Staff White Paper

California Air Resources Board Staff Current Assessment of the Technical Feasibility of Lower NOx Standards and Associated Test Procedures for 2022 and Subsequent Model Year
Medium-Duty and Heavy-Duty Diesel Engines

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Mobile Source Regulatory Development Branch

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State of California
California Air Resources Board

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I. Background

Exposure to fine particulate matter (PM2.5) and ozone is associated with premature death, increased hospitalizations and emergency room visits due to exacerbation of chronic heart and lung diseases, and other serious health impacts. As a toxic air contaminant, diesel PM poses especially serious health risks.

Although California has made significant progress in improving air quality over the past five decades, over 12 million California residents still breathe unhealthy air. The South Coast still has the highest ozone levels in the nation while the San Joaquin Valley has the greatest PM2.5 challenge. The South Coast and San Joaquin Valley are the only two extreme ozone areas in the nation, with an attainment deadline of 2031.[1] The San Joaquin Valley's attainment dates for the 24-hour and annual PM2.5 standards are 2024 and 2025, respectively. The health and economic impacts of exposure to elevated levels of ozone and PM2.5 in California are considerable; meeting national ambient air quality standards will pay substantial dividends in terms of reducing costs associated with emergency room visits and hospitalization, lost work and school days, and most critically, premature mortality. Reductions in diesel PM will further reduce statewide cancer risk and non-cancer health effects, especially for residents living near major sources of diesel emissions such as ships, trains, and trucks, operating in and around ports, rail yards, and heavily traveled roadways.

To meet the 2023 and 2031 national ambient air quality standards for ozone, the South Coast Air Basin will require an approximate 70 percent oxides of nitrogen (NOx) reduction from today's levels by 2023 and 80 percent NOx reduction by 2031. Since NOx is also a precursor to secondary PM2.5 formation, reductions in NOx emissions will also provide benefits for meeting the PM2.5 standards.

Heavy-duty trucks over 10,000 pounds gross vehicle weight rating (GVWR) are significant contributors to the formation of ozone, PM2.5, and diesel particulate matter emissions in California. For example, they are responsible for over 70 percent of NOx emissions from on-road mobile sources.[2] Exacerbating the challenge of cutting overall emissions, the number of vehicles and associated vehicle miles traveled have been continuously increasing each year. In order to meet California's air quality goals, despite the progress made, further reductions of heavy-duty truck NOx emissions are necessary.

The California Air Resources Board's (CARB or Board) strategy in reducing emissions from heavy-duty vehicles relies on a multipronged approach of regulatory and voluntary incentive programs that include establishing emissions and performance standards for new vehicles and engines, setting mandates and sales requirements for advanced

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[1] The South Coast attainment dates are 2023 for the 80 ppb 8-hour ozone standard, and 2031 for the 75 ppb 8-hour ozone standard. 2008 National Ambient Air Quality Standards (NAAQS) for Ozone (https://www.epa.gov/ground-level-ozone-pollution/2008-national-ambient-air-quality-standards-naaqs-ozone)

[2] Estimate based on 2019 calendar year heavy-duty vehicle inventory: CEPAM: 2016 SIP - Standard Emission Tool (https://www.arb.ca.gov/app/emsinv/fcemssumcat2016.php)

technologies, developing pilot programs, and implementing incentive and other programs to accelerate technology deployment (see Figure 1). In order to meet our air quality goals and GHG emission and petroleum use reduction targets, CARB is aiming to encourage the use of zero emission vehicles and equipment where possible, while simultaneously ensuring conventional technologies are as low-emitting as feasible. CARB has already approved the Innovative Clean Transit Regulation, for example, which requires public transit agencies to gradually transition to 100 percent zero-emission bus fleets by 2040.[3] Staff is also in the process of developing proposals for new heavy-duty vehicle strategies to achieve the transition from conventional combustion technologies to zero emission technology for vehicle applications that are best suited for zero emission technology.[4] The Heavy-Duty Low NOx program,[5] which is the subject of this white paper, is part of CARB's overall strategy to establish more stringent emission standards and in-use performance requirements to reduce emissions from heavy-duty combustion technologies. Together, these approaches are designed to achieve progressively cleaner in-use fleet emission levels.

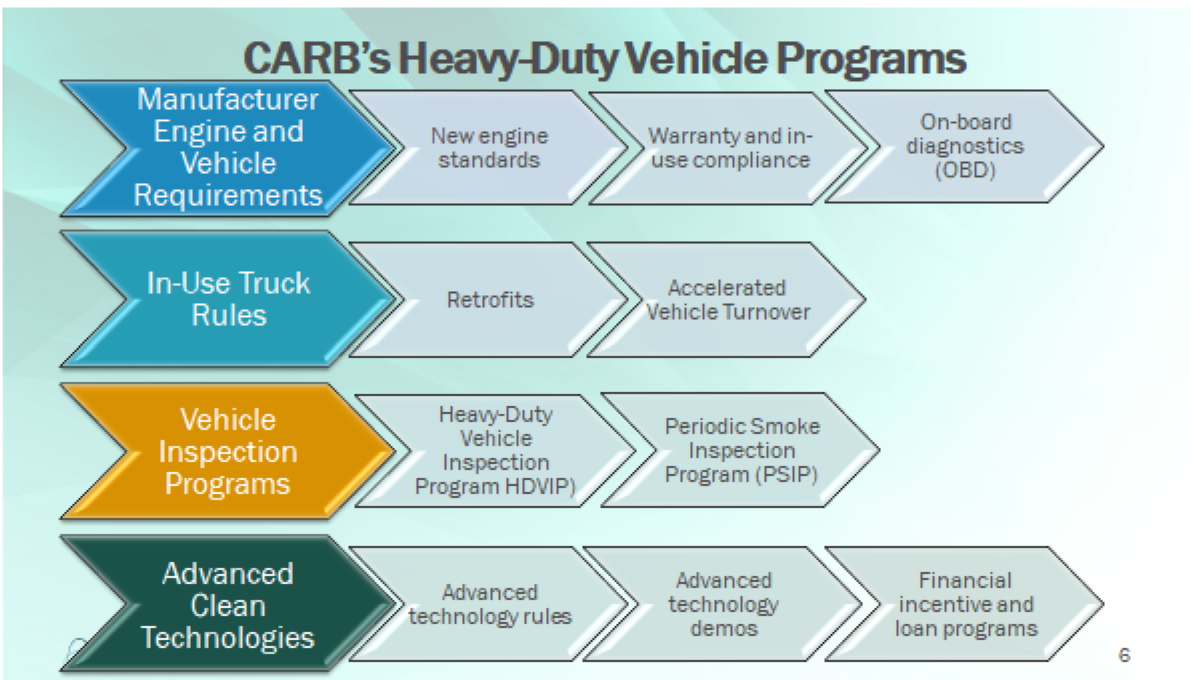

Figure 1 – CARB's Heavy-Duty Vehicles Programs

Over the last three decades, NOx and PM emission standards for heavy-duty on-road engines have become more stringent. For NOx, the standard has decreased from 6.0 grams per brake horsepower hour (g/bhp-hr) in 1990 to the current 0.20 g/bhp-hr standard in 2010. For PM, the standard has decreased from 0.6 g/bhp-hr in 1990 to 0.01 g/bhp-hr in 2010. In addition to the increasingly stringent standards, California has also adopted programs that provide substantial in-use emissions reductions such as

[3] Innovative Clean Transit program webpage: https://www.arb.ca.gov/msprog/ict/ict.htm
[4] Advanced Clean Truck program webpage: https://ww2.arb.ca.gov/our-work/programs/advanced-clean-truck
[5] Heavy-Duty Low NOx program webpage: https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm

vehicle idling restrictions and in-use fleet rules, including the Drayage Truck Regulation and the Truck and Bus Regulation. These fleet rules require the upgrade of older trucks and buses to newer, cleaner engines meeting the 2010 standards by 2023. To comply with these regulations, fleets have made substantial investments to purchase lower-emitting vehicles.

