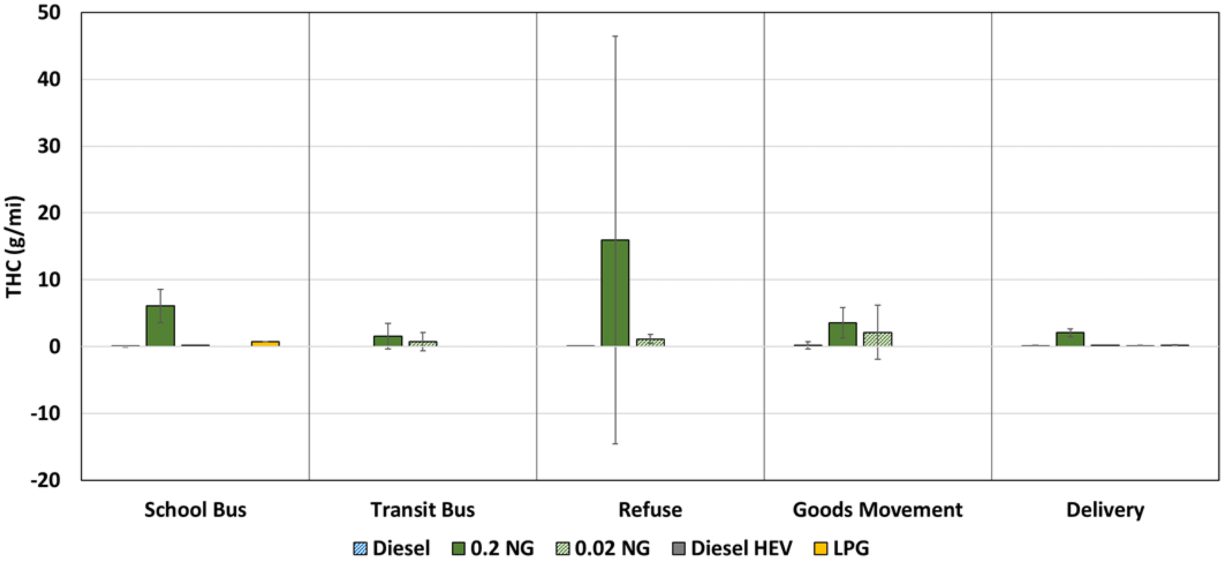
Figure 33 shows the daily average THC emissions in g/bhp-hr units for all HDVs tested with PEMS. Figure 34 shows the daily average THC emissions in g/mi units.

Figure 33: Averaged THC Emissions in g/bhp-hr for PEMS-Tested HDVs



Sources: Information provided by UCR and WVU, March 2022

Figure 34: Averaged THC Emissions in g/mi for PEMS-Tested HDVs



These two figures show averaged THC emissions for all PEMS-tested HDVs (97 HDVs, 100 tests), in g/bhp-hr (top figure) and g/mi (bottom figure).

Sources: Information provided by UCR and WVU, March 2022

3.2.3.2 Discussion for THC

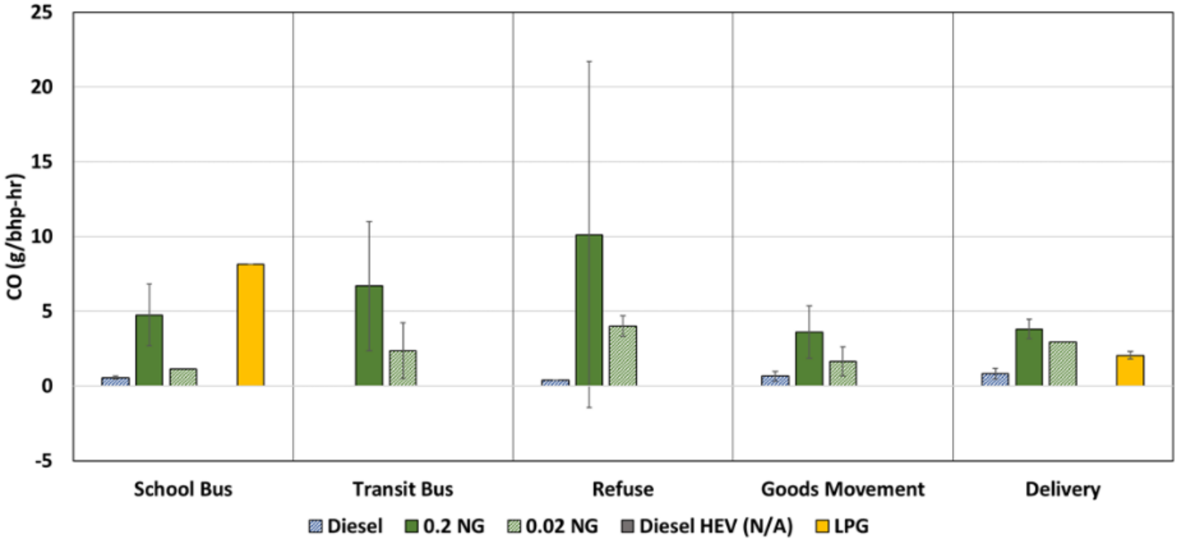
Not surprisingly, due to the inherently lean combustion of diesel engines, all diesel fueled HDVs exhibited low daily average THC emissions. The HDV type that exhibited the highest THC emissions was the 0.2g NG refuse truck. However, nearly all THC emitted by natural gas HDVs consists primarily of methane, which does not contribute to ozone formation. However, methane is a more-potent GHG than CO_2, which makes it an important contributor to climate change. There was also some correlation of higher NOx emissions with higher THC emissions suggesting an aftertreatment malfunction. Methane emissions were discussed more in detail in the chassis dynamometer results section, as methane was measured directly with the mobile labs.

3.2.4 CO Emissions from PEMS Testing

3.2.4.1 Results for CO

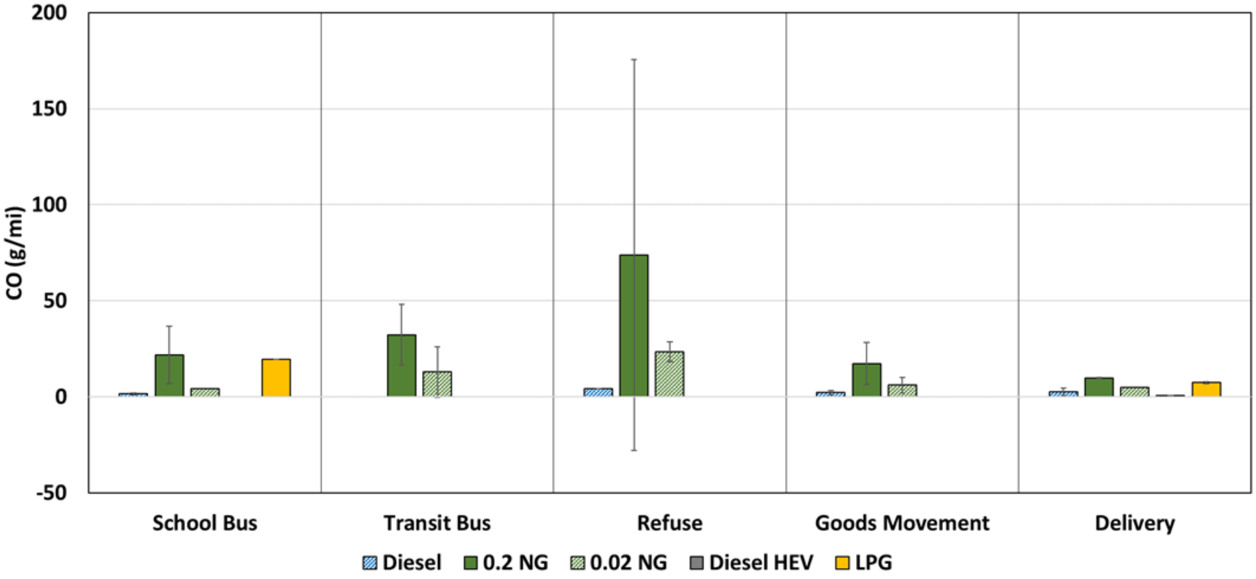
Figure 35 and Figure 36 show the averaged CO emissions in g/bhp-hr and g/mi units for all HDVs tested with PEMS.

Figure 35: Averaged CO Emissions in g/bhp-hr for PEMS-Tested HDVs



Sources: Information provided by UCR and WVU, March 2022

Figure 36: Averaged CO Emissions in g/mi for PEMS-Tested HDVs



These two figures show averaged CO emissions for all PEMS-tested HDVs (97 HDVs, 100 tests), in g/bhp-hr (top figure) and g/mi (bottom figure).

Sources: Information provided by UCR and WVU, March 2022

3.2.4.2 Discussion for CO

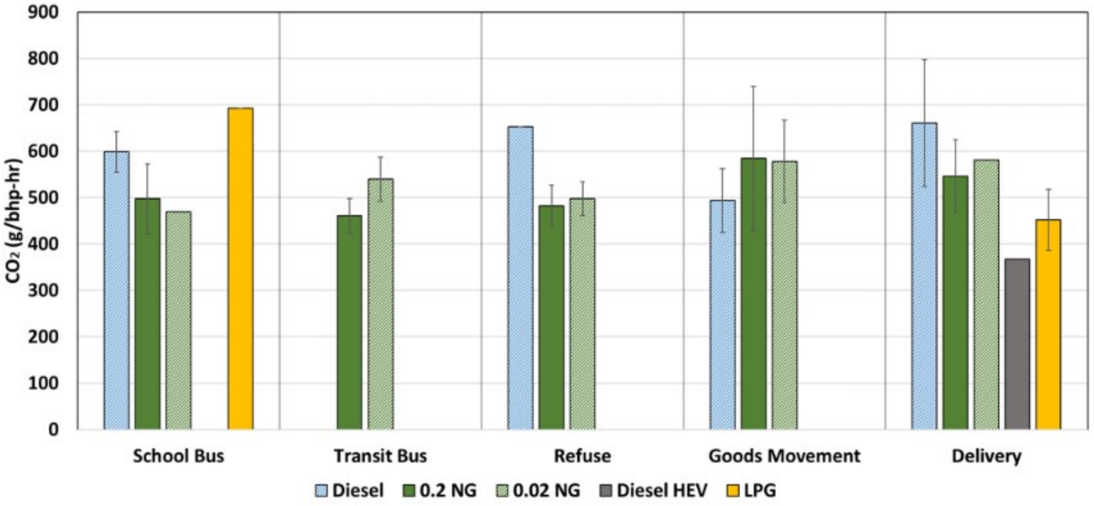
Similar to THC, all diesel-fueled HDVs also exhibited low in-use CO emissions. This is not surprising, due to the inherently lean combustion of diesel engines. As expected, the HDV types that exhibited the highest CO emissions were spark-ignited stoichiometric natural gas and propane HDVs.

3.2.5 CO_2 Emissions from PEMS Testing

3.2.5.1 Results for CO_2

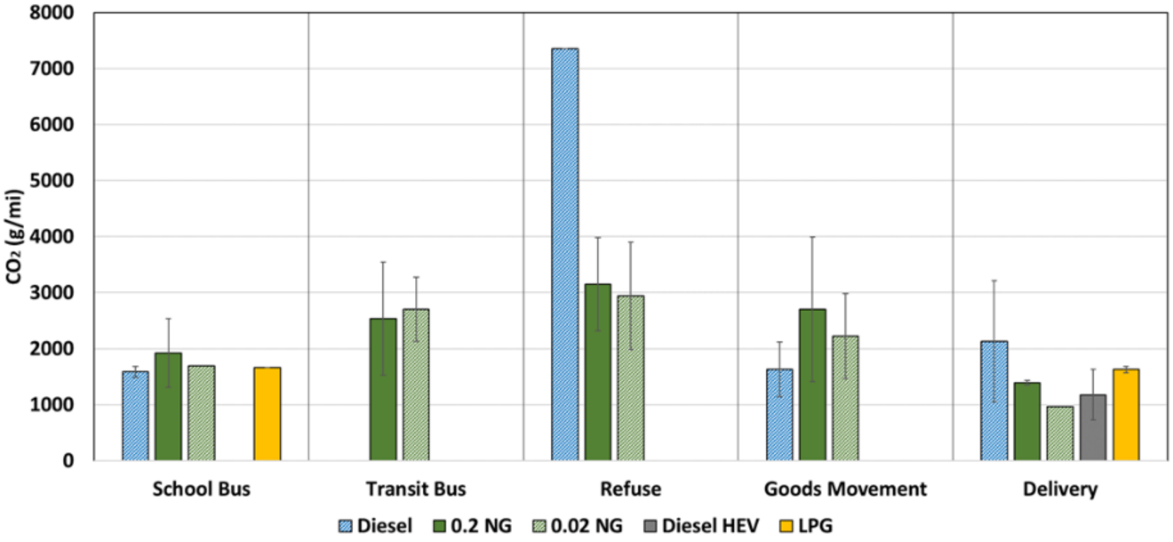
Figure 37 and Figure 38 and shows the average CO_2 emissions in g/bhp-hr and g/mi units.

Figure 37: Averaged CO_2 Emissions in g/bhp-hr for PEMS-Tested HDVs



Sources: Information provided by UCR and WVU, March 2022

Figure 38: Averaged CO_2 Emissions in g/mi for PEMS-Tested HDVs



These two figures show averaged CO_2 emissions for all PEMS-tested HDVs (97 HDVs, 100 tests), in g/bhp-hr (top) and g/mi (bottom).

Sources: Information provided by UCR and WVU, March 2022

3.2.5.2 Discussion for CO_2

For more than a decade, the U.S. EPA has categorized CO_2 as a regulated "pollutant" when emitted from motor vehicles,[24] due to its role as the major GHG and climate-change forcer. As can be seen in the Figure 37 and Figure 38 above, the results show differences in CO_2 emissions among different vocations, and between technology types within a particular vocation. Note that CO_2 is directly correlated to fuel economy. The refuse hauler category generally showed the highest CO_2 emissions, particularly in the case of the diesel refuse haulers. This is likely due to the demanding duty cycle, including the stop-and-go nature of refuse hauler operations, with curbside pick-up that requires extensive use of the hydraulic system that causes poor fuel economy and high CO_2 emissions. The school buses and delivery trucks generally showed lower CO_2 emissions, which could be attributed to lower vehicle loads and less aggressive duty cycles, as well as possible differences in vehicle and payload/test weights.

3.2.6 NTE Results and Analysis

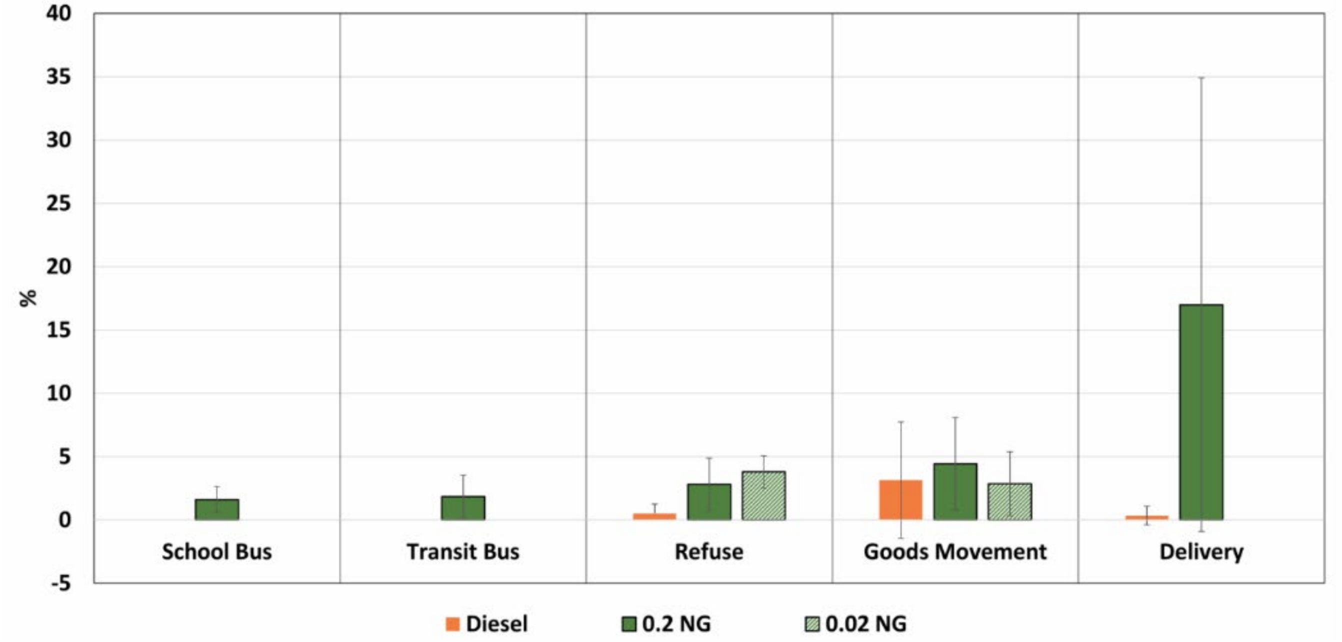
3.2.6.1 NTE Findings

Similar to previous work, this study also found a low percentage of PEMS data that met the criteria for a valid NTE event. Figure 39 illustrates the fraction of time PEMS-tested HDVs spent in valid NTE events. As shown, the percent time of NTE events is fairly low (less than 5 percent) for the majority of the HDVs. In fact, many of the HDVs did not spend any operational time at all in any valid NTE events. Of the five HDV types/applications, the 0.2g NG delivery truck category had the highest percentage, with approximately 17 percent of time with valid NTE events. In comparison with daily average PEMS NOx emission rates presented in Section 3.3.2, NOx emission rates during NTE events were significantly lower.

---

[24] DieselNet, "US Supreme Court decides CO2 is a pollutant," April 3, 2007, https://dieselnet.com/news/2007/04epa.php#:~:text=In%20one%20of%20the%20most,2%20emissions%20from%20new%20cars.

Figure 39: Percentage of HDV Activity in Valid NTE Events



Sources: UCR and WVU

These PEMS-based derived results further document that the NTE region was a better tool for characterizing in-use HDV emission exceedances under highway driving conditions (that is, predominantly steady state and cruise driving) than under urban driving conditions (that is, extensive "stop & go" and idle, during which 30 continuous seconds of NTE-zone operation do not generally occur). The PAMS analysis (in phase 1 of the Program) also observed this same finding, that the majority of the tested HDVs spent most of their operating time in low-speed, low-load driving that does not get captured by the current NTE method.

Thus, the 200 HDV Testing Program provides important new information to help improve the existing NTE in-use testing protocol. The need for this has been corroborated through other recent research by CARB, and other key entities. For example, in 2019 the International Council on Clean Transportation (ICCT) published a white paper concluding that the NTE protocol "is inadequate to evaluate the in-use (emissions) performance of HDVs in the United States, especially at low-speed conditions." ICCT found that the NTE protocol "evaluates less than 10 percent of the total emissions data to determine compliance for heavy-duty in-use NOx emissions," and "adoption of a different tool for proper in-use compliance evaluation" was needed that "includes low-speed, low-load, and idle data" to "ensure that engine dynamometer emission results obtained in the laboratory translate to real-world benefits." ICCT has also concluded that European certified heavy-duty diesel engines have lower emissions over the full range of engine operation, despite having a NOx emission standard that is 72 percent greater than the U.S. EPA standards.[25]

---

[25] International Council on Clean Transportation; "Current State of NOx Emissions from In-Use Heavy-Duty Diesel Vehicles in the United States;" Huzeifa Badshah, Francisco Posada, Rachel Muncrief; November 26, 2019.