In 2013, CARB established optional low-NOx standards with the most stringent optional standard being 0.02 g/bhp-hr, which is a 90 percent reduction from the current standard. The optional low-NOx standards were developed to encourage the development of cleaner engines and improved emission control systems, paving the way for setting future standards. In addition, incentive programs were developed to further encourage the development of advanced engine and aftertreatment systems and, to-date, 10 natural gas or liquefied petroleum gas engines have been certified to the 0.02 g/bhp-hr optional NOx standard.

In March 2017, the Board approved the 2016 State Strategy for the State Implementation Plan (SIP).[6] One of the key measures in the SIP is the establishment of on-road heavy-duty low-NOx engine emission requirements that would provide a 90 percent reduction in NOx emissions compared to today's engines. To complement this measure, the SIP also included a "Lower In-Use Emission Performance Level" measure that would ensure that heavy-duty vehicles remain "clean" in-use, as they were originally certified when new. These two measures are critical for attaining federal health-based air quality standards for ozone in 2031 in the South Coast and San Joaquin Valley air basins, as well as PM2.5 standards in the next decade.

Because trucks that were newly purchased outside of California accrue about 60 percent of total heavy-duty vehicle miles traveled in the South Coast on any given day, it is critical that the U.S. Environmental Protection Agency (U.S. EPA) take action to establish a new national low-NOx standard for heavy-duty trucks.[7] In response to petitions for a low-NOx rulemaking from over 20 organizations, including state and local air agencies from across the country, on November 13, 2018, U.S. EPA announced the "Cleaner Trucks Initiative" to develop regulations to further reduce NOx emissions from on-road heavy-duty trucks and engines. U.S. EPA intends to publish a proposed rule in 2020.[8]

Staff has been working on developing new significantly lower NOx emission standards and other strategies to implement the SIP measures described above. Specifically, the proposed changes include development of new NOx emission standards on existing certification cycles such as the Federal Test Procedure (FTP) and the Supplemental Emission Test Ramped Modal Cycle (RMC-SET); the development of a new certification

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[6] Proposed 2016 State Strategy for the State Implementation Plan. May 17, 2016 (https://www.arb.ca.gov/planning/sip/2016sip/2016sip.htm)

[7] https://www.epa.gov/regulations-emissions-vehicles-and-engines/petitions-revised-nox-standards-highway-heavy-duty
https://www.epa.gov/sites/production/files/2016-12/documents/additional-petitioners.pdf

[8] EPA Acting Administrator Wheeler Launches Cleaner Trucks Initiative. https://www.epa.gov/newsreleases/epa-acting-administrator-wheeler-launches-cleaner-trucks-initiative

low load cycle (LLC) and associated NOx emission standard; revisions to the Not-to-Exceed (NTE) Heavy-Duty In-Use Testing (HDIUT) program; lengthening the useful life and warranty periods; clarifications to warranty corrective action provisions; and revisions to the durability demonstration procedures. Staff is preparing to bring a proposal to the Board for a comprehensive well-integrated Heavy-Duty Low NOx rule incorporating all the aforementioned elements, referred to as the "Heavy-duty Low NOx Omnibus Rulemaking," in the first quarter of 2020.

To support the development of these new requirements, CARB, in partnership with the South Coast Air Quality Management (SCAQMD), U.S. EPA, and the Manufacturers of Emission Controls Association (MECA) has been funding several research programs with Southwest Research Institute (SwRI) to demonstrate the feasibility of lower NOx emissions from on-road heavy-duty engines. The results from Stage 1[9] of the SwRI program were published in April 2017 and helped inform staff's feasibility assessment for model year (MY) 2024. The final results from Stages 2 and 3 of the SwRI research program are expected to become available during the third or fourth quarter of 2019. Stage 2 is a continuation of the Stage 1 program and its objectives include the development of an LLC (potentially to be used as a certification cycle), optimization of the Stage 1 engine-aftertreatment system (EAS) under low load operations, and development of in-use measurement metrics under low loads. Stage 3 is a low NOx demonstration program using a newer model engine and includes optimization of an EAS under the certification and vocational cycles including the low load cycles developed in Stage 2. Stages 2 and 3 will help inform staff regarding the feasible level of emissions standards for the FTP, RMC-SET, and LLC, and the heavy-duty in-use testing program applicable for 2027 and subsequent MY engines.

Historically, it has been assumed that the establishment of laboratory emission standards and manufacturer compliance with those standards would result in emission reduction trends in the real world. However, as CARB staff has investigated over-the-road emissions with the use of Portable Emissions Measurement Systems, tallied emission warranty claims reflective of non-durable parts, and examined the effectiveness of current processes and test procedures to implement the heavy-duty emission standards over the past several years, it has become clear that the expected emissions reductions from the adoption of our laboratory emissions standards have not been fully realized in the real world. Although the actual emission rates of engines in the field will always vary depending on the specific duty cycle of the engine, adding a new LLC to the already existing FTP and RMC-SET requirement will provide certification test results that more accurately capture the range of real-world activity. In addition, CARB must shore up implementation and compliance programs to ensure the total emission benefits envisioned with a laboratory based certification emission standards are attained and reflected in real world emission performance. Thus, the potential regulatory elements described in this paper extend beyond just a proposed certification emission standard.

[9] Sharp, C.A., Webb, C.C., Neely, G.D, Smith, I., "Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles", Southwest Research Institute (SwRI) Project No. 19503 Final Report (2017). (https://www.arb.ca.gov/research/single-project.php?row_id=65182)

During the last several years, staff has been reaching out to stakeholders by holding workshops, workgroup meetings, meetings with industry associations and individual one-on-one meetings with engine manufacturers and technology providers. Since November 2016, CARB has held two public workshops and five workgroup meetings. Furthermore, staff met with the heavy-duty industry's Truck and Engine Manufacturers Association (EMA) and individually with the major engine manufacturers multiple times to discuss the planned rulemaking, seek their input, and listen to their overall concerns. At the workgroup meetings and the most recent January 2019 workshop, CARB staff presented to stakeholders detailed concepts on several of these regulatory elements such as changes to the HDIUT program, new durability demonstration procedures, and lengthened useful life and warranty periods.

II. Purpose of this White Paper

The main objective of this white paper is to outline staff's assessment regarding technical feasibility and cost effectiveness of possible NOx reduction programs for 2022 and subsequent MY diesel medium-duty and heavy-duty engines.[10] Although some elements of the Heavy-duty Low NOx Omnibus Rulemaking will affect medium-duty and heavy-duty Otto cycle engines as well, this white paper focuses solely on an assessment for diesel engines.

During recent meetings, many engine manufacturers indicated that they are in the process of settling on engine design and development plans to meet the 2024 MY Phase 2 greenhouse gas (GHG) requirements.[11] They further indicated that, in order to accommodate NOx reductions on the same hardware platform, engine manufacturers have requested feedback in terms of staff's thinking for any nearer term (2022-2023 MY) amendments to existing programs as soon as possible. They have repeatedly emphasized the need for sufficient product development time to incorporate NOx requirements along with the Phase 2 GHG requirements. This white paper is intended to provide a technical response to these requests.

It is important to emphasize that this white paper is strictly staff's current assessment of what is currently considered as technically achievable and cost effective for 2022 and subsequent model years. As additional and/or updated technical information becomes available between now and the Board hearing date, and because the Board has the ultimate authority to accept, reject, or change staff's proposal as it sees fit, this white

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[10] This white paper is applicable only to heavy-duty and medium-duty engines certified through Title 13, California Code of Regulations, Section 1956.8. It covers engines for use in vehicles over 10,000 pound gross vehicle weight rating (GVWR).

[11] The Phase 2 standards for medium- and heavy-duty engines and vehicles are implemented in three steps: 2021, then 2024, and then 2027. See California Greenhouse Gas Emissions Standards for Medium- And Heavy-Duty Engines and Vehicles (Phase 2) (https://www.arb.ca.gov/msprog/onroad/caphase2ghg/caphase2ghg.htm)

paper cannot predict with certainty what CARB will ultimately adopt in its Heavy-duty Low NOx Omnibus Rulemaking.

III. CARB Staff Assessment

Based on a survey of current baseline engine certification emission levels and CARB co-sponsored research programs, staff is considering a three-step phase-in for the low NOx program. In order to minimize the burden on product development cycles, staff believes synchronizing the implementation dates for the low NOx regulations with the Phase 2 GHG implementation dates would be advantageous. These three steps are described in detail below.

Step 1 (2022-2023 MY)
The key components of Step 1 are outlined in Table 1 below. Step 1 mainly involves changing the limits on the carve-out regions for the NTE method, and the requirement to perform HDIUT emission calculations and report the data using the modified Euro VI(D) method.

Staff believes that, based on current NOx control technologies implemented on 2010 and later MY engines and the universal availability of ultra low sulfur diesel fuel, several of the existing carve-outs in the NTE are antiquated, unnecessary and hence feasible to remove for MY 2022 and later. Staff also believes it is feasible for manufacturers to begin performing HDIUT emission calculations and reporting the data using the modified Euro VI(D) method, which is based on a moving average window (MAW) approach.[12]

Staff is also planning to revise the regulatory language for the Emission Warranty Information Reporting program to further clarify existing CARB requirements and accelerate the timeline for corrective action when emissions problems are found.

Step 2 (2024-2026 MY)
Table 2 provides a summary of the Step 2 program elements. Staff believes that all of the requirements in Step 2 can be met without the introduction of any major engine hardware changes, but they would likely require changes to engine calibration and the emission aftertreatment system.

Staff believes a reduction to the NOx and PM emissions standards is feasible, along with the introduction of a new certification LLC in Step 2. A reduction of the clean idle NOx standard and adoption of the modified MAW-based Euro VI(D) program for HDIUT are also considered feasible in this timeframe.

Other programmatic changes include the requirement for full useful life (UL) aging of engine and aftertreatment systems for durability demonstration, with the option to use

[12] Compliance determinations during this period will be based on the current NTE method with minor modifications to the carve-out region and limits.

accelerated aftertreatment aging for a portion of useful life. Staff also believes the periodic submittal of NOx sensor data from in-use vehicles is feasible and would be helpful in order to evaluate a future alternative durability program that relies on a combination of dynamometer aging, accelerated aftertreatment aging, and NOx sensor reporting. The objective of the alternative durability program would be to reduce upfront certification durability requirements and rely more on reporting of in-use data. The periodic NOx sensor reporting from Step 2 would be essential in validating any future alternative durability programs.

Finally, CARB and U.S. EPA have historically endeavored to harmonize their emissions requirements for heavy-duty engines, in recognition of the fact that such harmonization allows the industry to design and produce a single set of engines for use throughout the nation. If such harmonization is not possible, there may be a need for California to establish a California-only bank for emission credits. If so, there would be restrictions and sunset provisions included in the California-only bank.

It should be noted that 2024-2026 MY low NOx implementation dates would coincide with the second part of Phase 2 GHG implementation dates. This would allow the engine manufacturers to introduce the necessary calibration and hardware changes for low NOx and GHG simultaneously.

Step 3 (2027 and subsequent MYs)
A summary of potential Step 3 requirements is provided in Table 3 below. Staff believes that the future emission standards in Step 3 would likely require the introduction of engine hardware upgrades, but the 2027 MY implementation date would provide sufficient lead-time for product development and design.

At this point, it is essential to note that staff does not have sufficient data to provide specific details on what may be technically achievable and cost effective in 2027 and subsequent model years. Key inputs to the proposal for MY 2027 and beyond are anticipated to become available from the ongoing heavy-duty NOx demonstration program underway at the SwRI.

Although specific details are not currently available, CARB plans to introduce another set of more stringent NOx emissions standards applicable for 2027 and subsequent MYs, as well as further enhancements to the in-use testing program, warranty, and useful life requirements. Once again, it should be noted that the final Phase 2 GHG implementation dates and Step 3 implementation dates are synchronized to reduce the burden on product development.

Table 1 – CARB Staff Assessment of Feasible Standards and Requirements for MY 2022 and 2023

2022 and 2023 MY Engines Assessment (Heavy-Duty and Medium-Duty Engines for > 10,000 pounds GVWR)	
NOx Standards	Existing FTP, RMC-SET and idling standards
HDIUT	1) Continuing with current NTE method with the following changes: - Modify Cold Temperature Operation - Ambient Temperature Exclusion ≤ 7°C 2) Reporting of all data including a compliance evaluation report required by the modified moving average window-based Euro VI(D)[13] method planned for 2024 MY engines. Compliance determinations would be based on the NTE method (see also Appendix 1b)
Durability Demonstration Program	CARB certification staff continuing to work individually with manufacturers and EMA on issues related to their durability demonstration programs.
Emission Warranty Information Reporting (EWIR)	1) Basing the need for corrective action solely on warranty claim rates 2) Adding compliance with EWIR and corrective action as a condition under which the Executive Order is granted to help ensure expeditious action by the manufacturer 3) Other clarifying items as discussed in the workshop presentation of 1/23/2019 (See Appendix 2 for presentation slides)

[13] COMMISSION REGULATION (EU) No 582/2011, May 25, 2011 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02011R0582-20180118&from=EN); and COMMISSION REGULATION (EU) 2018/932, June 29, 2018 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0932&from=EN)

Table 2 – CARB Staff Assessment of Feasible Standards and Requirements for MYs 2024 through 2026

2024 through 2026 MY Engines Assessment (Heavy-Duty and Medium-Duty Engines for > 10,000 pounds GVWR)	
NOx standards	1) 0.05 to 0.08 g/bhp-hr NOx on the FTP and RMC-SET 2) (1 to 3) x FTP = (0.05 to 0.24 g/bhp-hr) NOx on the LLC[14] 3) 10 g/hr NOx idling standard (controlled within 5 minutes of cold start)
PM standards	0.005 g/bhp-hr PM on the composite FTP and RMC-SET
HDIUT	1) Compliance based on modified moving average window-based Euro VI(D) method (replacing current NTE method) (See Appendix 1a) - Conformity factor: 1.5 - In-use threshold: 1.5 x FTP Standard - Regular customer route - Pre-approval of test plan: operation type, location, etc. - Manufacturer could invalidate test day if over 50% of windows are below 10% of engine's peak power. Retest until a valid test day is completed 2) Pilot program to demonstrate how the collection and reporting of on-board diagnostic data (e.g., Real Emissions Assessment Logging (REAL) data) could be used as an alternative compliance option.
Durability Demonstration Program	Three options: 1) Full UL EAS aging with defined cycles on an engine dynamometer (see Appendix 3 for further detail). 2) ½ UL aging of EAS on engine dynamometer using defined cycles, followed by ½ UL aging of aftertreatment system using the Diesel Aftertreatment Accelerated Aging Cycle (DAAAC) protocol. This option would only be applicable for heavy heavy-duty diesel (HHDD) engines and would require periodic NOx sensor reporting (see Appendix 3 for further detail). 3) Full UL aging of EAS using accelerated aging protocols under development jointly by CARB, U.S. EPA and EMA. This option would require periodic NOx sensor reporting.
Averaging, Banking and Trading Credits	1) Termination of all pre-2010 MY generated credits 2) Expiration of post-2010 MY credits after 5 years 3) Potential establishment of California-only credit bank

[14] Staff evaluated various candidate LLCs and are considering using LLC candidate #7 as a certification cycle. For a discussion of the LLC development, please refer to Appendix 4, Heavy-Duty Low NOx Program Workshop - Low Load Cycle Development Presentation. January 23, 2019 (https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm) (See Appendix 4 for slides)

Table 3 – CARB Staff Assessment of Feasible Standards and Requirements for MYs 2027 and later