3.2.6.2 New Development of Engine Testing Methods

In 2020, the CARB adopted California's sweeping new Heavy-Duty Engine and Vehicle Omnibus Regulation (Omnibus regulation). A key objective of the Omnibus regulation is to aggressively close the gap between emission levels emitted and measured during new engine certification and in-use HDVs testing. Specific Omnibus regulation provisions include the following:

- Promulgates stringent new NOx standards for new heavy-duty engines: starting with model year 2024 engines, the current FTP/SET NOx standard will cut by 75 percent to 0.05 g/bhp-hr; starting with model year 2027, the NOx standard will be further reduced to 0.02 g/bhp-hr (that is, California's current lowest-tier Optional Low-NOx Standard).
- Introduces a low-load certification cycle with a 0.2 g/bhp-hr certification level for model year 2024 that further declines to 0.05 g/bhp-hr for model year 2027.
- Extends the useful life period for new heavy-duty engines from 435,000 miles to 800,000 miles.
- Adopts an in-use emissions testing metric based on 3-Bin Moving Average Windows (3B-MAW).
- Introduces a Real Emissions Assessment Logging (REAL) program to assess NOx across the entire vehicle population via onboard emission sensors.

In summary, the newly adopted Omnibus regulation will impose significant changes regarding how future combustion engine technologies are certified and operated in California. By improving the existing NTE method, adopting the 3B-MAW in-use emissions testing metric, and addressing other shortfalls, the Omnibus regulation is expected to move in-use emission levels significantly closer to those measured during certification testing. This will result in important NOx reductions and ambient air quality improvements in the SCAB, where many HDVs operate in low-speed, low-load modes that are not captured by the current NTE methodology. At the end of 2022, EPA also adopted similar regulation with phasing in dates starting model year 2027.

3.3 Results and Discussion for Chassis Dynamometer Testing

3.3.1 Introduction to Chassis Dynamometer Testing

A total of 52 unique HDVs were tested with a chassis dynamometer over the UDDS and their respective vocation cycles by the two university teams. Table 10 summarizes the number of HDVs for each vocation and fuel type/emission standard. Performance testing was also conducted on four zero-emission HDVs for comparison with non-zero-emission HDVs under controlled laboratory conditions.

---

https://theicct.org/publication/current-state-of-nox-emissions-from-in-use-heavy-duty-diesel-vehicles-in-the-united-states/.

Table 10: Counts of HDVs for Chassis Dynamometer Testing

HDV Type	Transit Bus	School Bus	Refuse Hauler	Delivery Truck	Goods Movement Truck	Totals
0.2 g Diesel	0	1	1	3	7	12
No-SCR Diesel	0	1	0	1	2	4
Diesel HEV	0	0	0	2	0	2
0.2 g NG	2	2	5	2	2	13
0.02g NG	6	1	3	1	4	15
0.02g LPG	0	1	0	1	0	2
Battery Electric	0	1	0	0	2	3
H2 Fuel Cell	1	0	0	0	0	1
Totals	**9**	**7**	**9**	**10**	**17**	**52**

Sources: UCR and WVU

While 52 HDVs were tested with a chassis dynamometer, data for 17 vehicles were excluded from the analysis in this section. So, the results that follow are for the remaining 35 HDVs. Eight of the excluded vehicles included the four no-SCR diesel trucks, as regulations will phase them out; one 0.02 liquefied petroleum gas (LPG) delivery truck due to an issue with the test weight setting; and two vehicles with unusually high emission results that were deemed to have rare/random causes (see exclusion criteria in Appendix C). The remaining nine excluded vehicles were all 8.9L 0.2g and 0.02g NG vehicles that had elevated NOx levels during idle due to rare/random errors caused by the CVS measurement system "artifact" (see Appendix C). In addition, six 0.2 g diesel HDVs were retested for with RD, which are included in the figures below. For clarity, the sample size (n) for each data point is listed in the figures below. As shown in Table 11, all HDVs were tested with the UDDS cycle along with other cycles that were more specific to the vocation of the vehicle.

Table 11: Chassis Dynamometer Test Cycle Schedule

Test Cycle	Transit Bus	School Bus	Refuse Hauler	Delivery Truck	Goods Movement
UDDS	X	X	X	X	X
CARB HHDDT Cruise Cycle				X	X
Modified SCAQMD Refuse-Cycle			X		
Goods Movement Truck Cycle (Markov)					X
Double Central Business District Cycle	X				
OCTA Cycle	X				
South-Coast School Bus Cycle (Markov)		X			
Delivery Truck Cycle (Markov)				X	

Sources: UCR and WVU

3.3.2 Chassis Dynamometer NOx Emission Results over UDDS

3.3.2.1 UDDS NOx Emission Rates for 0.2g Diesel HDVs

Twelve 0.2g Diesel HDVs were chassis dynamometer tested over the UDDS cycle, as indicated in Figure 40. The cycle averaged NOx emission rate for all 18 0.2 diesel HDVs' measurements was 0.686 g/bhp-hr. As indicated with the red circles, six measurements show high values. Excluding the six high-value HDVs, the average NOx emission rate for this category of HDVs was 0.403 g/bhp-hr.

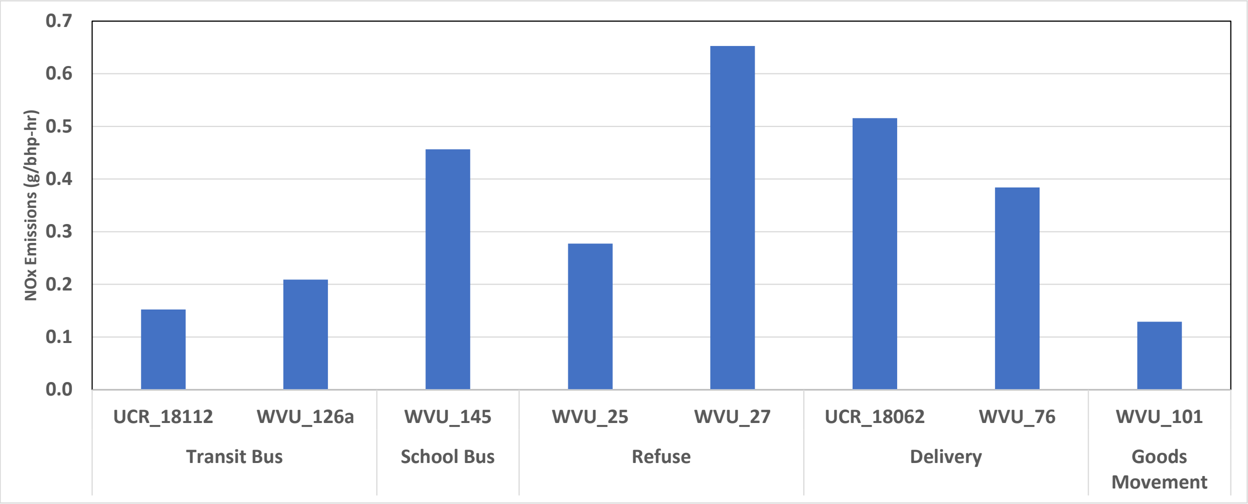
Figure 40: Cycle Averaged NOx Emissions for 0.2g Diesel HDVs (UDDS)

Sources: UCR and WVU

3.3.2.2 UDDS NOx Emissions for 0.2g Natural Gas HDVs

Thirteen 0.2g NG HDVs were chassis dynamometer tested over the UDDS cycle. As discussed in detail in Appendix C, a rare/random CVS measurement "artifact" impacted five 8.9L 0.2 NG vehicles in this group (not shown here). Two other 0.2 NG vehicles also had very high emissions (3.77 and 6.11 g/bhp-hr) due to potential mal-maintenance issues (rare/random) that caused aftertreatment failures with the vehicles, which are not included in Figure 41. As indicated in Figure 41, the averaged NOx Emissions for the remaining eight valid 0.2 NG HDVs was 0.315 g/bhp-hr.

Figure 41: Cycle Averaged NOx Emissions for 0.2 Natural Gas HDVs (UDDS)

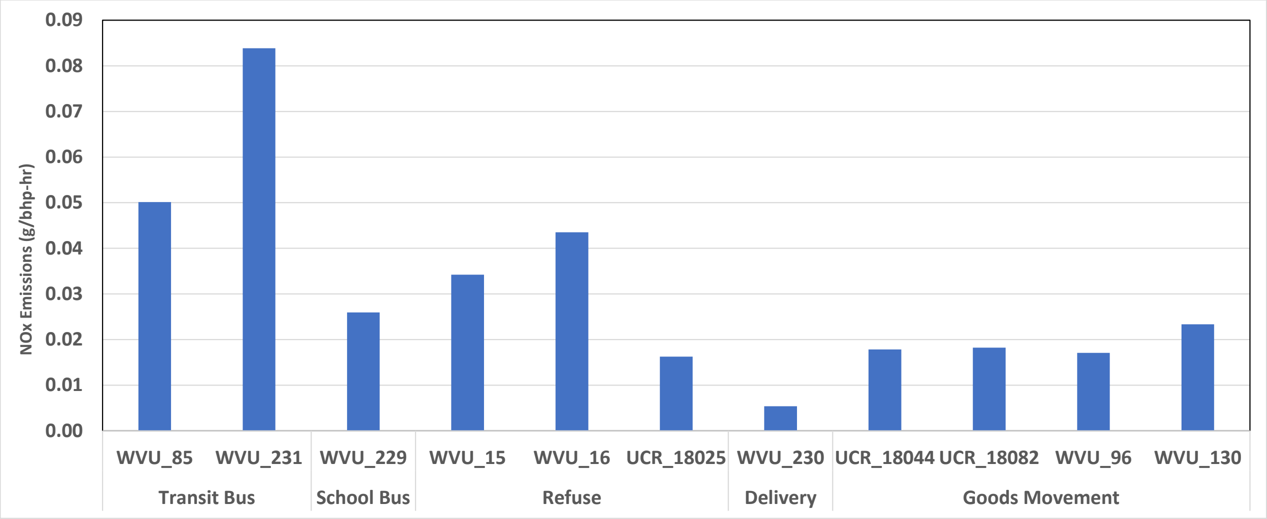


Sources: UCR and WVU

3.3.2.3 UDDS NOx Emissions for 0.02g Natural Gas HDVs

Figure 42 shows the fifteen 0.02g NG HDVs that were tested with the chassis dynamometer testing under the UDDS cycle. As discussed in detail in Appendix C, a rare/random CVS measurement "artifact" impacted four 8.9L 0.02 NG vehicles in this group (not shown here). The cycle averaged NOx emissions for the 11 valid 0.02 NG HDVs was 0.031 g/bhp-hr.

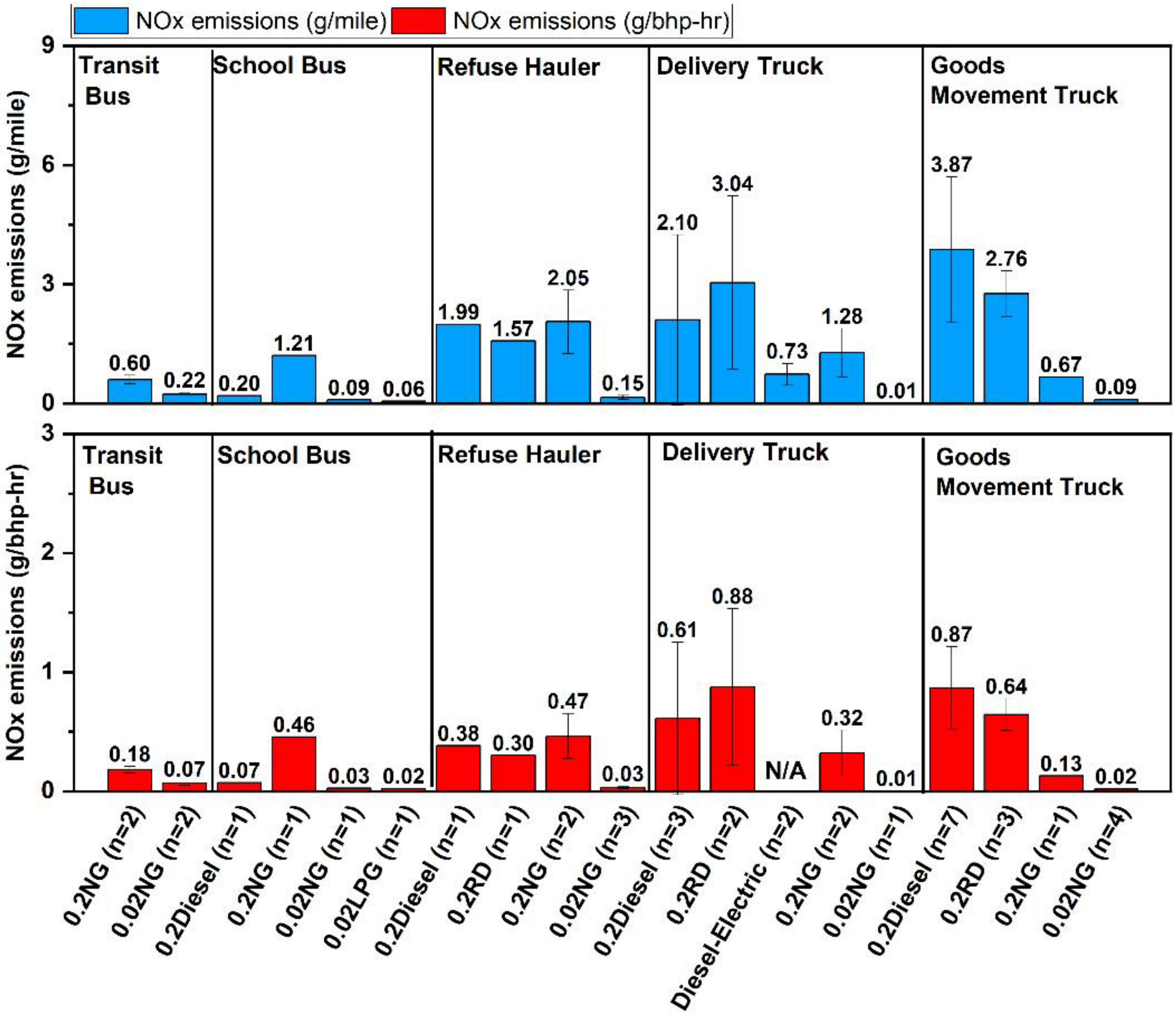
Figure 42: NOx Emission Levels for 0.02g Natural Gas HDVs (Chassis Dynamometer)



Sources: UCR and WVU

To provide a better comparison between vocations as well as technologies, the cycle averaged NOx emission rates over the UDDS measured with the chassis dynamometer are further grouped and averaged by vocations and by fuel types and emission standards (for example, 0.02g NG), as presented in Figure 43. The UDDS and vocational cycles were tested with both cold and hot start. For simplicity, cold-hot cycles were combined using the 1/7 and 6/7 ratio, which is similar to how composite FTP emissions are calculated. Note due to insufficient availability of electronic control module (ECM) data, only the g/mi results are reported for diesel HEV and 0.02 g LPG HDVs.

Figure 43: Cycle Average Chassis Dynamometer NOx Emission Rates under UDDS



Note: The error bars represent one standard deviation of the averages for the respective vehicle category. The sample size for each vehicle category is noted in the x-axis labels ("n=1", etc.).

Sources: UCR and WVU

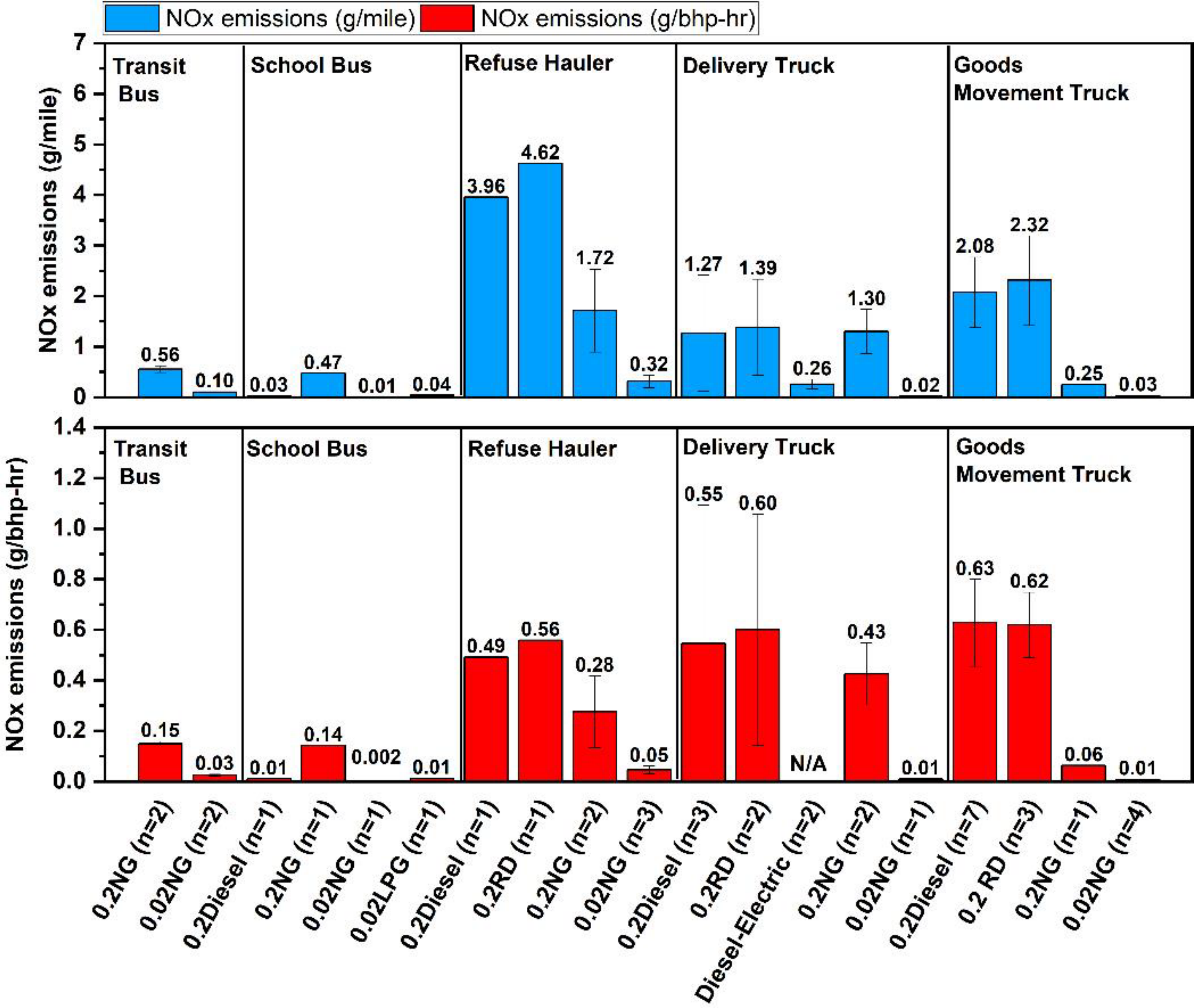
Some key observations include:

- Different than the "daily" averages presented in the PEMS section, the UDDS "cycle" averaged results were more similar across different vehicle categories. Moreover, the UDDS cycle was used in the development of the FTP certification test cycle, which is the primary cycle over which engines are benchmarked for emissions. While UDDS chassis dynamometer data is not directly comparable to certification engine testing values, nevertheless, UDDS data provides a reasonable comparison point to understand the NOx emissions in this context.
- As shown, some vehicle categories/technologies had NOx emission rates comparable to their respective certification standards, including most of the 0.02g vehicles (school bus, refuse hauler, delivery truck, and goods movement truck), the 0.2g NG transit buses, the 0.2g diesel school bus, and the 0.2g NG goods movement truck.
- The remaining categories had NOx emission rates higher than the respective certification standards, including 0.02g NG transit bus, 0.2g NG school bus, three fuel types of refuse haulers (0.2g diesel, 0.2g RD, and 0.2g NG), three fuel types of delivery trucks (0.2g diesel, 0.2g RD, and 0.2g NG), and two fuel types of goods movement trucks (0.2g diesel and 0.2g RD). Potential causes for the higher emissions are further discussed in Appendix C.
- The average emission rates were comparable across the different 0.2g NG vocations, ranging from 0.18 to 0.47 g/bhp-hr, with the school buses and refuse vehicles showing higher NOx emissions and the transit buses and goods movement vehicle showing lower NOx emissions compared to the other vocations in this technology category. Note that the higher school bus and refuse trucks suggest the potential for aftertreatment deterioration issues. As reported in other studies, some higher-mileage 0.2g NG heavy-duty vehicles have shown elevated emissions due to degradation of the TWC (Thiruvengadam et al., 2021; Thiruvengadam et al., 2016).
- For vocations with well-established diesel baselines, such as delivery and goods movement categories, the NG HDVs showed significantly lower NOx emissions. The emission levels were on the order of between 26-78 percent lower for 0.2g NG and 97-99 percent lower for 0.02g NG than the respective diesel HDVs. This is consistent with other studies (Quiros et al., 2016; Thiruvengadam et al., 2015; Lee et al., 2011; Li et al., 2019; Zhu et al., 2020).
- The diesel hybrid electric delivery vehicles showed around 65% lower average NOx emission rates on a g/mi basis than the conventional diesel delivery trucks, but not as low as the 0.02g NG delivery vehicles. For comparison with hybrid HDVs, it is more appropriate to use the g/mi data, since the g/bhp-hr values do not consider the energy supplied by the battery.

As presented in Figure 44, additional vocational cycles were tested to get a better assessment of the true emissions over the intended duty cycles. The vocational cycles were developed based on activity data collected from the PAMS phase. Although the relative trends between technology were similar to those for the UDDS cycles (e.g., 0.02g NG lower than 0.2g NG HDVs), the cycle averaged NOx emissions showed some minor differences compared to the UDDS. For the purpose of emissions inventories like EMFAC, these vocational cycles were used as additional input data for developing of the emissions factors at different average speeds.

Along with the vehicle activity, the additional data provides a more accurate assessment of the emission inventory for each specific region.

Figure 44: Cycle Average Chassis Dynamometer NOx Emission Rates under Vocational Cycles



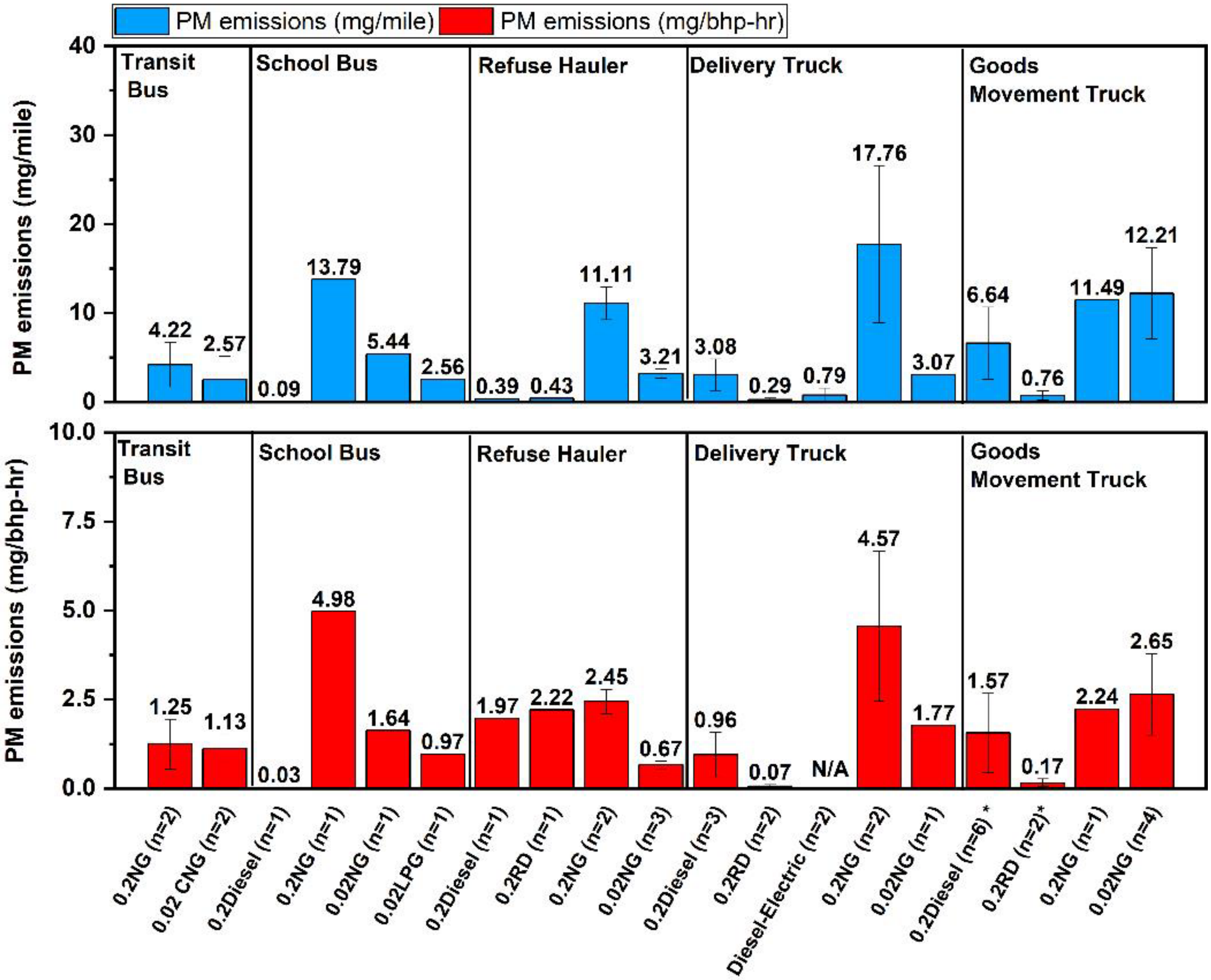
Sources: UCR and WVU

3.3.3 Chassis Dynamometer Particulate Matter Emission Results under UDDS

Results for PM

Figure 45 shows the average PM emission rates for HDVs measured by the two universities on the UDDS cycle.

Figure 45: Average Chassis Dynamometer PM Emission Rates under UDDS



The top graph shows average PM emission rates during the UDDS cycle on a distance-specific metric (mg/mile); the bottom graph present PM emission rates on a work-specific metric (mg/bhp-hr).

Sources: Information provided by UCR and WVU, March 2022

Discussion for Particulate Matter

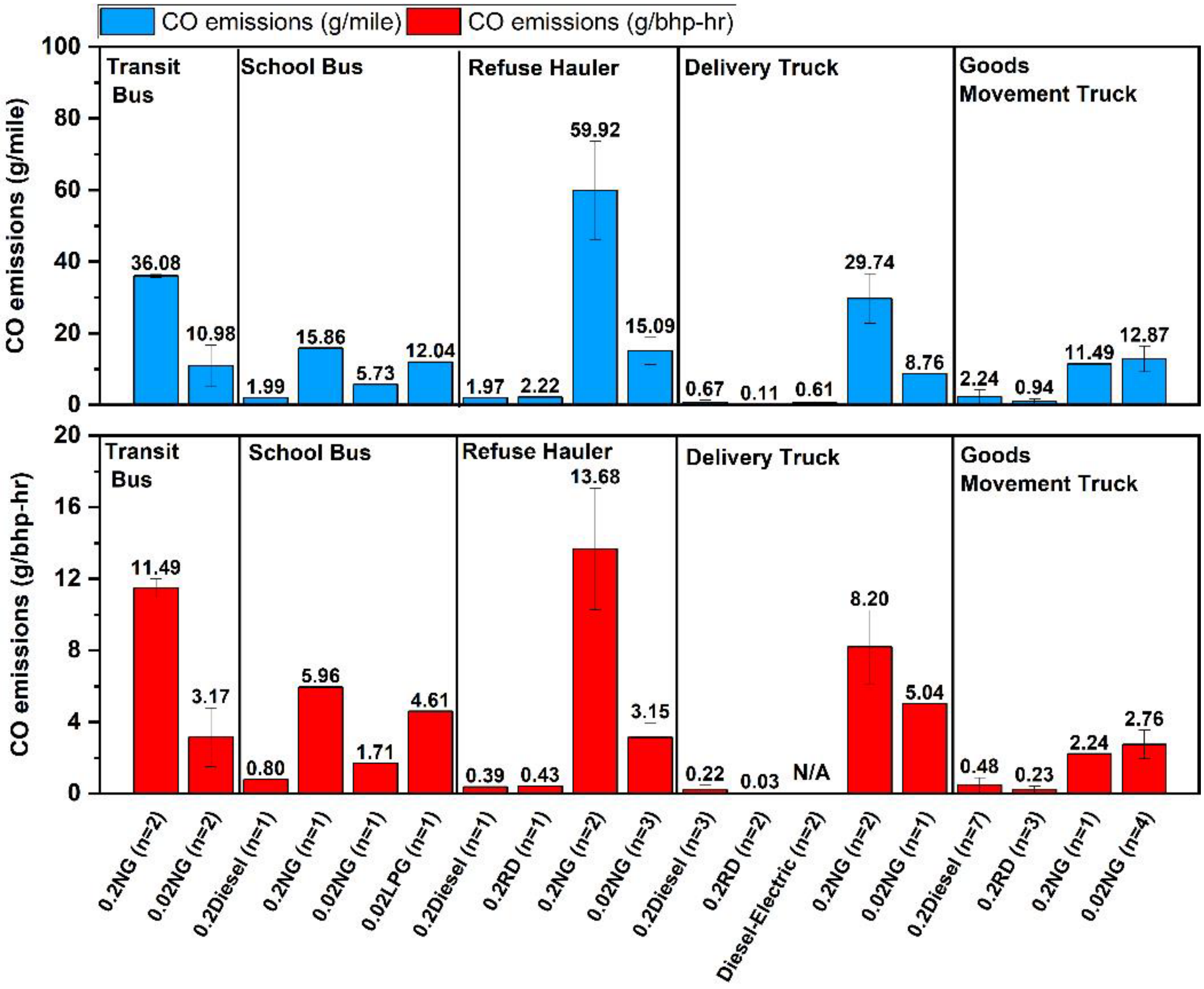
PM mass emission rates were very low for most of the tested HDVs. For diesel and natural gas HDVs, PM emission rates were well below 10 mg/bhp-hr limit and below the 5 mg/bhp-hr proposed limit. In a few cases, PM emissions were also below the 1 mg/bhp-hr level, which is typical for properly functioning diesel particulate filter-equipped diesel vehicles. For the goods movement truck category, the highest cycle-average PM emissions were observed for the 0.02g NG HDV category, specifically, the HDVs outfitted with the larger (12L) NG engine platform. The higher PM was largely comprised of elemental carbon (EC) as expected from increased oil consumption rates for these HDVs reported by the fleet operators. Additional PM analysis can be found in appendices A and B.

3.3.4 Carbon Monoxide Emissions (Chassis Dynamometer / UDDS)

3.3.4.1 Results for Carbon Monoxide

Figure 46 shows the average CO emissions in g/mi and g/bhp-hr units for all UDDS cycles.

Figure 46: Average CO Emissions - UDDS Chassis Dynamometer Testing



This graph shows average CO emissions measured during chassis dynamometer testing over the UDDS; the top graph provides distance-specific metric CO emissions (g/mi), and the bottom graph provides work-specific CO emissions (g/bhp-hr).

Sources: Information provided by UCR and WVU, March 2022

3.3.4.2 Discussion for Carbon Monoxide

Similar to PEMS results, CO emissions were highest for the natural gas and LPG HDVs. This is due to the nature of stoichiometric spark-ignited engines compared to lean-burn diesel engines. CO emission levels for all valid tests on these non-diesel HDVs (0.2g NG, 0.02g NG, 0.2g LPG), however, yielded CO levels well below the 15.5 g/bhp-hr limit, for all cycles. The higher CO HDVs also corelated to higher NOx HDVs and some were noted to have a malfunctioning aftertreatment system. Also as expected, CO emissions for 0.02g NG HDVs were lower than those for 0.2g NG HDVs. The 0.02 LPG HDVs emitted at CO levels that were generally comparable to those for the 0.02 NG HDVs but only one HDV were tested.

3.3.5 Ammonia Emissions

Although not shown in this report, ammonia (NH3) emissions showed differences between the different technology categories, with NH3 emissions for the NG vehicles showing higher emissions than those of the diesel vehicles. This is because NH3 is typically not a combustion product, but rather forms as a reaction product over the TWC after the catalyst has reached its light-off temperature. Very low NH3 emissions were seen for the diesel (no SCR) and RD (no SCR) vehicles, diesel-electric delivery vehicles, and diesel (no SCR) and RD (no SCR) vehicles. Detailed NH3 results can be find in the university reports (appendices A and B).

3.3.6 Inter-Lab Comparison for Chassis Dynamometer Testing Results

Three HDVs were cross-tested on chassis dynamometers by the two university teams in their own facilities. Ultimately, a 0.2g diesel goods movement truck and a 0.02g NG transit bus were used for a cross-laboratory comparison of chassis dynamometer test results. (The UCR 0.02g LPG delivery truck results were excluded, due to incorrect inertia mass settings.) Both HDVs were tested using the test cycles listed in Table 12.

Table 12: Test Cycles for Chassis Dynamometer Cross-Lab HDV Testing

Test Cycle for Chassis Dynamometer	0.2g Diesel Goods Movement Tractor	0.02g NG Transit Bus
UDDS Cycle	√	√
Goods Movement Cycle	√	
CARB HHDDT Cycle	√	
Central Business District Cycle		√
OCTA Cycle		√

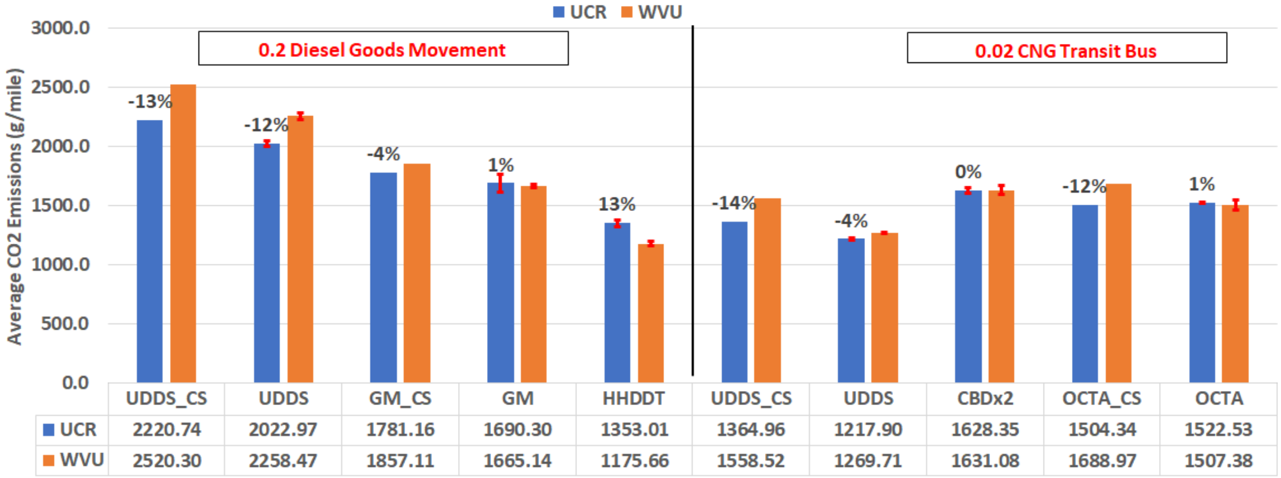
Sources: UCR and WVU

Although all emissions pollutants were measured, the cross-laboratory comparisons in Figure 47, Figure 48, and Figure 49 are focused on emissions of CO_2 and NOx, and cycle work.

3.3.5.1 Carbon Dioxide Emission Rates Comparison

Figure 47 compares CO_2 emissions in g/mi measured by the two university teams. The left side compares average CO_2 emissions from the same 0.2g diesel-fueled goods movement truck, and the right side compares average CO_2 emissions from the same 0.02g NG transit bus. For comparison purposes, the cold start cycles are listed separately as additional data points.

Figure 47: Inter-Lab Comparison (Distance-Based) for Chassis Dynamometer CO_2 Measurements



	UDDS_CS	UDDS	GM_CS	GM	HHDDT	UDDS_CS	UDDS	CBDx2	OCTA_CS	OCTA
UCR	2220.74	2022.97	1781.16	1690.30	1353.01	1364.96	1217.90	1628.35	1504.34	1522.53
WVU	2520.30	2258.47	1857.11	1665.14	1175.66	1558.52	1269.71	1631.08	1688.97	1507.38

Sources: UCR and WVU

Overall, the CO_2 emission rates compared reasonably well between the two cross-tested HDVs. Among the different test cycles for the 0.2g diesel goods movement truck, UCR's results were -13 percent to 13 percent different from WVU's. For the 0.02g NG transit bus, UCR's results were -14 percent to 1 percent different from WVU's. Differences between average CO_2 emissions measured by the two laboratories within ranges of ±14 percent, depending on the test cycle and specific HDV. The higher differences were mainly observed on cold-start operations for both vehicles and on the HHDDT cycle for the diesel truck. In comparison, government-industry-run Engine Manufacturers Association/U.S.EPA "round-robin" test programs in more controlled engine certification test cells have typically reported results from different laboratories to be within a difference of 20 to 25 percent.[26]

3.3.5.2 Cycle Work Comparison

CO_2 emissions have a strong correlation with engine cycle work. The comparison of cycle work can help understand differences observed on the CO_2 emission data between the two laboratories.

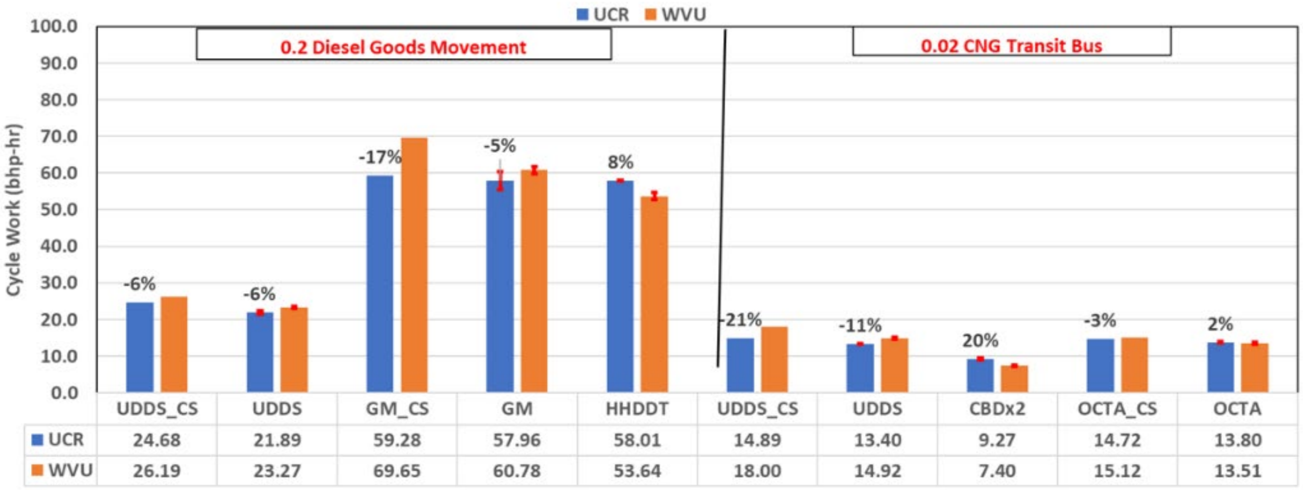
As Figure 48 shows, the two cross-tested HDVs performed less cycle work at the UCR laboratory compared to WVU in seven out of the ten test cycles. The design differences of the two chassis dynamometers were the main reason. As previously described in Section 2, UCR's chassis dynamometer was a traditional roller type. The tested HDV sat directly upon twin rollers; simulated cycle load was applied to the rollers and transferred through the HDV's tires to the drivetrain. WVU's chassis dynamometer input the simulated load directly through a set of hub-adapters to the driveshafts of the test HDV, effectively eliminating any losses between the dynamometer and the HDV's drive-axle. The design difference became more impactful for highly transient test cycles such as the CBD with periodic rapid accelerations/decelerations between 0 and 20 mph. Cold-start tests in particular experienced higher work differences between these two types of chassis dynamometer systems as the two universities conducted

---

[26] WVU testing staff, personal communication to GNA, May 2022.

the test in different seasons with one being colder than the other. The WVU dynamometer design included a number of additional components that could cause additional losses during cold-start operation, hence require more work/fuel required. This resulted in the same HDV tested on UCR's dynamometer doing modestly less work per cycle than it did on WVU's dynamometer.