2027 and Subsequent MY Engines Assessment (Heavy-Duty and Medium-Duty Engines for > 10,000 pounds GVWR)	
NOx standards	-0.0x g/bhp-hr NOx on the FTP and RMC-SET -FTP, RMC-SET, LLC, and Idling standards to be determined based in part on results from SwRI Stage 3 Low NOx Demonstration program.[15]
PM standards	0.005 g/bhp-hr PM on the composite FTP and RMC-SET
HDIUT	1) Compliance based on modified Euro VI(E) method (See Appendix 1a) - Conformity factor: 1.5 - In-use threshold: 1.5 x FTP Standard - Power threshold: down to idle - Include cold start emissions in the compliance determination - Regular customer route - Pre-approval of test plan: operation type, location, etc. - Manufacturer could invalidate test day if over 50% of windows are below 10% of engine's peak power. Retest until a valid test day is completed 2) Possible alternate compliance option based upon completion of a successful pilot program using NOx sensor data such as those collected using REAL or other metrics (depending on NOx sensor technology development)
Durability Demonstration Program	Possible initiation of an alternate durability program upon successful completion of the 2024-2026 MY pilot program. Program could rely on NOx sensor reporting combined with some dynamometer aging and/or accelerated aftertreatment aging.
Averaging, Banking and Trading Credits	Continuing the MY 2024-2026 program
Useful Life & Warranty	For all engine classes: - Lengthen useful life and Warranty (Step 2) (specific lengths to be determined)

[15] 0.0x indicates that the staff is still evaluating the appropriate level of the standard, i.e., the x in 0.0x is still to be determined.

IV. Data and Sources Used in CARB Staff Assessment

In October 2015, CARB released technology assessment reports[16] that discussed the various engine calibration and aftertreatment strategies that could be employed to significantly reduce NOx emissions from heavy-duty engines. One assessment found that emissions from heavy-duty diesel engines can be significantly reduced utilizing a systems approach combining advanced aftertreatment systems with engine management strategies. For diesel engines, the report concluded that an engine meeting an optional NOx standard of 0.10 g/bhp-hr on the FTP could likely be certified within a year or two of the release of the document. This conclusion was based on (1) an assessment by one engine manufacturer that stated a 0.1 g/bhp-hr NOx standard on the FTP can be achieved with improvements to the current selective catalytic reduction (SCR) system, and (2) the low certification levels of some late model engine families. However, the report also concluded that reducing NOx further to the 0.02-0.05 g/bhp-hr levels and simultaneously reducing GHG emissions would require more development time and significant improvements in engine combustion efficiency, thermal management strategies, and advanced aftertreatment technologies.

As mentioned above, CARB is currently funding research projects with SwRI to demonstrate feasibility of low NOx emissions from on-road heavy-duty engines. There are three main stages of the SwRI low NOx research program referred to as Stages 1, 2 and 3 and 2 supplemental contracts referred to as SwRI Stages 1b and 3b. A Program Advisory Group representing engine manufacturers, aftertreatment suppliers, together with local and national regulatory agencies has been formed to consult SwRI at critical decision points including selecting aging protocols, hardware configurations, and low load challenge conditions.

The Stage 1 project[17] involved development work on both a 2012 MY 12-liter Cummins natural gas engine and 2014 MY 13-liter Volvo diesel engine with a target NOx emission rate of 0.02 g/bhp-hr on the FTP and RMC-SET test cycles. The Stage 1 project was a $1.6 million project funded by CARB with support from MECA, SwRI, and Volvo, which was completed in April 2017. This development work achieved a 0.01 g/bhp-hr NOx over the FTP and a 0.001 g/bhp-hr NOx level over the RMC-SET on the Cummins natural gas engine. Several natural gas and propane engines from 6 to 12 liters are currently commercially available meeting the CARB Optional Low NOx standard of 0.02 g/bhp-hr. In addition, the Volvo diesel engine achieved a 0.034 g/bhp-hr NOx level over the FTP and a 0.038 g/bhp-hr NOx level over the RMC-SET (the baseline NOx levels were 0.14 g/bhp-hr on the FTP and 0.08 g/bhp-hr on the RMC-SET). These results were achieved on full useful life aged advanced aftertreatment systems. The results for the diesel engine did not achieve the target NOx emission rate of 0.02 g/bhp-

[16] (1) CARB, Draft Technology Assessment: Lower NOx Heavy-Duty Diesel Engines, September 29, 2015
(2) CARB, Draft Technology Assessment: Low Emission Natural Gas and Other Alternative Fuel Heavy-Duty Engines, September 29, 2015. (https://ww2.arb.ca.gov/resources/documents/technology-and-fuels-assessments)

[17] Sharp, C.A., Webb, C.C., Neely, G.D, Smith, I., "Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles", Southwest Research Institute (SwRI) Project No. 19503 Final Report (2017). (https://www.arb.ca.gov/research/single-project.php?row_id=65182)

hr. However, the results were encouraging because despite this engine having a very challenging turbocompounding system which greatly cooled the exhaust and hence made NOx control harder, and despite a mechanical failure of the metal housing surrounding the catalyst substrate and the supporting mat (i.e., a canning failure) during the full useful life (435,000 miles) aging procedures, emissions were significantly reduced. The failure could have been prevented by a properly designed catalyst housing system. Overall, carbon dioxide (CO_2) emissions over the FTP test cycle increased by about 2.5 percent and over the RMC-SET by about 1.6 percent. The optimized EAS was also tested on vocational cycles such as the New York Bus Cycle (NYBC), the Cruise-Creep Cycle, and the Orange County Bus cycle (OCTA). Even though the diesel aftertreatment system was not optimized on these vocational test cycles, tailpipe emissions were significantly reduced due to the engine optimization on the FTP and RMC-SET with the advanced aftertreatment systems. Compared to baseline emissions testing, NOx emissions were reduced by 66 percent on the NYBC and by 52 percent on the OCTA cycle. CO_2 emissions were reduced by about 2 percent on the NYBC while on the OCTA cycle CO_2 emissions increased by 2.6 percent.

In addition to NOx emissions, Stage 1 also measured other criteria pollutant emissions to assess how these pollutants were impacted due to low NOx optimization/calibration and the selected advanced aftertreatment systems. Specifically, on the Volvo diesel engine, PM emissions levels remained low for the baseline engine system as well as the optimized EAS. Baseline emissions were 0.001 g/bhp-hr on the FTP and 0.002 g/bhp-hr on the RMC-SET. For the optimized engine with the advanced aftertreatment system, PM emissions were about 0.0007 g/bhp-hr on the FTP and 0.0002 g/bhp-hr on the RMC-SET.

The abnormal canning failure of the diesel engine aftertreatment system led CARB and other stakeholders to launch the Stage 1b project, currently in progress. It involves aging of a second set of identical Stage 1 aftertreatment components in order to assess the impact of the canning failure and to determine the effect of normal degradation on the aftertreatment system. Stage 1b is a $480,000 project funded by SCAQMD with support from MECA.

The Stage 2 project involves the development of a new LLC, which also involves further optimization of the Stage 1b diesel engine and aftertreatment system on vocational cycles and the developed LLC. This is needed because emissions from modern diesel engines are significant at low load operations. As shown in Figure 2, although vehicle miles traveled at low speed (and hence low load) represent less than 10 percent of the miles traveled, the NOx emissions from such operation are expected to constitute half of all emissions by 2030. This is because current SCR systems are inactive at low loads and low exhaust temperatures. Also, SwRI will benchmark the accuracy of estimated power information from late model diesel engines and evaluate other load measurement metrics for improving the in-use testing methods for determining emissions accuracy at low engine power conditions. Development of candidate LLCs has been completed and released for stakeholder feedback. Final LLC selection, system optimization, and development of low load measurement metrics are currently in progress. The project is expected to be finalized by late April 2019. Stage 2 is a $1.05 million project funded by CARB with support from Volvo and MECA.