Figure 48: Inter-Lab Comparison of Engine Cycle Work Performed on Chassis Dynamometer



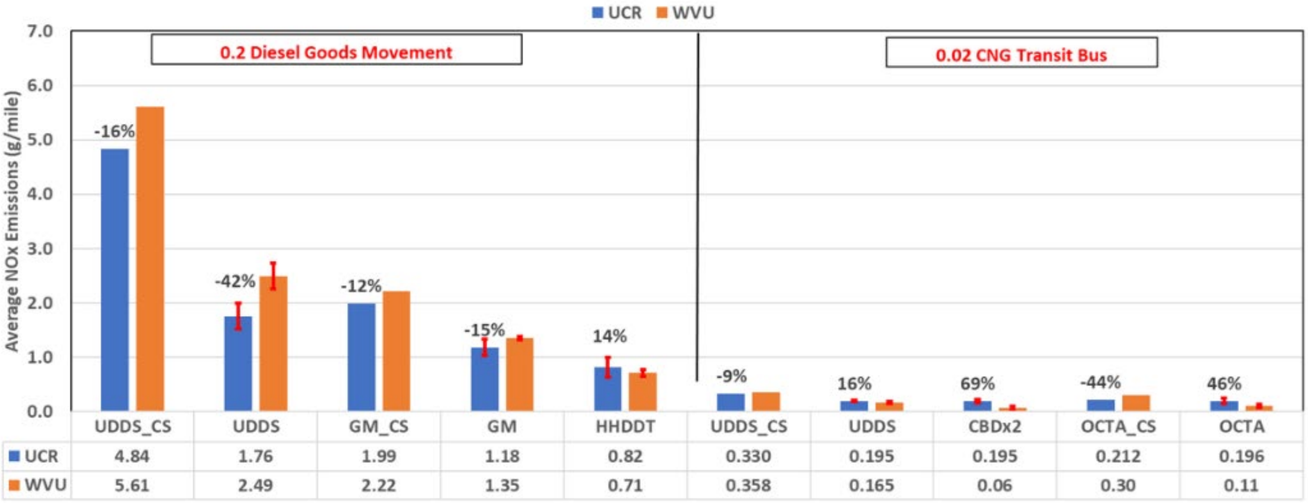
	UDDS_CS	UDDS	GM_CS	GM	HHDDT	UDDS_CS	UDDS	CBDx2	OCTA_CS	OCTA
■ UCR	24.68	21.89	59.28	57.96	58.01	14.89	13.40	9.27	14.72	13.80
■ WVU	26.19	23.27	69.65	60.78	53.64	18.00	14.92	7.40	15.12	13.51

Sources: UCR and WVU

3.3.5.3 NOx Emissions Comparison

Figure 49 shows the comparison for NOx emission rates in g/mi units between the tests conducted by UCR and WVU for the two HDVs.

Figure 49: Inter-Lab NOx Comparison (Distance-Specific) on Chassis Dynamometer



	UDDS_CS	UDDS	GM_CS	GM	HHDDT	UDDS_CS	UDDS	CBDx2	OCTA_CS	OCTA
■ UCR	4.84	1.76	1.99	1.18	0.82	0.330	0.195	0.195	0.212	0.196
■ WVU	5.61	2.49	2.22	1.35	0.71	0.358	0.165	0.06	0.30	0.11

Source: UCR and WVU

3.3.5.4 Laboratory Differences for NOx Emissions from 0.2 Diesel Truck

The largest differences in NOx emission rates were observed during the UDDS cycle (42 percent) for the 0.2 diesel goods movement truck, as shown in Figure 49. The UDDS cycle also experienced the largest cycle-to-cycle variability within individual University's testing, as shown by the error bars. As the dynamometers were both outside, some of the differences could be due to ambient conditions, or slight differences in how quickly the aftertreatment warms up during the cycle. It is possible that additional SCR aftertreatment pre-conditioning might be needed. Typically, during certification testing, an engine and aftertreatment system would be conditioned over a set of cycles to assure a consistent amount of urea buffer in the SCR at the start of the actual test cycle. For the current project, the preconditioning consisted of a coast-down and a short carbon-balance check cycle the day before the cold-start UDDS test. An extra UDDS was then performed after the cold start UDDS prior to conducting the hot start UDDS cycle. An unknown urea buffer state in the SCR at the start of testing could lead to larger variability in the subsequent test cycles. The observed lab-to-lab differences are generally within typical lab variabilities in the range of 20 to 25 percent observed from government-industry-run EMA-EPA "round robin" test programs. Note that percent differences were reduced on the goods movement and HHDDT cycles, due to the preconditioning in the earlier UDDS cycle sequences.

3.3.5.5 Laboratory Differences for NOx Emissions from Natural Gas Transit Bus

It should be noted this the date from this particular 0.02g NG transit bus was remove and was part of 8.9L NG HDVs that had rare/random issues related to CVS measurement system "artifact." Therefore, for the purpose of the inter-laboratory comparison of the transit bus, the dataset was modified excluding all idle operation and thereby was focused solely on emissions while the bus was being driven. This was justified since the different emissions rates during idle were not due to measurement differences between the laboratories, but rather due to different engine control behavior during idle operation, as discussed in Appendix C. It is important to note that the relative percent differences as well as absolute difference shown in Figure 46 must be considered in light of the very low absolute emission levels measured for any HDV engine certified to the CARB's Optional Low NOx Standard of 0.02 g/bhp-hr.

At the same time, combusted natural gas yields exhaust gases with significantly higher moisture content compared to exhaust from diesel combustion. The higher moisture level paired with the ultra-low NOx concentration could have led to increased variability in NOx emissions measurements, since the exhaust sample is first dried (i.e., moisture is removed before directed into the analyzer), and the measured NOx concentration is subsequently mathematically corrected for the removed moisture content. This led to additional challenges on measuring since any slight differences in this process could become impactful at very low (sub -1 ppm) NOx concentration levels, as was observed for the natural gas (0.02 g/bhp-hr) transit bus.

In light of factors, the differences of NOx measurements on this ultra-low-NOx natural gas HDV between the two laboratories are acceptable given the low emission level. Further, cold-start cycle emissions over the UDDS and OCTA cycles were similarly higher for both laboratories compared to the corresponding hot-start cycles. The largest difference between the laboratories was observed over the CBD cycle where the difference in engine cycle work was high too. In general, no systematic offset or trend between the two laboratory measurements was observed with emissions being higher over some cycles and lower over others, for either of the laboratories. Additionally, the results suggest that the primary source of variability for the chassis dynamometer testing was between the individual test HDVs themselves, rather than differences between the analytical systems or methodologies employed by the two universities.

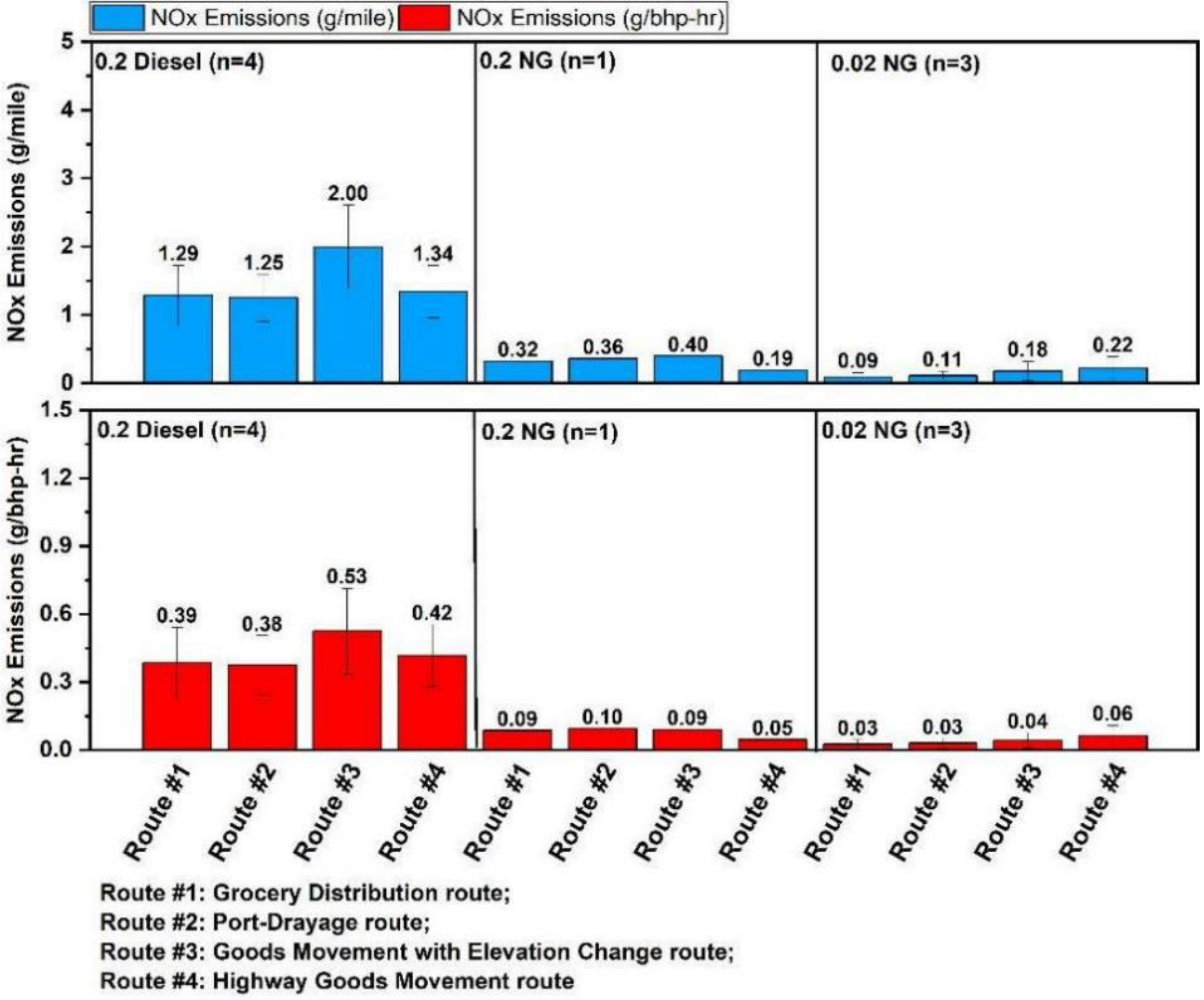
3.4 Results and Discussion for On-Road Testing with Mobile Labs

A total of 10 HDVs were tested on the roads of Southern California by the two university teams. The HDVs in this phase were exclusively Class 7/8 goods movement trucks capable of legally towing the specially designed mobile emissions laboratories weighing about 62,000 to 65,000 lbs. Of the 10 HDVs, two were diesel fueled without SCR (excluded from the data comparison below to be consistent with PEMS and chassis results), four were 0.2g diesel trucks, one was a 0.2g NG truck, and three were 0.02g NG trucks. The tests were done on the four different routes representing typical goods movement driving routes in Southern California, as described in Chapter 2. Compared to the emissions data presented for the PEMS and chassis dynamometer testing, the NOx and fuel economy were averaged over the entire-test route. The "route" average results are similar to the "daily" averaged PEMS results except the route is fixed (as well as the load) amongst all 10 trucks.

3.4.1 NOx Emissions and Discussion

Figure 50 shows NOx emissions in g/mi (top) and g/bhp-hr (below) units for the six trucks grouped by fuel/technology types.

Figure 50: On-Road NOx Emission Rates by Fuel Types and Routes



Sources: UCR and WVU

In contrast to the larger variability during PEMS and chassis testing, the route averaged NOx emissions trends and variability of the on-road testing were largely as expected. In part, this could be attributed to the smaller data sample as well as to the single vocation. Further, the fixed routes also help to reduce any duty-cycle variability that more significantly impacted the daily averaged NOx emissions from the PEMS testing. Lastly, the mobile reference lab offered better instrumentation compared to PEMS and provided a fixed curb weight throughout the route. Key summarized results for the on-road testing are as follows:

- For the 0.2g diesel goods movement trucks, the route averaged NOx emission rates ranged from 0.38 to 0.53 g/bhp-hr. This result was lower than the cycle averaged UDDS and vocational chassis dynamometer measurements of 0.63 to 0.87 g/bhp-hr (Figure 43 and Figure 44, respectively) and lower than the daily averaged PEMS measurements of 0.58 g/bhp-hr (Figure 27) for the same category of vehicles.
- The 0.2g NG goods movement truck had very low NOx emissions route averaged emission rates, ranging from 0.05 to 0.10 g/bhp-hr amongst the four routes, which are lower than the corresponding cycle averaged UDDS (0.19 g/bhp-hr) and vocational

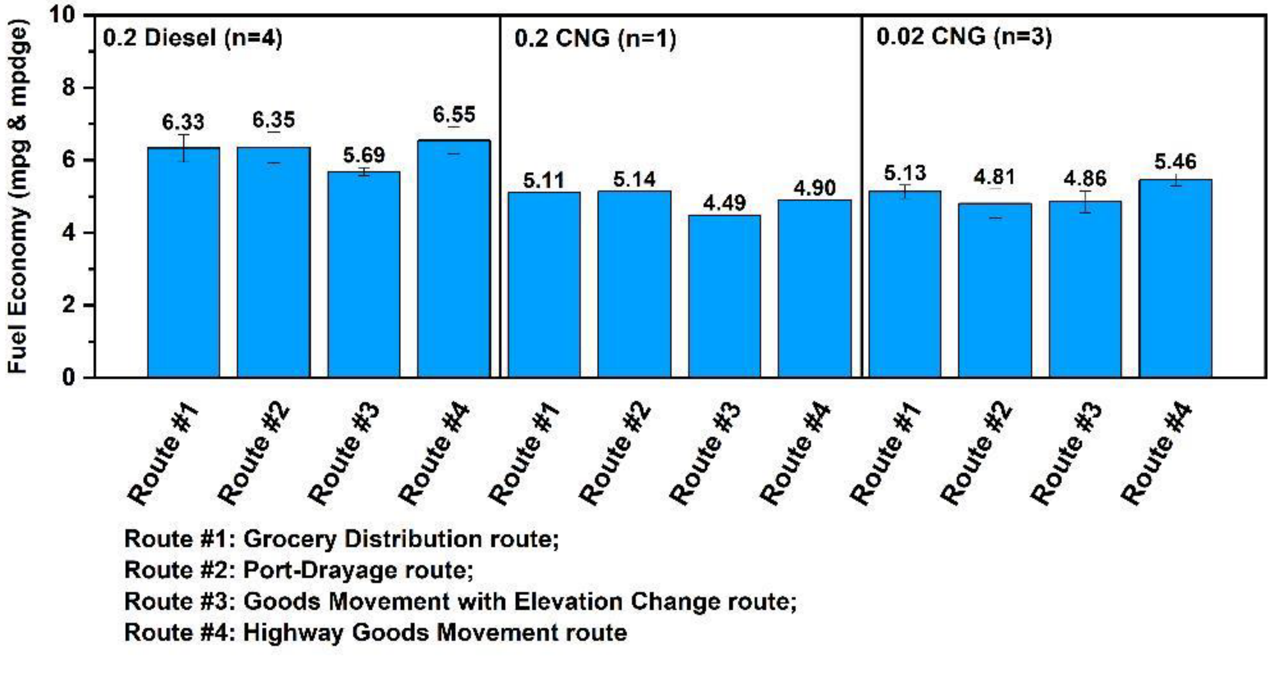
chassis dynamometer (0.064 g/bhp-hr) measurements (Figure 43 and Figure 44) and the corresponding daily averaged PEMS measurement of 0.33 g/bhp-hr (Figure 29). Note the PEMS testing was only conducted on this very HDV #101. The vehicle specific chassis UDDS and vocational measurements for this truck are 0.129 and 0.065 g/bhp-hr, respectively, which were higher than its route averaged measurements. This was a clear indication that the duty cycle can be a large contributor to the variation in emissions.

- The 0.02g NG trucks had very low route averaged NOx emissions rates in the range of 0.03 to 0.06 g/bhp-hr. The route averaged results are higher than the respective UDDS and vocational cycle averaged chassis dynamometer measurements of 0.019 to 0.008 g/bhp-hr for the 0.02g NG goods movement trucks (Figure 43 and Figure 44, respectively) but lower compared to the corresponding PEMS measurement of 0.062 g/bhp-hr (Figure 30). As shown in Figure 50, higher route averaged NOx emissions for the route #3 and route #4 where extended highway option with elevation change were observed. Upon closer analysis, the higher NOx rate was observed after long periods of downhill driving where the motoring operation cooled down the aftertreatment. Thus, the higher NOx level is to be expected and duty cycle related.

3.4.2 Fuel Economy and Discussion

Figure 51 shows the fuel economy values that UCR and WVU measured over the four different routes. Fuel economy results are presented in miles per gallon (mpg) or in miles per diesel gallon equivalents (mpdge) for natural gas tractors ("0.2g CNG" and "0.02g CNG"). The 0.2g diesel trucks were all between model year of 2013 and 2015, the single 0.2 NG truck was a model year 2010, and all 0.02 NG trucks were model year 2018 or newer.

Figure 51: Fuel Economy for Three Class 8 Truck Types by On-Road Test Route



Sources: UCR and WVU

As shown in Figure 51, the four 0.2g diesel tractors averaged 6.23 mpg over the four test routes. The two natural gas HDV categories averaged 4.97 mpdge over the same set of test routes, which was approximately 20 percent lower than that for the diesel tractors. The lower fuel economy for the NG tractors was largely due to the reduced thermal efficiency that spark-ignited engines (including natural gas) exhibit, compared to similar-sized compression-ignited (diesel) engines. Other factors, including throttling losses at part load and higher curb weights for natural gas HDVs compared to diesel HDVs, also likely contributed to the reduced fuel economy measured for the natural gas tractors during this real-world testing. It is also notable that Class 8 trucks with natural gas engines are less efficient during stop-and-go goods movement driving with frequent idling. This is because the air-fuel ratio enrichens (excess fuel) to control NOx, resulting in in higher CO_2 and lower fuel economy.

CHAPTER 4:
Knowledge Transfer Activities

The 200 HDV Testing Program represents an important milestone for CARB, CEC, the South Coast AQMD, SoCal Gas and the U.S. EPA. As previously described, results from the program are very instrumental in ongoing efforts to shape, improve and implement policies designed to attain ambient air quality standards, mitigate climate change, and displace fossil-derived diesel with low-carbon alternative transportation fuels. Consequently, all the key stakeholders intend to widely disseminate the program's results with minimum focus on their specific jurisdictions of authority and/or expertise.

The following summarizes key examples of how various organizations–including the four co-sponsors and the two universities–will conduct knowledge transfer activities related to this milestone testing program. This process is already well underway, as described.

4.1 California Energy Commission

In 2021, the CEC staff completed a study required under Assembly Bill 2127 to assess California's needs to build-out electric vehicle charging infrastructure by 2030.[27] This assessment included application of the Medium- and Heavy-Duty Electric Vehicle Infrastructure Load, Operations and Deployment (HEVI-LOAD) model, which was developed under a collaboration between Lawrence Berkeley National Laboratory and the CEC. The model is being used to help characterize charging infrastructure needs for on-road medium- and heavy-duty electric vehicles across a broad range of applications. HDV activity data collected by UCR during the test program (using PAMS) played a key role to inform inputs for the model (for example, how frequently heavy-duty electric trucks will need to recharge).

4.2 South Coast Air Quality Management District

South Coast AQMD considers the 200 HDV Testing Program as being a key part of its overarching mission to attain National Ambient Air Quality Standards in the SCAB and restore healthful air quality. SCAQMD staff uses findings and results from the project to directly inform development of control measures in its Air Quality Management Plan. [28]

South Coast AQMD staff members have presented preliminary results from the 200 HDV Testing Program at semi-annual meetings of the South Coast AQMD Clean Fuels Advisory

---

[27] California Energy Commission, "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support ZEVs in 2030," July 14, 2021, [Electric Vehicle Charging Infrastructure Assessment - AB 2127 | California Energy Commission](#).

[28] South Coast Air Quality Management District, "Clean Fuels Program 2020 Annual Report & 2021 Plan Update," March 2021, http://www.aqmd.gov/home/technology/reports.

Group.[29] The Advisory Group consists of approximately 13 individuals having strong relevant expertise as representatives of "scientific, academic, entrepreneurial, environmental, public health communities." Representatives are included from the CEC, as well as other key State agencies such as CARB and academic institutions such as University of California, Irvine. Advisory Group members "provide direction and guidance" for South Coast AQMD's Clean Fuels Program, including assessing its "overall direction" related to regional air quality plans and the many types of clean alternative fuels and advanced technologies needed to help attain national ambient air quality standards. The feedback for this work has been generally positive from the advisors and the public and provided a key basis for South Coast AQMD's ongoing effort for NOx reduction in the near term. The final results of the 200 HDV Testing Program were presented by South Coast AQMD/CARB staff and university partners in the fourth quarter of 2022.

4.3 California Air Resources Board

The CARB has prepared fact sheets and summaries based on results-to-date from the 200 HDV Testing Program. For example, under the umbrella of "Activity Data Collection Projects," CARB summarizes preliminary results from the test program on its web page.[30] The CARB notes that study results "will be used to benchmark the CARB's emissions inventories, inform State Implementation Plans (SIPs), characterize activity patterns from different HDV vocations, and evaluate the performance and deterioration of different engine technologies and emissions certification levels." Thus, the 200 HDV Testing Program is likely to be referenced and highlighted by the CARB in a wide array of technical written documents and policy initiatives beginning in late 2022.

As one example, the CARB staff analyzed NG PEMS data (32 0.2-certfied NG and 15 0.02-certified low NOx NG) to update EMFAC2021 emission rate inputs. Prior to this study, EMFAC only modeled NG emissions from refuse trucks and transit buses due to the lack of NG data for other truck categories. This provides a more accurate picture of emissions from NG trucks and buses operating in California. More information on these updates can be found in the EMFAC2021 Technical Document.

As another preliminary output (pending completion of the study and all related reports), the CARB produced a July 2021 fact sheet titled "In-Use Performance of Heavy-Duty Natural Gas Vehicles–Lessons describing emissions from the NG HDVs."[31] The fact sheet focuses on the in-use emission performance of two natural gas fueled HDV types in the test matrix. Thirty HDVs had natural gas engines certified to today's standard of 0.2 g/bhp-hr NOx, and 15 HDVs had natural gas engines certified to the CARB's optional low-NOx standard of 0.02 g/bhp-hr. Citing

---

[29] South Coast AQMD, Clean Fuels Program Advisory Group Meeting, September 15, 2021, https://www.aqmd.gov/docs/default-source/technology-research/clean-fuels-program/clean-fuels-advisory-agenda_september-15-2021.pdf?sfvrsn=13

[30] California Air Resources Board, "CCMER's On-Road Heavy-Duty Vehicle Research," https://ww2.arb.ca.gov/resources/documents/ccmer-heavy-duty-vehicle.

[31] Ibid.

testing results gathered by UCR and WVU during PEMS testing of these 45 natural gas HDVs, the CARB's document states the following key preliminary finding: "In general, 0.02-certified NG engines have significantly lower NOx emissions than 0.2-certified diesel and natural gas technologies. However, in-use emissions performance of 0.02-certified technology can limit those emistsion reductions."

The CARB will continue to update its understanding of NG and diesel engine in-use emissions based on newer data from this study and future test projects. As a follow-on project, the CARB has just kicked off another study to further assess the in-use emissions for large sample (100) of 0.02 g NG HDVs, this time with emissions sensors.

4.4 Southern California Gas Company

The SoCalGas intends to host or co-host a public workshop that will be focused on the program's key findings regarding in-use emissions from various HDV types and fuel-technology platforms. The SoCalGas also tentatively plans to make the final report and related information available to stakeholders and the general public via social media channels (such as LinkedIn). Finally, SoCalGas expects to present program results to/at key relevant organizations, and at events and forums. Likely examples are the Natural Gas Vehicle Association, the California Natural Gas Vehicle Coalition, and the California Transit Association.[32]

4.5 University Presentations and Events

Both UCR and WVU presented preliminary findings of this work throughout the course of this project on various subtopics since 2020. The venues have included the Coordinating Research Council Real World Emissions Workshop, the UCR International PEMS Conference, and the SAE International Annual World Congress Conference.

In addition to conference presentations, UCR published its portion of the PEMS data in 2021.[33] The work provides additional analysis to the PEMS data other than the daily averages presented in this report, and has already had nearly 30 citations. The UCR also has several journal articles prepared for submission on the chassis dynamometer and on-road testing results.

Both universities have expanded this work. As mentioned earlier, the UCR and the CARB kicked off a sensor-based emissions measurement campaign on more than 100 0.02 g NG HDVs in 2022. In 2021, WVU received a research grant from the U.S. Department of Energy with additional funding from the South Coast AQMD and SoCalGas to perform a maintenance cost study on alternative fuel HDVs.

---

[32] Personal communication from Michael Lee (Technology Development Project Manager, Southern California Gas Company) to GNA, April 6, 2022.

[33] Cavan McCaffery et.al. "Real-world NOx emissions from heavy-duty diesel, natural gas, and diesel hybrid electric vehicles of different vocations on California roadways", Science of The Total Environment, Volume 784, 2021,https://doi.org/10.1016/j.scitotenv.2021.147224.

4.6 Knowledge Transfer for Industry to Improve HDVs

Heavy-duty engine manufacturers understand that to continue making and selling heavy-duty alternative fuel/technology powertrains for on- and off-road applications in California, they must continually drive down NOx and PM emissions to very low levels when measured in real-world use as well as during certification testing.

As the manufacturer of two heavy-duty natural gas engines that power a wide array of HDVs tested under the project, Cummins Engine Company gained valuable experience and new insight from project data into how it can ensure further optimization of its spark-ignited heavy-duty natural gas engine technology to maintain low emissions in real-world use. Engine manufacturers must continually drive down NOx and PM emissions to very low levels, when measured in real-world use as well as during certification testing. Cummins is also a major manufacturer for heavy-duty diesel engines, and this project provided new information and insight that can help the company improve emissions performance of the in-use fleet, while also preparing to meet increasingly stringent certification standards from the U.S. EPA and/or the CARB.

This study also provided third party insight to potential issues. For example, deterioration and malfunctions were observed on a number of NG HDVs ; WVU will continue to work with original equipment manufacturers (OEMs) and fleets to perform maintenance studies to assess the cause of these failure events. Second, the observation of a CVS measurement "artifact" causing air leaks prior to the aftertreatment system, which could also lead outward leaking of untreated exhaust, and impact all exhaust measurement, will likely be the subject of future investigations.

Moreover, partly due to this project, Cummins has certified its B6.7N engine down to the same lowest-tier Optional Low NOx Standard level (0.02 g/bhp-hr) that was initially achieved with the L9N engine. In addition to enabling a "right-sized" near-zero emission engine option to power yard tractors, this provided a near-zero emission option for multiple other HDV types, because the B6.7N also powers medium-duty trucks, shuttle buses, and school buses. More recently, Cummins announced a new 15L natural gas engine that will be meeting the model year 2024 CARB and EPA requirements.

The test matrix for this project has included HDVs made by virtually every major OEM in the North American market, across five HDV types (transit buses, school buses, refuse trucks, delivery trucks, and goods movement trucks). Hence, the results will serve to inform a full range of HDV manufacturers of potential issues that can occur with full vehicle implementations that may not be readily apparent from engine testing alone.

This project gathered valuable duty cycle data that can help vendors of HDV emission control systems to improve the design, effectiveness, robustness, and real-world durability of modern exhaust aftertreatment systems.

CHAPTER 5: Conclusions and Recommendations

5.1 Conclusions

This study represents one of the most extensive emission studies for HDVs conducted to date. It included testing using portable emissions measurement systems, portable activity measurement systems, chassis dynamometer emissions testing, and on-road testing with a fully equipped testing laboratory. The testing included 227 in-use PAMS tests, 100 in-use emissions PEMS tests, 55 stationary chassis dynamometer tests, and 10 on-road tests with mobile emission laboratories. The tested HDVs represented 22 vehicle OEMs and nine engine OEMs. The tested vehicles included transit buses, school buses, refuse trucks, delivery trucks, and goods movement trucks fueled with a combination of alternative fuels, conventional and renewable diesel fuels, and dual fuels and at three emission certification levels. The participants came from 25 different fleet partners covering nine different engine/powertrain technologies. In addition to the emissions testing, a comparison to existing emissions inventories as well as a technology assessment was performed to evaluate the technology impact, issues, improvement, and benefits.

This project has helped the understanding of the operation activities, engine performances, duty cycles, and other aspects for the range of the tested HDVs. The emission measurements collected by the Program established a comprehensive picture for the HDVs that are currently running on the roads in Southern California, especially for the cleaner 0.02 g/bhp-hr natural gas engines, which just became commercially available in 2016. The project also identified issues and causes that could lead to higher emissions, especially for NOx, than the certification standards when the HDVs are operated on road in the real world. Specifically, the data of this project suggests that

- Truck activity patterns were highly associated with functions of HDVs and varied among the vocations.
- The technology improvements implemented into the 0.02g NG engines have been effective in reducing NOx emissions.
- The results confirm and further quantify the observation of elevated NOx emissions for 0.2g diesel HDVs under a range of different conditions.
- Natural gas HDVs may also have higher NOx emissions under different conditions, although in general they are lower emitting than the corresponding diesel vehicles.
- Extended idling/low load operation could also cause relatively high NOx emissions, for both diesel and natural gas HDVs.
- Systemic issues for the 12L 0.2 and 0.02g NG HDVs uncovered in this study warrant further in-use emission investigation.

In addition to the important ways the project has helped provide benefits to ratepayers (see the next section), it has successfully resulted in the following milestones and accomplishments:

- Provided OEMs with valuable "lessons learned."
- Enabled successful technology and knowledge transfer among OEMs, end users, and various other types of stakeholders about heavy-duty alternative (non-petroleum) fuel engines, vehicles, control systems, aftertreatment systems, and optimization to produce in-use emissions that are the same as or lower than certification emissions.
- Provided new PEMS and chassis dynamometer emissions test data that further support emissions inventory development.
- Helped support key goals of the CEC to transition to cleaner energy and alternative fuels and create a low-carbon economy.
- Helped support key goals of the CARB to achieve GHG emission reductions and improve air quality.
- Helped support key goals of the South Coast AQMD to reduce NOx emissions in its region and protect the public health of local communities, especially the ones disproportionately affected by truck traffic.

A summary of study highlights follows. Chapter 3 includes detailed accounts of the study results.

5.1.1 PAMS Result and Cycle Development

The PAMS data collected by the two university teams represents the real-world activity characteristics of the 227 trucks. The PAMS profile data from the 200 HDV Testing Program were shared with CARB for emission inventory development. Ultimately, 168 HDVs from this study--pooled together with 90 HDVs from a previous UCR study[34]--were included in CARB's EMFAC2021. Collectively, these two data sets accounted for the majority of HDV activity updates in this latest EMFAC model. Per CARB's EMFAC2021 technical documentation, when compared to EMFAC2017, the new data show that the majority of the HDV categories have a "higher percentage of VMT at higher speeds, higher starts per day and longer soak time, and less extended idling time." The CARB also observed that HDV activity has "no significant difference between fuel types." Whenever applicable, the new PAMS data update was also applied to regions in California outside of Southern California Association of Governments (SCAG) areas in EMFAC2021.[35]

---

[34] Kanok Boriboonsomsin, Kent Johnson, George Scora, Daniel Sandez, Alexander Vu, Tom Durbin, and Yu (Jade) Jiang, "Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles" https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/13-301.pdf

[35] See CARB documents: 1) "EMFAC2021 Volume III Technical Document," March 31, 2021, https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf; and 2) "EMFAC202x Updates," July 30, 2020, https://ww2.arb.ca.gov/sites/default/files/2020-07/EMFAC202x_2nd_Workshop_07302020_ADA.pdf.

- The test team observed differences between known standard chassis test cycles and typical real-world operating patterns in Southern California for three HDV types: school buses, goods movement trucks, and delivery trucks. To test these HDV types under more representative conditions, the test team developed three new chassis dynamometer test cycles specific to these three categories. In addition, PAMS activity data from refuse haulers indicated the need to modify the existing test cycle to better simulate additional work that engines of these trucks must perform to power the hydraulic actuators that enable curbside refuse pick-up and compaction, which was accounted for by adding a varying grade feature to the curbside pick-up portion of the standard refuse cycle.
- Four real-world driving routes were also developed by analyzing PAMS activity data from Class 8 tractors primarily operated in Southern California by four HDV fleets. The main routes of these four fleets intersect with the routes of other typical Class 8 tractor fleets. In comparison to PEMS, the On-Road tests allowed additional control of variability with full mobile emissions lab and fixed routes, while also offering real-world components in comparison to chassis testing.

5.1.2 Results and Discussion for PEMS Data

The PEMS testing incorporated a wide variety set of vehicles, fleet operators, and operating conditions/duty-cycles. As expected, the PEMS results showed high variability of NOx emission levels among vocations as well as engine technologies. The high variance was to be expected, since the PEMS emissions were averaged over the entire test day, regardless of the vocation and the duty cycles. This same pattern was also observed in the previous work on SCR performance under in-use conditions. Detailed emissions data can be found in Chapter 3, and additional work is underway to further analyze this dataset with 2/3B-MAW method.

5.1.3 Results and Discussion for Chassis Dynamometer Data

The university team tested a total of 52 unique HDVs with a chassis dynamometer over the UDDS and their respective vocation cycles by the two university teams. Performance testing was also conducted on four zero-emission HDVs for comparison with non-zero emission HDVs under controlled laboratory conditions. However, 17 vehicles were excluded from this analysis due to factors described in Appendix C.

- Different than the "daily" averages observed from PEMS testing, the chassis UDDS "cycle" averaged results were similar across different vehicle categories. Moreover, the UDDS cycle, although not identical, is a close resemblance of the FTP certification test cycle.
- Over the course of the testing, it was observed that a subset of 0.2g NG and 0.02g NG HDVs exhibited elevated NOx emissions during idle and when deemed to be data outliers. For the 8.9L 0.2g and 0.02 NG trucks with this issue, the root cause was determined to be an "artifact" where ambient air was leaking into the exhaust prior to the aftertreatment system, which was caused by a vacuum generated by the CVS measurement system interference (which is not part of real-world operation). As a result of this finding, the affected 8.9L NG chassis outlier data (9 vehicles) were removed from the data comparison. The 12L NG outliers were not affected by this "artifact" and was included as part of the data comparison.

- The average emission rates were comparable across the different 0.2g NG vocations, with the school buses and refuse vehicles showing higher NOx emissions and the transit buses and goods movement vehicle showing lower NOx emissions compared to the other vocations in this technology category.
- For vocations with well-established diesel baselines, such as delivery and goods movement categories, the NG HDVs showed significantly lower NOx emissions. The emission levels were on the order between 26-78 percent lower for 0.2g NG and 97-99 percent lower for 0.02g NG than the respective diesel HDVs. This is consistent with other studies (Quiros et al., 2016; Thiruvengadam et al., 2015; Lee et al., 2011; Li et al., 2019; Zhu et al., 2020).
- The diesel hybrid electric delivery vehicles showed around 65 percent lower average NOx emission rates in g/mi than the conventional diesel delivery trucks, but not as low as the 0.02g NG delivery vehicles.
- Renewable diesel results in general showed a 0 to 20 percent reduction in NOx emissions relative to conventional diesel.
- Vocational cycle trends were not too different from those for the UDDS cycles, although the absolute cycle averaged NOx levels showed some minor differences.

5.1.4 Results and Discussion for On-Road Data

The university teams tested a total of 10 HDVs were tested over on-road routes in Southern California. The HDVs in this phase were exclusively Class 7/8 goods movement trucks capable of legally towing the specially designed mobile emissions laboratories weighing about 62,000 to 65,000 lbs. The tests were done on the four different routes representing typical goods movement driving routes in Southern California, as described in Chapter 2. Compared to the emissions data presented for the PEMS and chassis dynamometer testing, the NOx and fuel economy were averaged over the entire-test route. The route averaged results are similar to the daily averaged PEMS results, except that the route (as well as the load) was fixed amongst all 10 trucks.

In contrast to the larger variability observed for the PEMS and chassis dynamometer testing, the route averaged NOx emissions showed more consistent trends and lower variability for the On-Road testing. In part, this can be attributed to the smaller data sample as well as the single vocation. Further, the fixed routes also reduced duty-cycle variability that more significantly impacted the daily averaged NOx emissions from PEMS testing. Lastly, the mobile reference lab offered better instrumentation compared to PEMS and provided a fixed curb weight throughout the route. Similarly, additional work is underway to further analyze this dataset with 2/3B-MAW method.

5.1.5 Technology Impact, Issues, Improvement, and Benefits

One of the goals of the study is to identify and potential technology benefits and shortfalls. Different vocation and vehicle technology combinations were evaluated with respect to multiple performance factors, such as emissions, mileage, or driving performance. A summary of the technology impact, issues, improvement, and benefits results is provided below.

- Diesel vehicles generally emitted the highest NOx emissions in comparison with those of the other technologies. This is due in part to the limitation of SCR systems to operate effectively at lower exhaust temperatures r over lower load operations. Both CARB and U.S. EPA are looking to lessen the gap between emissions standards and real-world emissions.

- Natural gas vehicles showed a range of results with some vehicles showing higher emissions than would be expected based on age, vocation, and the duty-cycle. In general, however, the latest generation 0.02g NG engines showed low emissions. It also appears that the technology improvements implemented into the 0.02g NG engines has been effective in reducing NOx emissions.
- Some emission issues were found for NG vehicles, however. This included the identification of some older 0.2g NG vehicles that experienced significant deterioration of the TWC, where in the worst case, resulted in tailpipe emissions essentially being comparable to engine out levels. As NG vehicles can be operating with TWCs that have deteriorated significantly, without obvious warning signs that can readily be identified by a driver or mechanic, these deteriorated TWCs can also lead to emissions that are significantly higher than those seen for diesel vehicles. While some high emitting NG vehicles were identified through this study, the fraction of the NG vehicle fleet that have problems with excessive NOx emissions is not known. A study to better characterize the fraction heavy-duty NG vehicles with high emissions should be conducted, perhaps utilizing sensor-based or mini-PEMS emissions measurement systems to cover a large population of HDVs similar to the PAMS phase of this work.
- Another issue that was identified with NG vehicles was high NOx during idle caused by an "artifact" related to the CVS measurement system. The issues were thought to be systemic at first but later re-testing confirmed that the high NOx was attributed to the engine operating either lean or less rich than during typical operations due to periods of lowered pressure caused by the CVS measurement system. For certain 8.9L NG engines, under low exhaust flow condition like idle, certain laboratory sampling system can create excessive suction that can cause fresh air ingress through exhaust clamps that's normally under positive pressure. The extra fresh air can cause false oxygen level reading and interreference with downstream oxygen sensor reading. The same issue was also seen from WVU's dataset but only impacted one vehicle (cross-lab). This error is documented in detail in the appendices.
- In contrast, for the 12-liter natural gas engine, elevated idle NOx emission rates only increased after a period of extended idle operation for both PEMS and chassis dynamometer testing. Both universities also attempted to analyze catalyst temperatures during extended idle operation when increased NOx emissions occurred. There were observed trends of catalyst temperatures dropping below 300C during the extended idle operation with higher NOx idle emissions rates for the larger 12-liter equipped NG HDVs. Preliminary response from the OEM suggests expected aftertreatment thermal management activity and additional analysis and testing are being performed during the time of this report.
- As the current 0.2g diesel vehicles have the highest emissions of any of the technology categories, it is suggested that the technology will need to be improved in all the vocational categories. The higher fuel energy density for diesel fuel in comparison with batteries and other fuels will also allow for these vehicles to maintain the longer ranges

needed for various operations. As diesel vehicles will likely remain part of the medium- and heavy-duty in-use vehicle fleet into the foreseeable future, it is suggested that efforts continue to develop and implement more advanced lower NOx strategies.