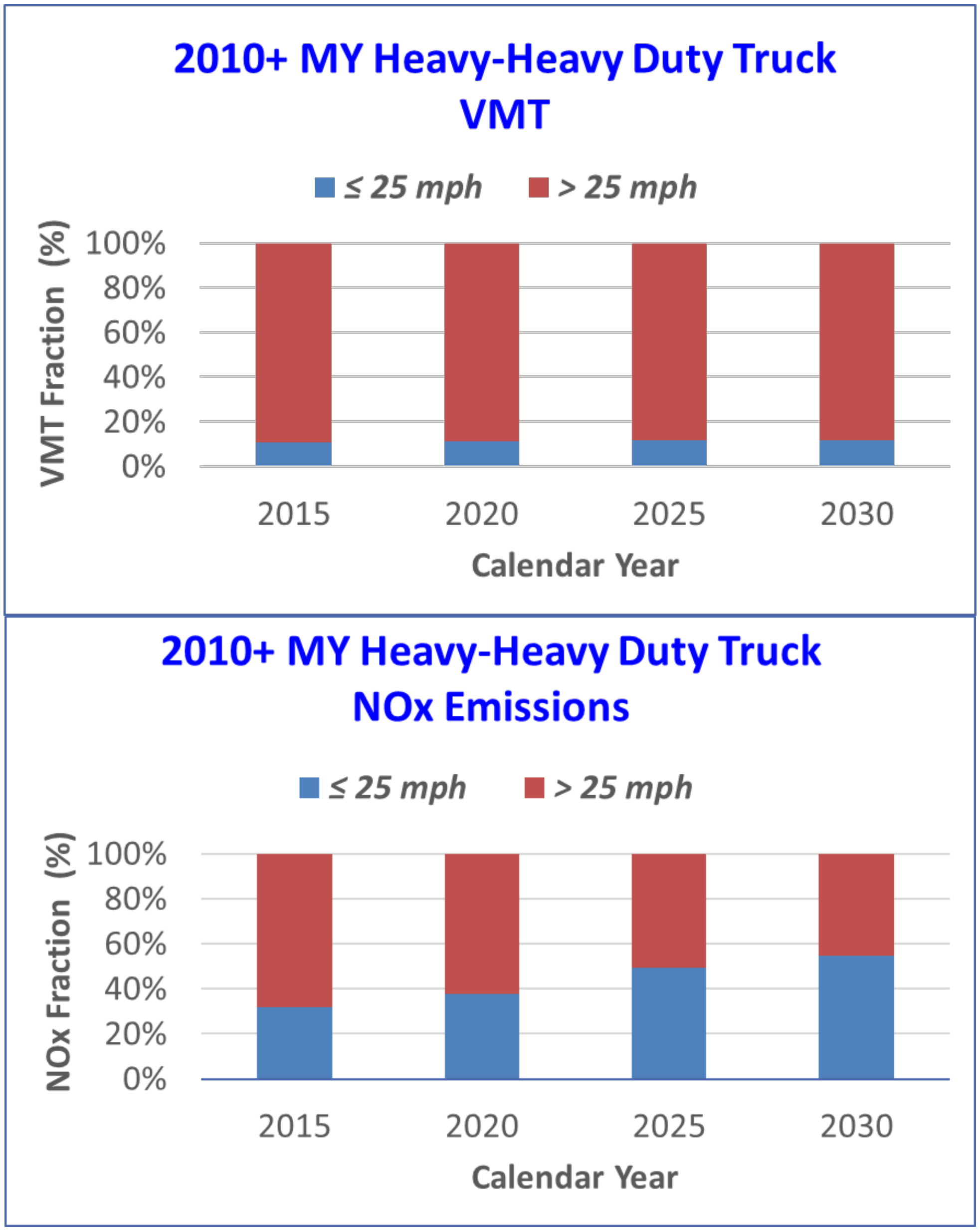

Figure 2 - NOx emissions from low-speed operation to become increasingly significant, due to SCR inefficiency at low loads[18]

Stage 3 involves evaluation of a more recent 2017 MY 15-liter Cummins diesel engine by optimizing/calibrating the engine and advanced emissions aftertreatment systems. The objective is to demonstrate low NOx technologies to achieve a target NOx emission

[18] Seungju Yoon et al., High In-Use NOx Emissions from Heavy-Duty Diesel Trucks Equipped with SCR Systems and Their Impact on Air Quality Planning in California. TRB paper #17-02027.

rate of 0.02 g/bhp-hr NOx on the FTP and RMC-SET, with simultaneous optimization of an EAS on vocational cycles and the selected LLC candidate developed in Stage 2. Stage 3 is a $1.375 million project funded by CARB, SCAQMD, and the Port of Los Angeles, with support from Cummins Incorporated and MECA.

Stage 3b is a $750,000 project funded by U.S. EPA, MECA, and the Clean High-Efficiency Diesel Engine VII) Consortium (which is managed by SwRI). It is a supplement to Stage 3, and it involves adding engine hardware technologies designed to reduce GHG emissions and improve the performance capabilities of advanced aftertreatment systems when engines operate under sustained low loads. Engine hardware to be investigated include cylinder deactivation, charge air cooler bypass, exhaust gas recirculation (EGR) cooler bypass, turbocharger bypass, and exhaust manifold insulation. Stages 3 and 3b are expected to be finalized in the 4th quarter of 2019.

Staff also looked at emission certification levels of current CARB certified heavy-duty engines. As shown in Figures 3 to 5 below, PM certification levels for the majority of heavy-duty diesel engines are below 0.005 g/bhp-hr on the FTP and RMC-SET. A small percentage of the light heavy-duty diesel and some natural gas engines, however, have PM certification levels between 0.005 and 0.01 g/bhp-hr on the FTP and RMC-SET.

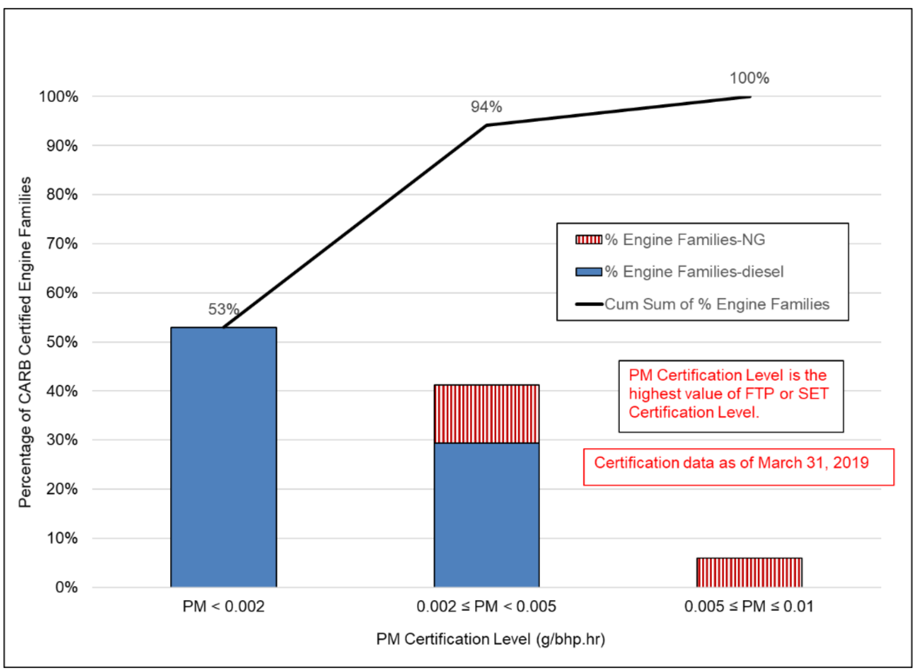

Figure 3 - PM emission certification levels for CARB certified 2019 MY heavy heavy-duty engines (GVWR > 33,000 pounds)

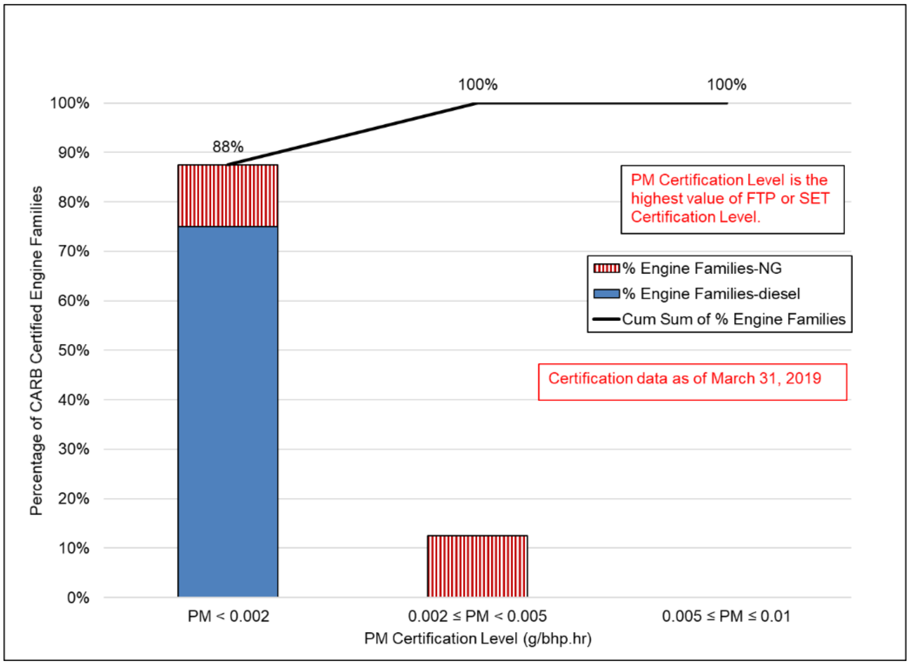

Figure 4 - PM emission certification levels for CARB certified 2019 MY medium heavy-duty engines (GVWR: 19,501-33,000 pounds)

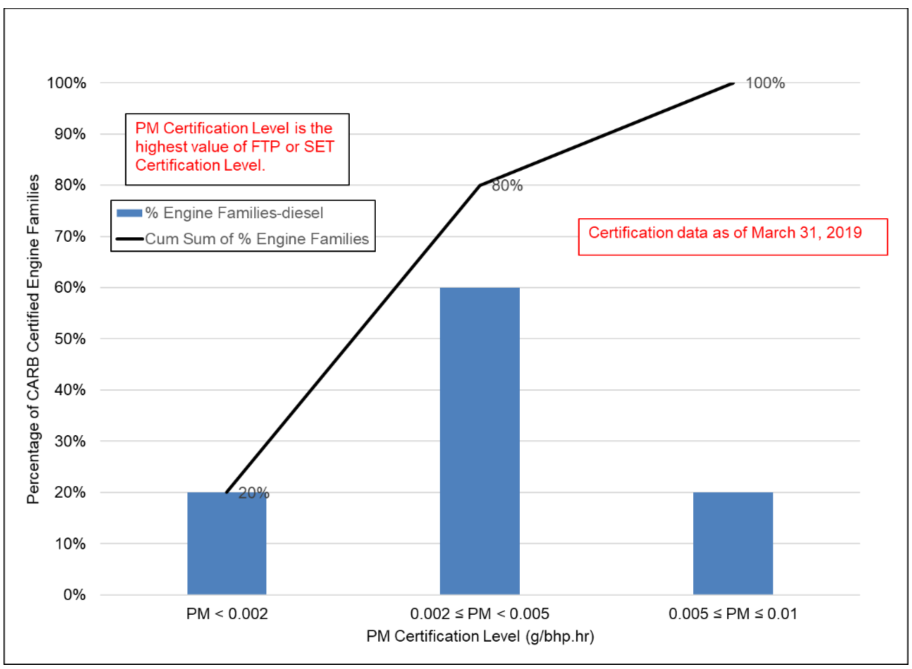

Figure 5 - PM emission certification levels for CARB certified 2019 MY light heavy-duty engines (GVWR: 14,001-19,500 pounds)

Similarly, Figures 6 through 8 show NOx emissions certification levels for current CARB certified heavy-duty engines. The charts show that many engine families have certification levels below 0.1 g/bhp-hr NOx with associated CO_2 emission levels below the 2027 MY Phase 2 GHG standards. Some of the heavy heavy and many of the medium and light heavy-duty engines have NOx certification levels close to the certification standard with associated CO_2 certification levels higher than the 2024 MY Phase 2 GHG standards, indicating the need for more development work to reduce both NOx and GHG emissions simultaneously.

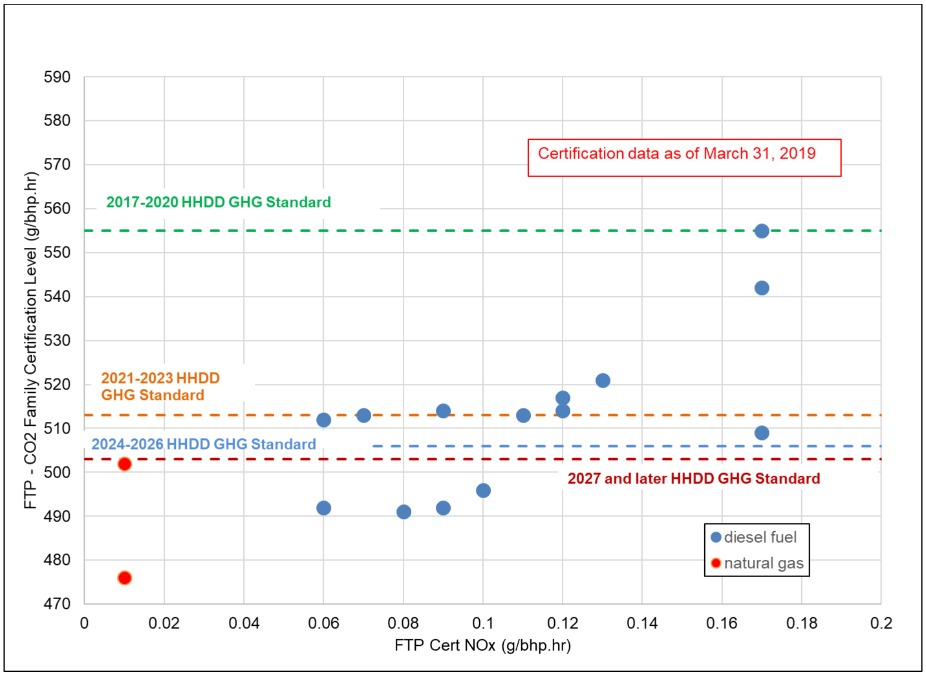

Figure 6 - Emission certification levels for CARB certified 2019 MY heavy heavy-duty engines (GVWR > 33,000 pounds)