- Overall, the data suggests that the newer 0.02g NG engine equipped vehicles could play an important role as a bridge technology as different vocations transition towards electrification over the next few decades. Low NOx 0.02g NG engines are available in 6.7-, 8.9-, and 12-liter sizes, as well as other medium duty gasoline conversion engines with larger displacement being announced. These engines cover a wide range of vocational categories and show good promise to achieve lower NOx levels in the near term with access to relatively mature refueling infrastructure. NG vehicles already represent the predominant fraction of heavy-duty vehicles in the transit bus, school bus, and refuse categories in the SCAB. To the extent that some of the older model 0.2g NG engines in these sectors can be transitioned to 0.02g NG engines, this could provide important further reductions in emissions in these categories in the near-term. The availability of the 0.02g NG engines in larger engine sizes, such as the 15-liter engine announced by Cummins for model year 2024, would also allow for the expansion of NG vehicles in the long-haul vocations. Despite the NOx benefit, some NG emissions issues will still need to be evaluated, as there was some evidence of higher emissions for some higher mileage NG vehicles, and as most of the 0.02g NG vehicles had relatively low mileage at the time of this study. Also, there are some ammonia, particulate matter, and particulate number issues with NG vehicles that could be minimized with further refinement of engine calibration.
- Ammonia emissions showed differences between the different technology categories, with ammonia emissions for the CNG vehicles showing higher emissions than those of the diesel vehicles. This is because ammonia is typically not a combustion product, but rather forms as a reaction product over the TWC after the catalyst has reached its light-off temperature. Interestingly, the single malfunctioning transit bus with defective TWC had considerably lower NH3 emissions than some of the other NG vehicles, which are consistent with other studies. Very low NH3 emissions were seen for the diesel (no SCR) and RD (no SCR) vehicles, diesel-electric delivery vehicles, and diesel (no SCR) and RD (no SCR) vehicles.
- Diesel-electric vehicles provided significant advantages in fuel economy and CO2 reductions, showing fuel economies that were in some cases nearly double those of other technologies in the delivery and other categories. As such, the hybridization of diesel (or other) engine technologies could provide significant benefits in terms of CO_2 emissions. The emissions testing on the small number of vehicles in this study suggests that NOx emissions can be controlled to levels comparable to those of the other advanced technologies and achieve lower levels as a combined system and could likely be refined to the extent that the technology is further developed.
- Many consider electric vehicles to be the most promising long-term technology for future transportation that can provide full sustainability as well as zero emissions. The current population of electric vehicles in the heavy-duty sector is still small, and testing of electric vehicles was relatively limited in this study. The number of electric vehicle applications in the heavy-duty sectors is continuing to grow and being heavily

supported in California. The level of interest and resources available for electrification in the heavy-duty sector prompt expectations that technology improvements and cost reductions will advance at a rapid pace in this area. As electric vehicle range will likely be one of the key limiting factors in deployment for HDV vocations, it is expected that applications on shorter routes with readily available charging infrastructure will be the most viable for initial deployment. Performance testing of electric vehicles is encouraged to better understand how this technology can be best applied to HDVs and to document advancements.

5.2 Recommendations

The Program provides important information that can be used to develop and assess engine and emission control technologies, policy, and emissions inventories, and was used to update the CARB EMFAC2021 model. The Program suggests that continued monitoring and characterization of emissions from HDVs is needed. In the future, such monitoring could be done using lower cost emissions method, including mini-PEMS, micro-PEMS, or on-board sensors as CARB will leverage in its Real Emissions Assessment Logging (REAL) program. While new regulations will tighten the monitoring requirements on diesel vehicles, it will also be important to continue to monitor emissions for other technologies, such as NG vehicles, to ensure that they also maintain their low emissions levels under different conditions, and throughout the useful life of the vehicle. The results showed the potential for other technologies, such as natural gas, liquefied petroleum gas, or diesel-hybrids that could also play a role as the fleet transitions toward zero emission vehicles going forward. In general, however, the implementation of new more stringent standards coupled with the transition toward zero emission vehicles suggests that HDVs are well on their path to zero emissions and towards a more sustainable future.

CHAPTER 6:
Benefits to Ratepayers

The CEC's ratepayer funded Gas Research and Development Program has supported projects to develop and demonstrate low NOx natural gas engines with the goal of certifying to the 0.02 g/bhp-hr standard.[36] Since the conclusion of some of these projects, engine manufacturers such as Cummins Westport Inc. have released commercial products and 0.02 NG HDVs have been successfully deployed in California. Largely driven by the CARB's Low Carbon Fuel Standard, around 97 percent of natural gas used for transportation in California is renewable natural gas or biomethane, with negative average carbon intensity ratings.[37] The combination of the availability of 0.02 NG engine technologies and market drivers for renewable natural gas can reduce both NOx and GHG emissions. This study builds on these past efforts by investigating in-use emission levels of these NG HDVs in the context of the 0.02 g/bhp-hr NOx certification standard, legacy 0.2 NG HDVs, multiple HDV vocations, and other fuel types. By identifying technology impacts and shortfalls potentially causing higher than expected in-use emissions, the project is informing further technology development and research opportunities to maximize emission reduction benefits from deploying 0.02 NG HDVs.

Additionally, the comprehensive dataset (and the models leveraging the data) can help policymakers better understand real world emissions of California's in-use fleet of approximately one million medium- and heavy-duty vehicles. Decision makers can leverage the study results to determine the best pathways forward for meeting transportation decarbonization and air quality goals. For example, The South Coast AQMD is currently developing its 2022 Air Quality Management Plan to attain to the ozone National Ambient Air Quality Standards. In conjunction with the CARB (which recently adopted its 2022 State Implementation Plan strategy) and the U.S. EPA (adopted more-stringent new NOx standard for heavy-duty engines also in 2022), the South Coast AQMD is developing its latest round of mobile source control measures designed to rapidly reduce vehicular NOx emissions. For the on-road fleet, most of those reductions will need to come from HDVs, including newly manufactured units as well as those already in use. This study's data will also be instrumental to help prepare these new control measures, for which it is critical that planners, modelers and rule-development staff have a robust, accurate, and up-to-date characterization of NOx emissions from the in-use HDV fleet, while being operated in real-world conditions.

---

[36] Zwissler, Ben and Stephen Ptucha. Cummins Westport Inc. 2019. *Ultra-Low Emission Natural Gas 12-Liter Engine for On-Road Heavy-Duty Vehicles*. California Energy Commission. Publication Number: CEC-500-2019-002. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2019-002.pdf

[37] California Air Resources Board. Low Carbon Fuel Standard Reporting Tool Quarterly Summaries. https://ww2.arb.ca.gov/resources/documents/low-carbon-fuel-standard-reporting-tool-quarterly-summaries

GLOSSARY AND LIST OF ACRONYMS

Acronym	Full Term/Definition
3B-MAW	three-bin moving average window
AQMD	(South Coast) Air Quality Management District
CARB	California Air Resources Board
CBD	Central business district (test cycle)
CEC	California Energy Commission
CFR	Code of Federal Regulations
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CVS	Constant volume sampler
EMFAC	Emission FACtor model (used by CARB)
EPA	U.S. Environmental Protection Agency
FTP	Federal Test Procedure
g	Gram
GHG	greenhouse gas
g/bhp-hr	grams per brake horsepower-hour
g/mi	grams per mile
GPS	global positioning system
HD	geavy-duty
HDIUT	Heavy-duty in-use vehicle testing (program)
HDV	Heavy-duty vehicle
LPG	liquefied petroleum gas
MIL	Malfunction indicator lamp
mpg	miles per gallon
NG	natural gas (primarily methane)
NGV	natural gas vehicle
NO_x	Oxides of nitrogen

NTE	Not to exceed
O_2	Oxygen
OCTA	Orange County Transportation Authority (test cycle)
OEM	original equipment manufacturer
PAMS	portable activity measurement system
PEMS	portable emissions measurement system
PM	particulate matter / particulate matter smaller than 2.5 microns diameter
RD	renewable diesel
SCAB	South Coast Air Basin
SCR	selective catalytic reduction
SoCalGas	Southern California Gas Company
THC	total hydrocarbons
TWC	three-way catalyst
UCR	University of California at Riverside
U.S. EPA	U.S. Environmental Protection Agency
UDDS	Urban Dynamometer Driving Schedule
WVU	West Virginia University
VMT	vehicle miles traveled

REFERENCES

Boriboonsomsin et al, "Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles" https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/13-301.pdf

California Air Resources Board, 2000–2019 GHG Emissions Trends Report Data, https://ww2.arb.ca.gov/ghg-inventory-data.

California Air Resources Board, "CCMER's On-Road Heavy-Duty Vehicle Research," https://ww2.arb.ca.gov/resources/documents/ccmer-heavy-duty-vehicle.

California Air Resources Board, "Certification and In-Use Testing for Heavy Duty Diesel Engines to Understand High In Use NOx Emissions," presentation by Tom Durbin of University of California, Riverside, Chairman's Seminar, March 27, 2019.

California Air Resources Board, "Low Carbon Fuel Standard (LCFS) Guidance 20-04: Requesting EER-Adjusted Carbon Intensity Using a Tier 2 Pathway Application," Table 5, April 2020.

California Air Resources Board, "EMFAC202x Updates," https://ww2.arb.ca.gov/sites/default/files/2020-07/EMFAC202x_2nd_Workshop_07302020_ADA.pdf., July 30, 2020

California Air Resources Board, "EMFAC2021 Volume III Technical Document," https://ww2.arb.ca.gov/sites/default/files/2021-03/emfac2021_volume_3_technical_document.pdf, March 31, 2021

California Air Resources Board, "2020 Mobile Source Strategy," https://ww2.arb.ca.gov/resources/documents/2020-mobile-source-strategy, September 28, 2021.

California Air Resources Board, 2020 Mobile Source Strategy, https://ww2.arb.ca.gov/sites/default/files/2021-12/2020_Mobile_Source_Strategy.pdf, 2021

California Air Resources Board, mobile source NOx inventory graph provided to GNA in August 2022.

California Air Resources Board, "Mobile Source Emissions: 2017 Estimated Annual Average Emissions Statewide," https://ww2.arb.ca.gov/applications/mobile-source-emissions.

California Air Resources Board, "Facts about the Low NOx Heavy-Duty Omnibus Regulation," https://ww2.arb.ca.gov/our-work/programs/heavy-duty-low-nox/hd-low-nox-omnibus-regulation-fact-sheet.

California Energy Commission, "Final 2020 Integrated Energy Policy Report Update, Volume I," https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2020-integrated-energy-policy-report-update, March 23, 2021.

Cavan McCaffery et al. "Real-world NOx emissions from heavy-duty diesel, natural gas, and diesel hybrid electric vehicles of different vocations on California roadways", Science of The Total Environment, Volume 784,https://doi.org/10.1016/j.scitotenv.2021.147224, 2021.

California Energy Commission, "Assembly Bill 2127 Electric Vehicle Charging Infrastructure Assessment Analyzing Charging Needs to Support ZEVs in 2030," Electric Vehicle Charging Infrastructure Assessment - AB 2127 | California Energy Commission, July 14, 2021.

Code of Federal Regulations (CFR) Title 40, Volume 20, Part 86.1370–2007, https://www.govinfo.gov/app/details/CFR-2012-title40-vol20/CFR-2012-title40-vol20-sec86-1370-2007.

Cushing et al., Racial/ethnic disparities in cumulative environmental health impacts in California: evidence from a statewide environmental justice screening tool (CalEnviroScreen 1.1). American journal of public health, 105(11), 2341-2348, 2015.

DieselNet, "US Supreme Court decides CO2 is a pollutant," https://dieselnet.com/news/2007/04epa.php#:~:text=In%20one%20of%20the%20most,2%20emissions%20from%20new%20cars, April 3, 2007.

DieselNet, NTE (Not-To-Exceed) Testing, https://dieselnet.com/standards/cycles/nte.php

Haugen et al.: Long-Term Fuel-Specific NOx and Particle Emission Trends for In-Use Heavy-Duty Vehicles in California, ES&T, 2018.

International Council on Clean Transportation; "Current State of NOx Emissions from In-Use Heavy-Duty Diesel Vehicles in the United States;" Huzeifa Badshah, Francisco Posada, Rachel Muncrief; https://theicct.org/publication/current-state-of-nox-emissions-from-in-use-heavy-duty-diesel-vehicles-in-the-united-states/, November 26, 2019.

Johnson et al, Final Report Measurement Allowance Project – On-Road Validation https://ww2.arb.ca.gov/sites/default/files/classic//research/apr/past/03-345a.pdf, 2008

Li et al., "Emissions from Advanced Ultra-Low-NOx Heavy-Duty Natural Gas Vehicles," SAE Technical Paper 2019-01-0751, doi:10.4271/2019-01-0751, 2019.

Preble et al.: Control Technology-Driven Changes to In-Use Heavy-Duty Diesel Truck Emissions of Nitrogenous Species and Related Environmental Impacts, ES&T, 2019.

Ruehl et al., Evaluation of Heavy-Duty Vehicle Emission Controls with a Decade of California Real-World Observations, JAWMA, 2021.

South Coast Air Quality Management District, "Final 2016 Air Quality Management Plan," http://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2016-air-quality-management-plan/final-2016-aqmp/final2016aqmp.pdf, March, 2017.

South Coast AQMD, 2022 Air Quality Management Plan, http://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan

South Coast Air Quality Management District, "Clean Fuels Program 2020 Annual Report & 2021 Plan Update," http://www.aqmd.gov/home/technology/reports, March 2021.

South Coast AQMD, Clean Fuels Program Advisory Group Meeting, https://www.aqmd.gov/docs/default-source/technology-research/clean-fuels-program/clean-fuels-advisory-agenda_september-15-2021.pdf?sfvrsn=13, September 15, 2021.

Tan et al., Paul Henderick, Seungju Yoon, Jorn Herner, Thomas Montes, Kanok Boriboonsomsin, Kent Johnson, George Scora, Daniel Sandez, and Thomas D. Durbin, "On-Board Sensor-Based NOx Emissions from Heavy-Duty Diesel Vehicles", Environmental Science & Technology 2019 53 (9), 5504-5511 DOI: 10.1021/acs.est.8b07048, 2019.

U.S. EPA, Policy Assessment for the Review of the National Ambient Air Quality Standards for Particulate Matter, External Review Draft, 2019.

Zhu et al., "Characterizing Emission Rates of Regulated and Unregulated Pollutants from Two Ultra-Low NOx CNG Heavy-Duty Vehicles," University of California, Riverside, Printed in Fuel 277 (2020) 118192, www.elsevier.com/locate/fuel, 2020.

APPENDIX A:
University of California Riverside Final Report

This Final Project Report includes as Appendix A the final report prepared by the University of California, Riverside, for its share of the 200 HDV Testing Program. This Appendix can be made available upon request by submitting an email to pubs@energy.ca.gov, scao@aqmd.gov, durbin@certr.ucr.edu.

APPENDIX B:
West Virginia University Final Report

This Final Project Report includes as Appendix B the final report prepared by West Virginia University. This Appendix can be made available upon request by submitting an email to pubs@energy.ca.gov, scao@aqmd.gov, arvind.thiruvengadam@mail.wvu.edu

APPENDIX C: Discussion of Potential Causes for Emission Data Outliers

C.1 Broad Types of Conditions Causing Emissions Outliers

The 200 HDV Testing Program investigated the different technology benefits and shortfalls under real-world operating conditions. The HDV emission patterns under in-use operational conditions cannot be fully reproduced with laboratory certification testing, which is conducted on heavy-duty engines mounted on a test stand under controlled environmental conditions. NOx and PM are the pollutant species of primary interest of the Program, because they are disproportionally emitted by diesel HDVs compared to other mobile sources, and both contribute heavily to unhealthy ambient air quality in California's urban areas.[38]

It is important to recognize that, under current regulations, the NOx level achieved by a heavy-duty engine during certification cycle testing is not directly comparable to emissions from a complete HDV in the real world, whether tested using PEMS over an entire day, or on a chassis dynamometer over predefined chassis cycles. Thus, it is important to choose correct metrics when comparing in-use HDV emissions to the levels achieved during certification. The suggested metric by WVU is to compare a HDV's NOx emission from this study (in g/bhp-hr) over a predefined cycle against the corresponding in-use standard. For example, a HDV powered by a heavy-duty engine certified at 0.2 g/bhp-hr NOx has an in-use standard of 0.45 g/bhp-hr of NOx.[39] For purposes of analyzing the large amount of emissions data from the 200 HDV Testing Program, the project team identified HDVs that emitted NOx at "outlier" levels. Roughly, this was defined to be approximately 2.5 times higher than the respective in-use standard.

The cause of outliers can be rooted in factors related to the key components of the HDV systems, including fuel equipment, engine/drivetrain, exhaust aftertreatment, and/or HDV body/chassis as summarized in Table C-1 and Table C-2 of this section. The following issues can cause elevated emissions during PEMS and chassis testing: 1) manufacturing defects with engines and emissions-related parts and components; 2) vehicle/equipment failure due to deterioration from age and/or high mileage; 3) "off-cycle" driving conditions that result in ineffective performance of the emissions control system; 4) acts of omission or commission that defeat, improperly maintain, and/or mis-fuel systems that collectively control emissions. and/or 5) "artifact" or failure related to emissions measurement system.

It should be noted that while HDVs powered by engines certified to the lowest NOx level, i.e., California's Optional Low NOx Standard of 0.02 g/bhp-hr can also exceed 0.02 g/bhp-hr, on an absolute level these exceedances can be much lower in magnitude. For example, one 0.02 g

---

[38] CARB (2021), 2020 Mobile Source Strategy, https://ww2.arb.ca.gov/sites/default/files/2021-12/2020_Mobile_Source_Strategy.pdf

[39] Johnson et al, (2008) Final Report Measurement Allowance Project – On-Road Validation https://ww2.arb.ca.gov/sites/default/files/classic//research/apr/past/03-345a.pdf

NG transit bus emitted 0.084 g/bhp-hr of NOx during chassis dynamometer testing. While this is more than four times higher than the 0.02 g/bhp-hr standard, these higher emissions would have a different impact when compared to HDVs emitting four times the 0.2 g/bhp-hr standard.

C.2 Potential Causes for HDV NOx Emission Outliers

The 200 HDV Testing Program observed many incidents where HDVs in the real-world emitted at higher-than-design levels for NOx and other key air pollutants. The two universities together provided recommendations for classification of the likely causes that resulted in outlier NOx emission levels into three categories: 1) Systemic, 2) Rare/Random, or 3) Duty Cycle Related, as defined in Table C-1.

Table C-1: Cause Categories for Higher Emissions

Category	General Description
Systemic: Expected problems / conditions that occur with fairly constant frequency **(These events could be considered as part of the typical emissions signature of a vehicle operation as they occur repeatedly and in a "quasi-predictive" manner)**	• Increased NOx emissions rate events would occur consistently if given conditions are met. • Key HDV system / emissions-control component fails (e.g., 3-way catalyst or SCR) or does not properly reduce NOx emissions. Causes generally understood, including accelerated deterioration under normal duty cycles / operational conditions. • Consistent higher emissions occur during certain operational modes (e.g. during long periods of engine idle).
Rare / Random: Unexpected / anomalous problems / conditions that occur at low frequency **(These events would be considered NOT representative of the typical emissions signature of a vehicle operation and excluded)**	• Increased NOx emissions rate events would be considered not representative of the typical emissions signature of a vehicle operation. • Key HDV system / emissions-control component fails and leads to higher emissions for reason(s) that are not widely encountered/measured. Causes could be unknown or poorly understood, or might include operator-induced problems such as mis-fueling. (e.g. low fuel warning that cause engine to go into certain operating modes). • Increased NOx emissions rate due to external "artifact", such as caused by CVS measurement system or measurement system failures.
Duty Cycle Related: High emission events during off-cycle real-world driving not reflected in certification testing **(These events could be considered as part of the typical real-world activity of a vehicle operation)**	• Increased NOx emissions rate events would occur in certain duty cycle / operational modes, such as extended-idle applications, or power take-off operation where exhaust temperatures are not high enough for proper NOx reduction. Such duty cycles do not occur during engine certification testing.

Sources: UCR and WVU

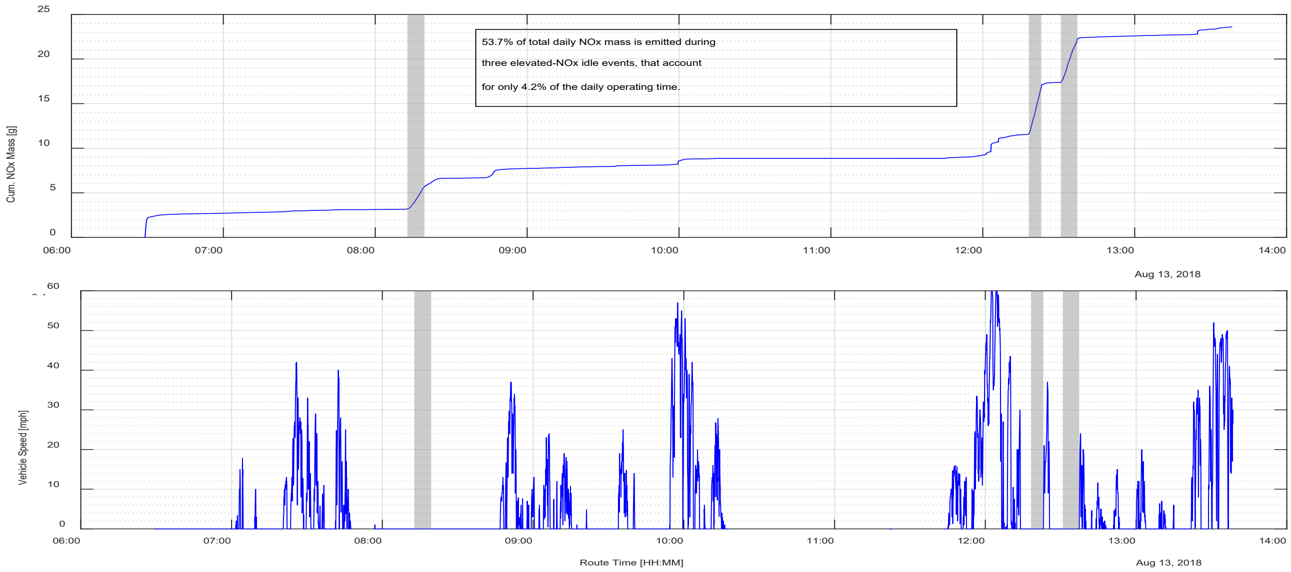
C.3 Outlier Examples

Examples are provided for each cause in this section for explanation and illustration.

C.3.1 Systemic Outlier

Figure C-1 shows an example where a goods movement truck (HDV#108, 0.02g NG) emitted higher-than-expected NOx during the PEMS testing with a daily average NOx emission rate of 0.153 g/bhp-hr. The top graph (cumulative NOx emitted) and bottom graph (vehicle speed) show that more than half of the daily NOx mass emissions from this Class 8 tractor occurred during three periods of extended engine idle events. This is an example of a systemic issue identified for 12L NG trucks during PEMS and chassis testing; see a more detailed description at the end of this chapter. Similar behavior was also observed during the long idle portion on the goods movement chassis cycle. Given that it was a relatively frequent occurrence, this was considered typical emission signature of the 12L NG vehicle operation as it occurred repeatably and in a "quasi-predictive" manner.

Figure C-1: HDV #108 (Goods Movement Truck, 0.02g NG) Elevated NOx at Idle

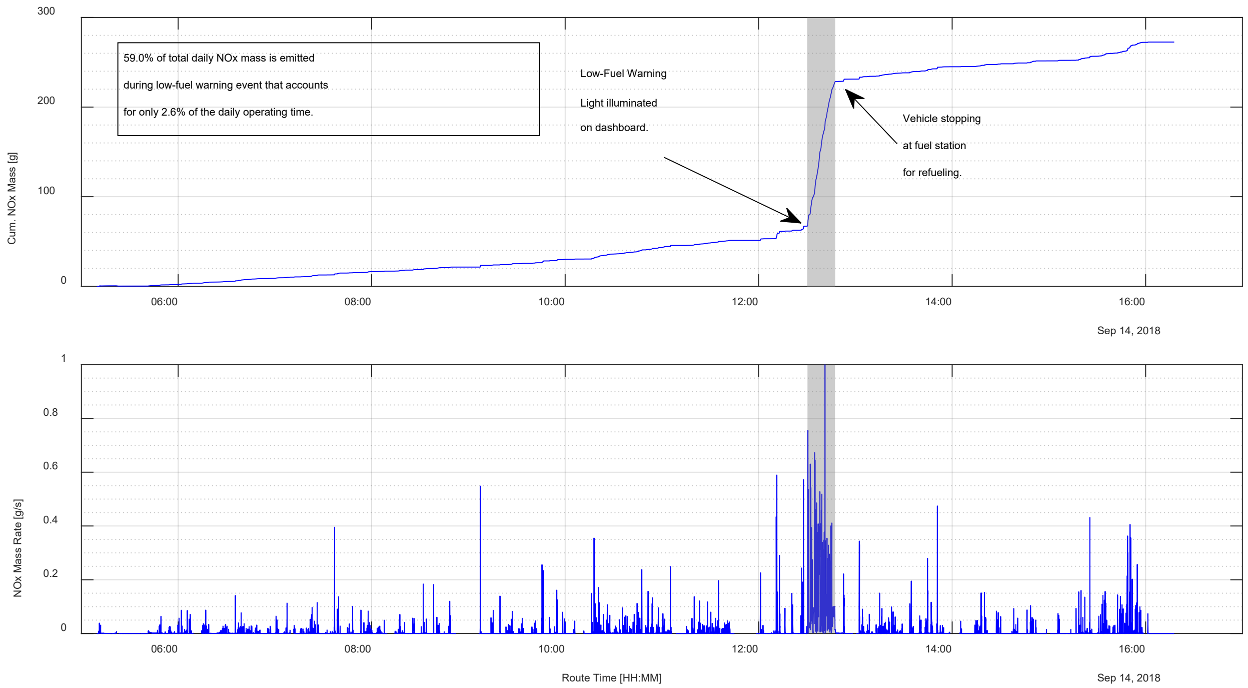


Source: WVU

C.3.2 Rare / Random Outlier

HDV #36 (0.02g NG refuse hauler) below was an example of rare/random outlier. The daily averaged PEMS NOx data was 0.36 g/bhp-hr, orders of magnitude above both the in-use NTE limit as well as the certification level. Further analysis of the real time PEMS data indicates that the HDV was performing at its expected low levels of in-use NOx, until its low-fuel warning light became illuminated. At this point, the HDV's NOx emissions began to spike. As shown in Figure C-2, the HDV emitted 59 percent of its total daily NOx during the brief period when the low-fuel light was illuminated (less than ten minutes). PEMS data further indicates that the natural gas engine shifted into lean-combustion operation while the light was illuminated, which was not a suitable condition for NOx reduction using a three-way catalyst system. Manufacturers of the engine/fuel system are further investigating this problem. Excluding this event, the daily averaged NOx rate would be 0.15 g/bhp-hr. Although the data could be reprocessed to exclude the low-fuel event, for the purpose of this report, the data is excluded from the comparison.

Figure C-2: HDV #36 (0.02g NG Refuse Hauler) Elevated NOx due to Low-Fuel

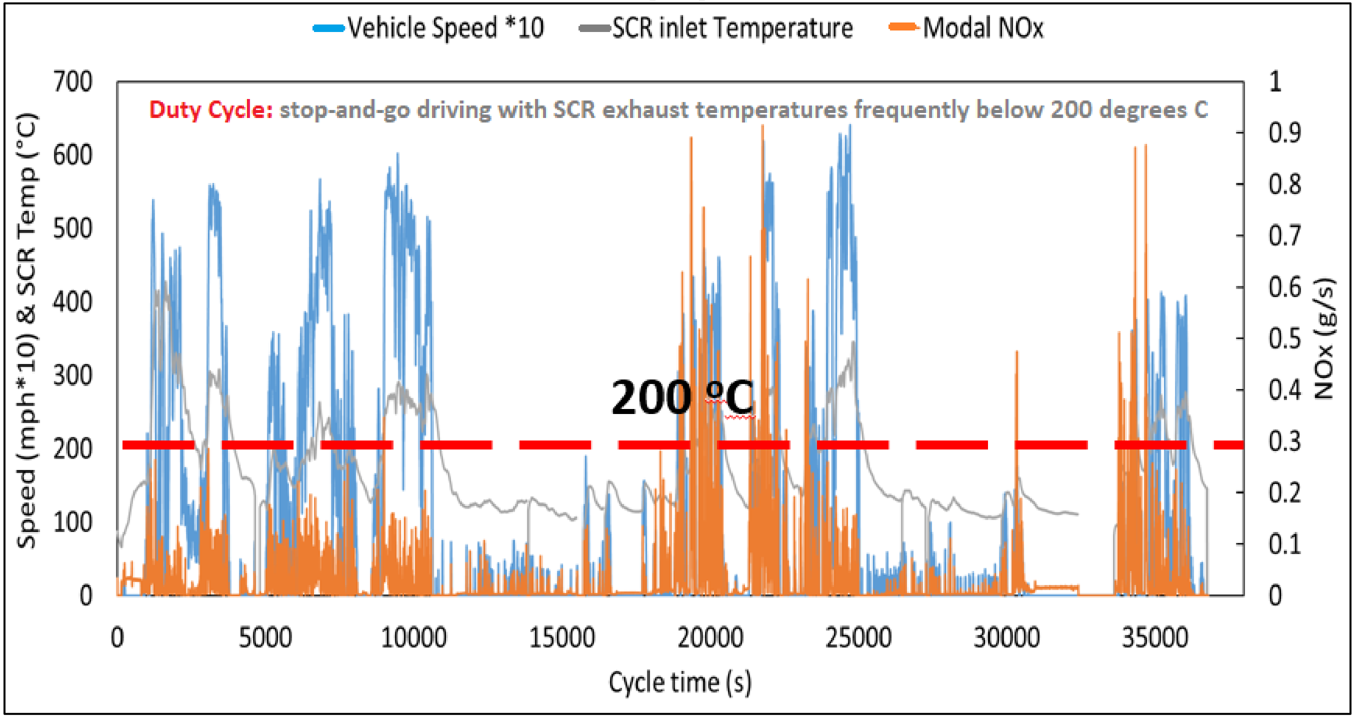


Source: WVU

C.3.3 Outlier due to Duty Cycle

Figure C-3 shows an example where an HDV (#18078, 0.2g diesel goods movement truck) emitted higher-than-expected NOx during the PEMS testing, the daily averaged NOx rate is 2.5 g/bhp-hr. Elevated NOx emissions were found during higher-speed driving events following the periods when the driving speed was low, or the engine was turned off. For portions of these high-speed events that occurred after lower speeds/engine off events, the SCR temperature was below the optimal operating temperature, which probably caused poor NOx conversion. Similar cases of high PEMS emissions due to duty cycle occurred for several other diesel-fueled goods movement trucks (e.g., HDVs #1, #5, and #69).

Figure C-3: HDV No. 18078 (0.2g Diesel Goods Movement) Elevated NOx due to Duty Cycle



Source: UCR

C.3.4 Process for Identifying Outliers

Outliers of NOx measurements were first identified by initial screening, as shown in Figure 27 through Figure 32 for the PEMS testing and Figure 40 through Figure 42 for the chassis dynamometer testing. After this initial screening, test results for HDVs data identified as "outliers" were analyzed more closely to better understand likely causes of the higher NOx emissions, and then categorized into each type of outlier described in Table C-1. Once a known systemic and/or rare/random issues was identified, all similar HDVs were further analyzed again to identify "outliers" events despite not necessarily having higher overall NOx emissions from the initial screening, because they exhibited similar systemic anomalies associated with elevated NOx emissions under certain operational modes (e.g., during engine idle).

C.4 Summaries of Outliers from the PEMS and Chassis Dynamometer Testing

Table C-2 identifies each specific HDVs that exhibited higher in-use NOx emissions, during PEMS and chassis dynamometer testing. Note duty cycle related issues are only found in the PEMS data since there was considerable variability in the "daily" routes and applications. No "outlier" emissions were observed during on-road testing.

C.4.1 Summary of PEMS Testing Outliers:

Fifteen HDVs had daily averaged NOx emission rates identified as outliers for the PEMS testing. Most of daily averaged NOx measurements from the PEMS testing were higher than the NTE levels for the respective engine certification categories. Outliers in the PEMS testing were mainly attributable to systemic issues and duty cycle issues. For 0.2g Diesel HDVs, most outliers were related to duty cycle issues, but one was caused by a systemic deterioration issue, likely due to age and mileage. For 0.2g NG HDVs, half of the outliers identified were due to systemic issues, which included possible deterioration of the O_2 sensors and TWC that could be related to high mileage and deterioration (vehicles #35 and #87), and a non-functioning O_2 sensor from mal-maintenance and lack of on-board diagnostic system feedback (vehicle #48). More Duty cycle issues and aggressive driving was also identified as a cause for the outlier measurements for vehicle #87. For 0.02g NG HDVs, of the five outliers in this category, three outliers were attributable to the systemic issue of idling for the 12L NG trucks. One 0.02g NG vehicle (#18094) had possible catalyst deterioration, or some other type of issue related to improper operation of the emissions control system. Another 0.02g NG vehicle (#36) exhibited duty cycle related NOx emission excursions during power take-off operation while unloading goods at elevated engine speeds. Two vehicles, #90 and #56, also had various issues with the PEMS measurements, thus, data are not reported.

C.4.2 Summary of Chassis Dynamometer Outliers:

The 0.2 diesel HDVs outliers all had either systemic causes, including low SCR temperatures leading to poor NOx conversion, or rare/random factors. For 0.2 NG HDVs, five outlier vehicles had rare/random issues related the CVS measurement system “artifact” on 8.9L NG HDVs, that were excluded from the comparisons in Section 3. Two additional 0.2 NG HDVs showed signs of deterioration but were left in the comparisons in Chapter 3. Four of the outliers for 0.02 NG HDVs were related to rare/random issues involving the CVS measurement system “artifact” on 8.9L NG HDVs, and these were excluded from the comparisons in Chapter 3.

Table C-2: Outliers of PEMs and Chassis Dynamometer Testing Results and Causes

Fuel & NOx Certification	Application	HDV ID	Test (Lab)	NOx Levels (g/bhp-hr)	Outlier Cause Category	Observed Likely Causes
0.2g Diesel	Goods movement	#90 and #56	PEMS (WVU)	NA	Rare/Random	Rare/Random: various issues with the PEMS measurements, missing/incomplete data.
0.2g Diesel	Goods movement	#18079	PEMS (UCR)	~2.3	Systemic	Systemic: High emissions occurred during high-speed operation, even under conditions where SCR temperature was sufficiently hot. Possible SCR deterioration. MY2010, 387k miles.
0.2g Diesel	Goods movement	#18048	PEMS (UCR)	~2.1	Duty Cycle	Duty Cycle: Higher NOx emissions were found during higher-load uphill driving.
0.2g Diesel	Goods movement	#18078	PEMS (UCR)	~2.5	Duty Cycle	Duty Cycle: High emissions observed during higher-speed driving when SCR was below optimal operating temperature (following lower speeds driving or engine off events).
0.2g Diesel	Delivery	#18051* #18093	PEMS (UCR)	~1.64 - 1.77	Duty Cycle	Duty Cycle: Frequent stops with engine-off events -- and limited driving in between -- led to multiple short high-emission trips.
0.2g Diesel	Delivery	#46	PEMS (WVU)	~3.62	Duty Cycle	Duty Cycle: Beverage application, engine turned off frequently during un-loading events; SCR output temperature below 200°C for nearly 97% of total daily operation caused reduced NOx conversion efficiency.