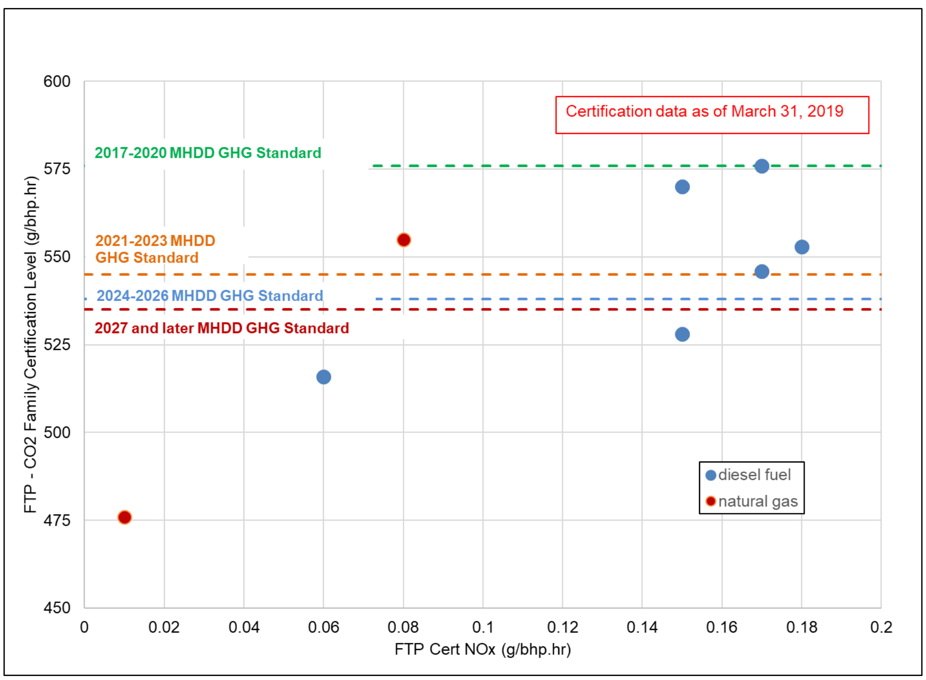

Figure 7 - Emission certification levels for CARB certified 2019 MY medium –heavy-duty engines (GVWR 19,501 to 33,000 pounds)

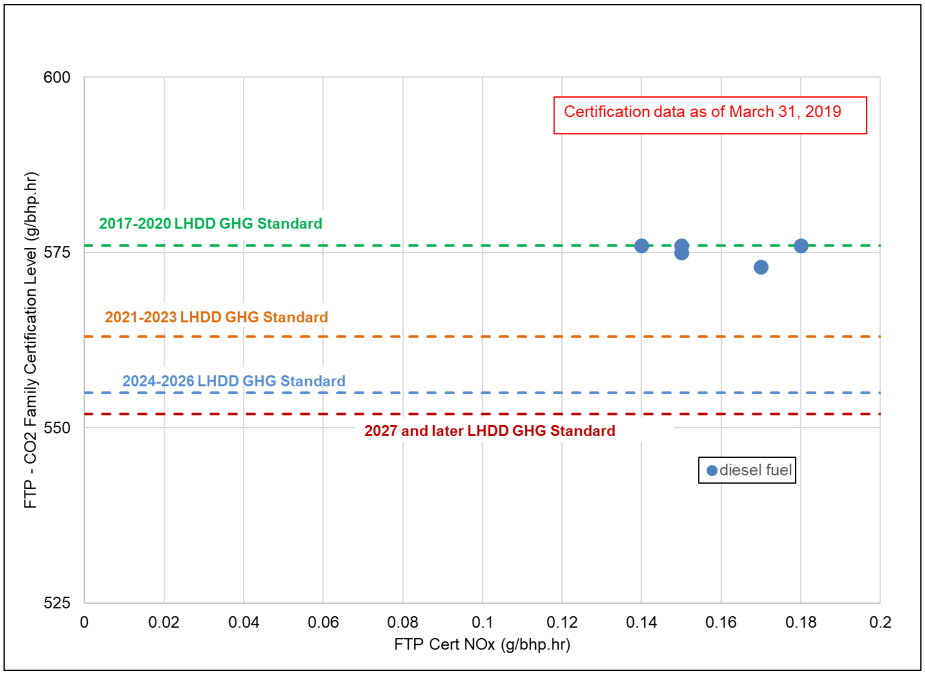

Figure 8 - Emission certification levels for CARB certified 2019 MY light heavy-duty engines (GVWR 14,001 to 19,500 pounds)

Staff also looked into an in-use data analysis performed by the International Council on Clean Transportation.[19] The analysis used emissions data from both the United States (U.S.) and European trucks to compare their in-use performance when evaluated using the U.S. NTE methodology and the European MAW based Euro VI methodology, respectively (Figure 9). It is important to note that the U.S. heavy-duty transient (FTP-based) certification NOx standard is significantly more stringent than the Euro VI standards. However, as shown in Figure 9 below, the analysis found that average brake-specific NOx emissions for U.S. trucks are about 3 to 4 times higher than European trucks, on average, indicating that European trucks are better in controlling emissions under most driving conditions. This is because Euro VI in-service conformity requirements force better calibration over the full duty cycle compared to the U.S. NTE methodology. In addition, the analysis found that there was a significant gap in emissions performance between European and U.S trucks at lower speeds in particular, further demonstrating the need to revise the current U.S. NTE methodology.

[19] Posada, Francisco, R. Muncrief, Preliminary results: A comparison of Real World Urban NOx Emissions measured with PEMS from HDVs in the US and the EU. August 2018 (CARB HDV In-Use testing workgroup meeting)

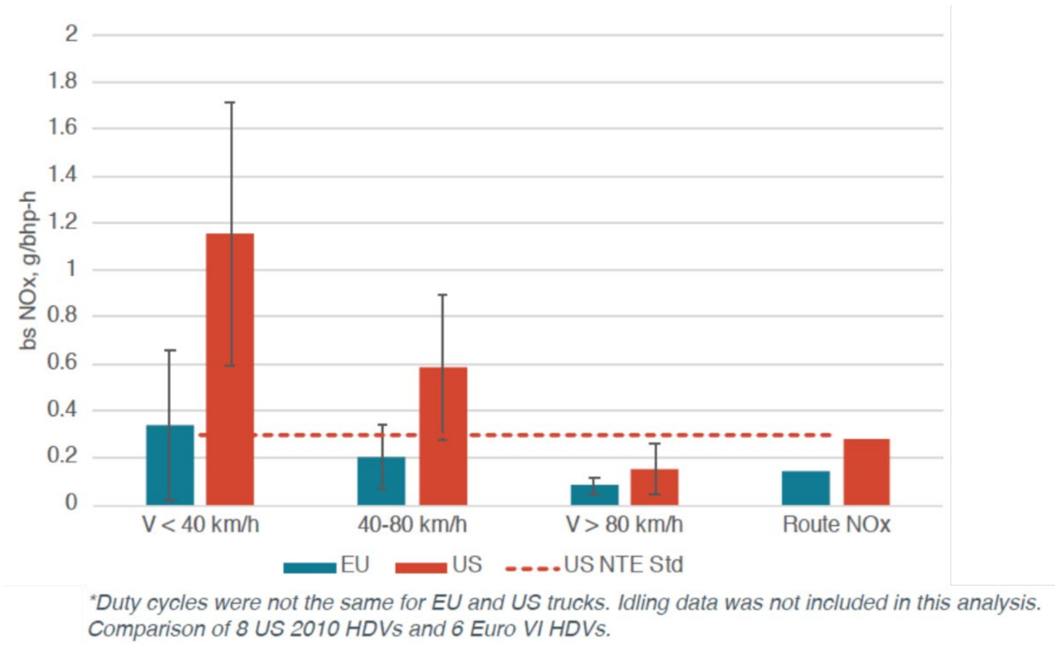

Figure 9 - Comparison between high selling U.S. vs EU heavy-duty engines: Large NOx emissions gap in more urban driving (Courtesy of ICCT – August 2018)

V. What requirements are feasible for 2022 and 2023 MY engines?

Staff believes the following improvements to the NTE protocol are technically feasible for 2022 and 2023 MY engines:

1. Changes to the current NTE method for MYs 2022 and 2023:
   Staff is considering changes to the existing NTE data exclusion protocol. Staff has identified the need to revise intake manifold temperature and the aftertreatment exhaust temperature exclusions based on technology improvements, including NOx control technologies implemented on 2010 and later MY engines that were not present during the NTE implementation phase in 2005 through 2009.

   The cold temperature exclusions relating to intake manifold temperature outlined in the 40 CFR 86.1370(f) to protect the EGR system from sulfur contamination and deterioration at low temperatures are antiquated and unnecessary for engines using ultra low sulfur diesel fuel, which is now universally available throughout the U.S. Engine manufacturers are currently using EGR during low temperature operation thereby demonstrating the intake manifold temperature exclusions are unnecessary. A minimum ambient temperature operation used in the Euro VI In-Service Conformity testing at 7°C will provide sufficient buffer from condensation within the EGR at cold temperatures.