Fuel & NOx Certification	Application	HDV ID	Test (Lab)	NOx Levels (g/bhp-hr)	Outlier Cause Category	Observed Likely Causes
0.2g Diesel	Goods movement	#5	PEMS /Chassis (WVU)	~1.80/0.89	Duty Cycle/Systemic	Duty Cycle: Drayage application, high idle time (53% time-weighted) and low-speed/low-load operation; ~83% total operating time SCR exhaust temperatures were below 200°C, resulting in poor overall NOx conversion efficiency. Same trend observed during chassis dyno testing.
0.2g Diesel	Goods movement	#69	Chassis (WVU)	~1.47	Systemic	Systemic: HDV experienced overall lower SCR temperatures (50% of operating time below 200°C during UDDS); performance improved during chassis dyno testing over HHDDT Cruise and GMT cycles.
0.2g Diesel	Delivery	#18051*	Chassis (UCR)	~1.5	Systemic	Systemic: low SCR inlet temperatures, resulting in poor NOx conversion efficiency.
0.2g Diesel	Goods movement	#1*	Chassis (WVU)	~1.30	Rare/Random	Rare/Random: HDV showed poor SCR conversion efficiency despite sufficiently high SCR temperatures over 90% of UDDS cycle; DPF regeneration event occurred before test; possible remaining low ammonia (NH_3) buffer during subsequent cycles. NOx performance improved (2-3 X standard) during chassis dyno testing over other relevant driving cycles (see Appendix B - WVU final report). Note: this Class 8 truck's NOx emissions were significantly reduced when tested with RD (relative to baseline ULSD testing). However, NOx emissions still fell in the "outlier" region as identified.
0.2g NG	Goods movement	#87	PEMS (WVU)	~1.50	Systemic / Duty cycle	Systemic: High age/mileage leading to possible malfunction or deterioration of the three-way catalyst. MY2008, 272k miles. Duty Cycle: Aggressive driving (acceleration/braking) by fleet observed during PEMS testing.
0.2g NG	Refuse Hauler	#35	PEMS (WVU)	~1.80	Systemic	Systemic: Highest mileage HDV tested by WVU; emissions aftertreatment systems likely had age-related reduced NOx conversion efficiency. MY2008, 292k miles.
0.2g NG	Refuse Hauler	#48	PEMS/ Chassis (WVU)	~2.50	Rare/Random	Rare/Random: HDV inspection indicated after-treatment systems were disabled (e.g., disconnected O_2 sensors) and dysfunctional; tailpipe NOx not reduced from engine-out levels
0.2g NG	Goods movement	#76 and #101	Chassis (WVU)	~0.30	Systemic	Systemic: <u>While not considered higher emitters</u>, these two 12L NG HDVs exhibited increased NOx emission rates during extended idling periods of the vocational cycle.
0.2g NG	Refuse Hauler	#27	Chassis (WVU)	~0.7	Systemic	Systemic: Highest mileage HDV tested by WVU; emissions aftertreatment systems likely had age-related reduced NOx conversion efficiency. MY2012, 157k miles.
0.2g NG	School Bus	#18002	Chassis (UCR)	~1.6	Rare/Random	Rare/Random: No MIL, ECM codes or obvious mechanical deficiencies observed; high engine-out O_2 (sensor reading) during idling period; abnormal for spark-ignited natural gas engines, which use stoichiometric combustion. This is

Fuel & NOx Certification	**Application**	**HDV ID**	**Test (Lab)**	**NOx Levels (g/bhp-hr)**	**Outlier Cause Category**	**Observed Likely Causes**
						one of the 8.9L HDVs that was impacted CVS measurement system "artifact".
0.2g NG	Refuse Haulers	#18023 and #18117	Chassis (UCR)	~1.6	Rare/Random	Rare/Random: No MIL, ECM codes or obvious mechanical deficiencies observed; high engine-out O_2 (sensor reading) during idling period; abnormal for spark-ignited natural gas engines, which use stoichiometric combustion. This is one of the 8.9L HDVs that was impacted CVS measurement system "artifact".
0.2g NG	Refuse Hauler	#18013	Chassis (UCR)	~0.4	Rare/Random	Rare/Random: While not considered higher emitters, these two HDVs exhibited increased NOx emission rates during extended idling periods. These two were part of the 8.9L HDVs that was impacted CVS measurement system "artifact".
0.2g NG	Goods movement	#18045	Chassis (UCR)	~0.2	Rare/Random	Rare/Random: While not considered higher emitters, this HDV exhibited increased NOx emission rates during extended idling periods. This is one of the 8.9L HDVs that was impacted CVS measurement system "artifact".
0.02g NG	Goods movement	#18094	PEMS (UCR)	~0.44	Systemic	Systemic: Consistently higher emissions throughout testing day, even when catalyst temperatures were sufficiently high. Possible catalyst deterioration or other maintenance issue. MY2018, 100k miles.
0.02g NG	Goods movement	#94	PEMS (WVU)	~0.053	Systemic	Systemic: Increased idle NOx emissions rates during extended idle operation. 36% of total NOx mass emitted during single idle event that accounted for 16% of daily operation.
0.02g NG	Goods movement	#108	PEMS (WVU)	~0.147	Systemic	Systemic: Increased idle NOx emissions rates during extended idle operation. 54% of total NOx mass emitted during three idle events that accounted for only 4% of daily operation.
0.02g NG	Goods movement	#131	PEMS (WVU)	~0.315	Duty Cycle / Systemic	Duty Cycle: High idle time (70% of operation, ~50% during PTO use (at high engine idle speeds) to unload cargo; ~84% of total daily NOx mass emitted during 3 unloading events at idle (only ~15% of operational time) Systemic: One of 12L NG HDV that had increased idle NOx emissions during extended idle time.
0.02g NG	Refuse Hauler	#36	PEMS (WVU)	~0.36	Rare/Random	Rare/Random: Total daily NOx emissions increased by 59% due to low-fuel warning event before vehicle refueling. 59% of daily NOx mass emitted during single event that accounted for only 2.6% of daily operation.
0.02g NG	Goods movement	#96 and #130	Chassis (WVU)	~0.02	Systemic	Systemic: While not considered higher emitters, these two 12L NG HDVs exhibited increased NOx emission rates during extended idling periods.
0.02g NG	Transit Bus	#223	Chassis (WVU)	~0.15	Rare/Random	Rare/Random: Increased idle NOx emissions rates during extended idle operation. This is one of the 8.9L HDVs that was impacted CVS measurement system "artifact".

Fuel & NOx Certification	Application	HDV ID	Test (Lab)	NOx Levels (g/bhp-hr)	Outlier Cause Category	Observed Likely Causes
0.02g NG	Transit Bus	#18113, #18114, and #18115	Chassis (UCR)	~0.45	Rare/Random	Rare/Random: Excess emissions at idle (tailpipe emissions comparable to engine out), indicating extremely poor NOx reduction by three-way catalyst. There were part of the 8.9L HDVs that was impacted CVS measurement system "artifact".

***=Diesel HDVs that were outliers when fueled by RD as well as baseline ULSD.**

This table summarizes HDVs documented for higher-NOx emission events, using PEMS and/or chassis dynamometer testing. The last column categorizes these elevated in-use NOx emissions by the three broad conditions (Table 12) and discusses specific possible causes.

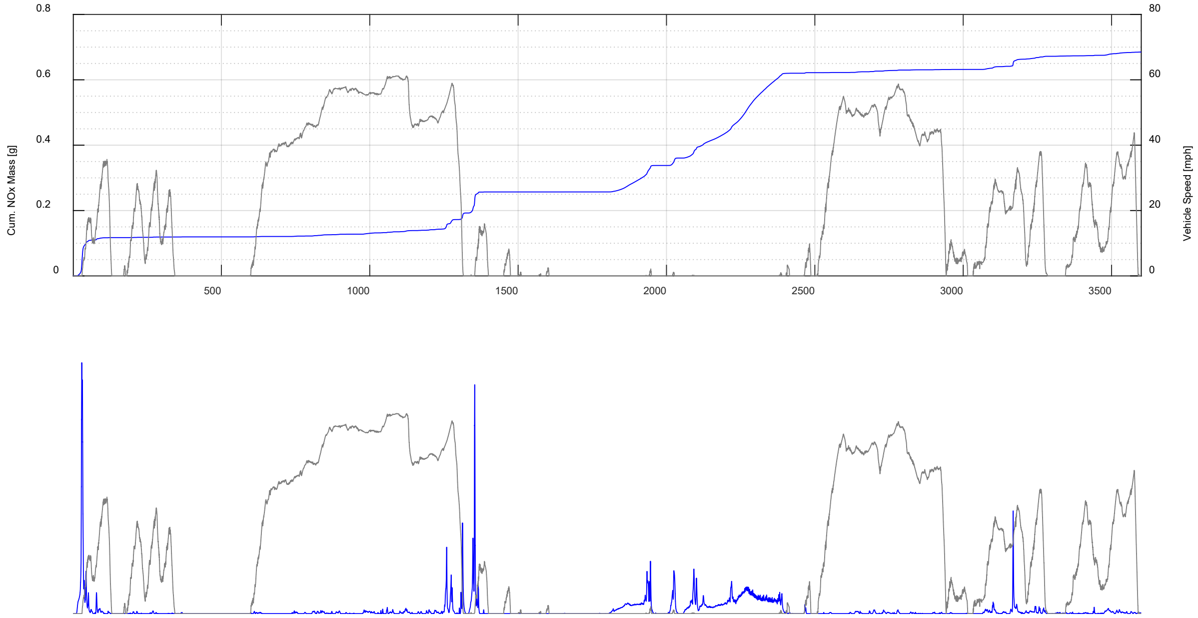
Sources: UCR and WVU

C.5 Elevated Idle NOx Phenomenon for NG HDVs

As mentioned earlier, due to the frequent occurrences, at first, the "high idle NOx emissions phenomenon" for the NG vehicles was categorized as a "systemic" behavior. Out of nearly 60 natural gas HDVs tested (0.2g and 0.02g NG), 15 HDVs, or approximately a quarter of the tested vehicles, exhibited a similar systemic increased NOx emission rates during idle operation in comparison to regular driving operation. Among them, three HDVs showed that behavior during on-road PEMS testing (all were 12L NG HDVs, see #108 example in Figure C-1), and the other 12 HDVs experienced the higher idle NOx emissions during chassis dynamometer testing. Note there is one 0.02g NG transit bus for which the same systemic high idle NOx issue was observed by both universities. The impacts of this systemic issue associated with idling varied among vehicles with different certification levels and engine displacements. For instance, for HDV #131, a 12L 0.02g NG good movement truck, the daily average NOx level was 0.315 g/bhp-hr, much greater than the in-use limit and NOx from idling events made up make than 84% of the daily average. When excluding the high idle NOx, the daily averaged NOx emissions dropped to 0.055g/bhp-hr, which was in the expected range for a 0.02g NG HDV during PEMS testing.

Between the 0.2g and 0.02g NG HDVs, whether 0.2 or 0.02 g/bhp-hr certification standards, there are also two sizes of the engine displacements (8.9L and 12L) manufactured by the same OEM. Even though the increased idle emission phenomenon was observed for both sizes of natural engines, there was a distinct difference in how the increased NOx emissions occurred between the two engine sizes. For the 8.9L natural gas engine, NOx emission rates increased almost immediately upon attaining idle operation on chassis cycles; but for the 12L natural gas engine, idle NOx emission rates only increased after a period of extended idle operation (see Figure C-4). After further analysis, for the 12L, it was found that the increased idle NOx emissions only occurred during goods movement cycle (GMC) after an extended idle operation for the chassis dynamometer testing and after long idle operation during PEMS testing. Unlike the 8.9L, the 12L did not have similar idle NOx issues during shorter idle periods, such as those in the UDDS cycle. For the 12L NG vehicles, since it occurred in a predictive manner, the high idle NOx issue was categorized as a systemic issue and included in Chapter 3 as part of the normal emissions signature.

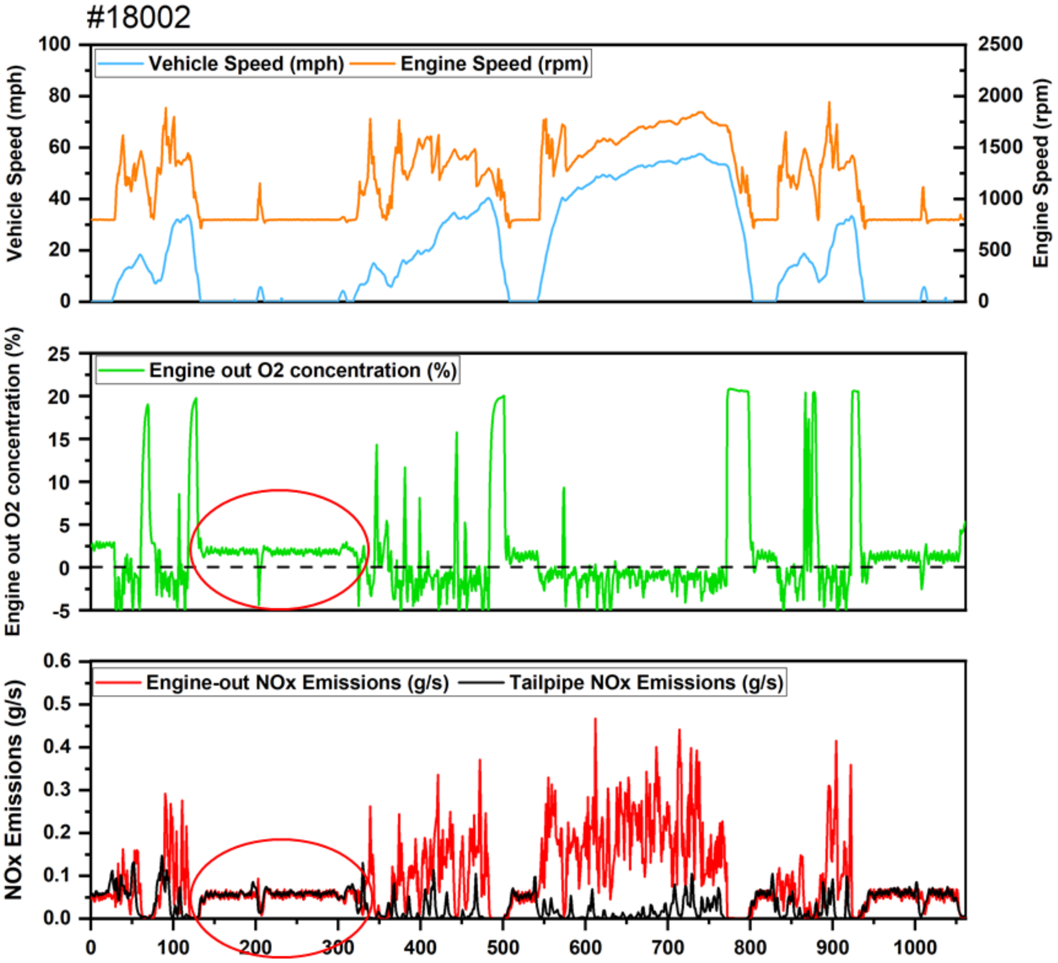
Figure C-4: NOx Mass Rate for a 12L 0.02g natural gas engine (vehicle 96), chassis dyno, goods movement cycle.



Source: WVU

For the 8.9L data, both universities analyzed various parameters during idle operation when increased NOx emissions occurred to look for a cause for the increase. Generally, for the vehicles where oxygen data was available, the oxygen levels during these higher idle periods were lean from an air-fuel ratio standpoint, which resulted in loss of efficiency of the TWC. These observations are illustrated in Figure C-5, which shows engine-out oxygen levels, engine-out NOx, and tailpipe-out NOx for one of the CNG vehicles that had this issue during testing. As circled in red, it’s evident that high idle NOx is associated with excess oxygen that led to poor NOx conversion.

Figure C-5: Real-time emissions and engine profile for UDDS cycle for vehicle #18002 (0.2g NG school bus).

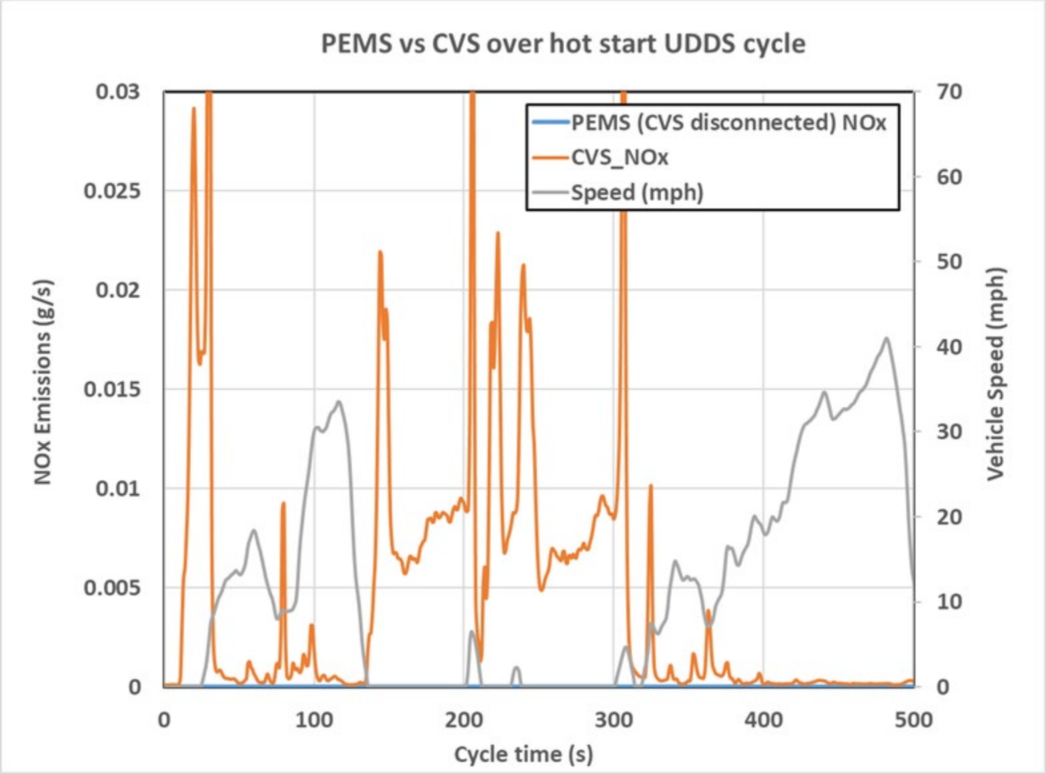


Source: UCR

The finding was reported to the project team as well as the engine manufacturer. The OEM attempted to evaluate this issue but was unable to replicate this issue on the 8.9L. As a follow-on study, South Coast AQMD provided additional funding to UCR to retest the 0.02g NG transit bus that was the inter-lab vehicle with the support of OEM and WVU. In August 2002, CNG transit bus #18114/#223 was brought back to UCR for retesting. The initial results for UDDS were able to replicate the high idle NOx issue. The subsequent retesting featured a number of tests included OEM's attempt to adjust the calibration as well as extensive lab checks. At one point during the retest, UCR's MEL was replaced by a PEMS for the emissions measurements, and unexpectedly the issue of high NOx spikes during idle was disappeared. This is most clearly demonstrated below in Figure C-6, which shows a close-up view of the first 500 seconds of the UDDS cycle where the PEMS was used, which illustrates that the high idle emissions were not observed, as opposed to during the tests with UCR's mobile lab's CVS system. Moreover, the OEM's engine data logs also indicated differences in downstream oxygen sensor readings, suggesting the possible ingress of ambient air prior the aftertreatment during the testing using the CVS sampling system. The project team suspected the fresh air ingress could have been caused by the vacuum from the CVS sampling, which might have resulted in a non-representative test condition. Subsequent data analysis of the

8.9L NG PEMS results, however, did not show any indication of ambient air ingress in the downstream oxygen sensor readings, or otherwise.

Figure C-6: NOx emissions and vehicle speed profile for UDDS hot start cycle between with/without CVS connection.



Source: UCR

To further identify the cause of this issue, a series of diagnostic tests were performed to evaluate the potential of CVS's ability to create a vacuum condition in the tailpipe. The vacuum at the tailpipe was measured as a function of CVS' tunnel flow rates. The results showed that the vacuum level increased with increasing CVS flow rates, the vacuum flow was measured up to 100 standard cubic feet per minute (scfm) while the engine was off. To investigate the possibility of any exhaust leakage, while running the CVS tunnel, UCR also performed a propane tracer test and confirmed inward flow at most of the exhaust connections/clamps prior the aftertreatment system. The tracer test confirmed possibility of fresh air ingress from suction of the CVS backpressure that caused higher oxygen sensor readings at the aftertreatment system and resulted in non-representative oxygen-rich exhaust conditions that prevented the TWC from eliminating NOx emissions. It should be noted that different CVS systems are designed to maintain different levels of back pressure. For example, WVU only observed the vacuum phenomenon in one 8.9L CNG vehicle but UCR observed this on eight out of ten vehicles tested. At the end of the retest, a best effort attempt was made to seal the leakage based on the propane tracer test results, one additional UDDS that was run showed idle NOx emissions had dropped significantly. This further confirmed that the inward leaks caused by CVS suction had a strong impact on the emissions results in the original sampling configuration.

Based on the results from the August 2022 retest, all the 8.9L CNG chassis dynamometer data were reevaluated to see if additional vehicles were significantly impacted by this sampling issue. The investigation identified five 8.9L 0.2 CNG vehicles (all from UCR testing) and four 8.9L 0.02 CNG vehicles (three from UCR and one from WVU) showed signs of relatively significant impacts from high idle emissions during the chassis dynamometer testing. The data for these nine vehicles were deemed unrepresentative of normal tailpipe emissions and it’s an “artifact” caused by the CVS measurement system. As such, they were categorized as rare/random outliers and excluded from the data results in Chapter 3. At the time of this report, additional analyses are being performed to further analyze and mitigate root cause of the measurement issue. Future study is being planned as well.

C.6 Potential Outward Leaks during In-Use Operation

Another consideration that should be mentioned based on the retest findings is the potential leaking in the opposite direction, i.e., outward, during high load operation where there are higher positive pressures in the pre-catalyst sections of the tailpipe. This phenomenon could be particularly impactful since the pollutants leaked out would be engine-out emissions that have not been reduced via the catalyst. It should also be noted that outward leaks can impact all types of combustion engines. The prevalence of outward leaks in the in-use fleet is beyond the scope of this study. It is suggested that additional work be conducted in this area to better understand the impact of potential outward exhaust leaks to air quality.