The exhaust temperature exclusion for engines equipped with SCR (40 CFR 86.1370(g)) was initially set at 250°C due to catalyst activation and efficiency limitations. Advances in SCR aftertreatment catalysts have widened the operating temperatures available for NOx control. SCR catalyst efficiencies have been observed to have increased to 90 percent or more at temperature ranges down to 200°C (versus only 70 percent efficient just six years ago).[20] As a result, staff believes modifying the aftertreatment exhaust temperature exclusion cut point from the current 250°C to 200°C for MYs 2022 and 2023 is clearly technically feasible.

In addition, staff plans to propose a requirement that, beginning in 2022; manufacturers would need to provide a compliance report, in addition to providing an NTE compliance report, similar to what is required by Euro VI(D) requirements. The early reporting of the Euro VI(D) parameters would enable staff and manufacturers to assess how 2022 and 2023 MY engines are performing based on the Euro VI(D) methodology that would take effect starting with 2024 MY engines.

2. Changes to the Durability Demonstration Procedures:
   Currently, aging of the engine and aftertreatment system is performed at 35 to 50 percent of full useful life on an engine dynamometer. Deteriorated full useful life emissions are then estimated by linear extrapolation of emissions data. This method is inadequate since it does not address real life component failures and emission deterioration of engine-aftertreatment systems. To strengthen this procedure, certification staff intends to work with individual manufacturers on a case-by-case basis to devise mechanisms that would better verify product durability and deterioration factors for 2020 to 2023 MY engines.

3. Emission Warranty Information Reporting (EWIR):
   Staff plans to revise the EWIR requirements as discussed in the January 23, 2019 workshop for implementation in 2022 and later MY engines. The changes involve clarifying language on the consequences for not addressing in-use warranty issues in an expeditious manner (already allowed by statute). (See Table 1 above)

VI. What requirements are feasible for 2024 through 2026 MY engines?

The following is staff's assessment on the feasibility of lower NOx standards for 2024 through 2026 MY engines based on information that is currently available to staff. Staff believes the changes discussed below are feasible without major engine and aftertreatment hardware changes such as cylinder deactivation, SCR coated on filter, passive NOx adsorber, and close-coupled light-off catalysts.

[20] (1) Newman, A. High Performance Heavy-Duty Catalysts for Global Challenges beyond 2020. Presentation at the 2018 SAE Heavy-Duty Diesel Emissions Control Symposium. October 17, 2018

A. NOx Emission Standard on Regulatory Cycles

Staff believes a NOx standard of 0.05 to 0.08 g/bhp-hr on the FTP and the RMC-SET is feasible for the 2024 through 2026 MY production.[21] As mentioned above, staff believes achieving this standard is feasible without significant hardware architecture changes. This assessment is based on the following information:

1. *Stage 1 Low NOx Project*: In this program, SwRI used engine calibration methods to increase exhaust temperatures and reduce engine-out NOx emissions in the cold start FTP. Calibration strategies used to achieve this objective were increased idle speed, double post injection, and increased EGR rates. Tests on the cold start and hot start FTP with the modified calibration and the stock aftertreatment system of the engine resulted in a FTP composite NOx level of less than 0.1 g/bhp-hr, as shown by the red arrow in Figure 10.[22] The corresponding GHG penalty was about 0.4 percent. No other strategies, such as EGR cooler or turbo bypass, were employed. Although the Stage 1 results are above 0.08 g/bhp-hr NOx, they nevertheless indicate that improved calibration can significantly reduce emissions and that further reductions are possible using improved thermal management and aftertreatment strategies during cold starts and low temperature operations, together with maintaining tight control thereafter.

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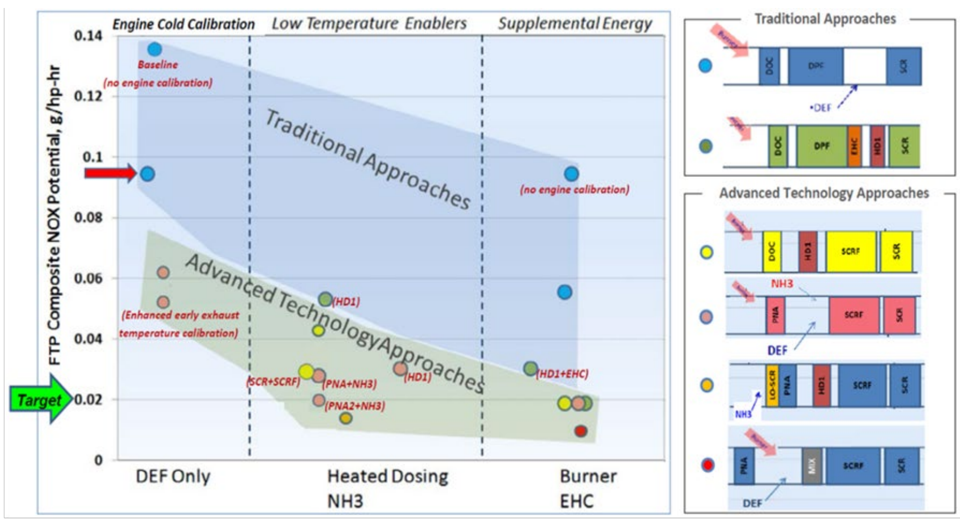

Acronyms
DOC: diesel oxidation catalyst **DPF**: diesel particulate filter **SCR**: selective catalytic reduction **DEF**: diesel exhaust fluid
EHC: electrically heated catalyst **HD1**: heated DEF dosing **SCRF**: SCR catalyst coated DPF **PNA**: passive NOx adsorber
PNA2: PNA with altered catalyst formulation **NH3**: gaseous ammonia injection **LO-SCR**: close-coupled light-off SCR

Figure 10 Stage 1 Diesel Aftertreatment Screening Test Results

[21] The HD engine certification standards are also utilized by a subset of medium-duty vehicles (MDVs) in the 8,500 to 14,000 lb GVWR range. To avoid a disparity in NOx stringency for MDVs, staff plans to assess and take steps necessary to ensure similar robustness in emission control stringency for chassis certified MDVs in a similar timeframe to the HD engine standards.

[22] Sharp, C.A., Webb, C.C., Neely, G.D, Smith, I., "Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles", Southwest Research Institute (SwRI) Project No. 19503 Final Report (2017). (https://www.arb.ca.gov/research/single-project.php?row_id=65182).

2. *Certification levels of CARB certified 2019 MY heavy-duty engines*: As discussed above, Figures 6 through 8 show NOx versus CO_2 certification levels for 2019 MY CARB certified heavy-duty engines. As shown in Figure 6, more than 50 percent of the heavy heavy-duty engines are certified at or below 0.1 g/bhp-hr NOx. Many of these engines also exhibit CO_2 levels below the 2024 Phase 2 GHG standards (with some even below the 2027 Phase 2 GHG standards). This indicates that it is possible to meet the 2024 GHG emission standards and a NOx emission standard of 0.05 to 0.08 g/bhp-hr with current technology and some engine calibration changes to meet both standards. Note that most of the engines with NOx certification levels above 0.1 g/bhp-hr also have higher CO_2 emissions. These engines would likely need improved engine calibration and/or some engine/aftertreatment hardware changes to meet both 2024 GHG standards as well as a NOx standard of 0.05 to 0.08 g/bhp-hr.

   Staff acknowledges that some engine manufacturers certify well below the emission standard to provide a compliance margin. Again, as shown in Figure 6, some of the engine families are certified well below 0.08 g/bhp-hr NOx indicating the feasibility of certifying engines with a compliance margin.

   Figure 7 shows emission certification levels for NOx and CO_2 for 2019 MY medium heavy-duty engines. Two of the diesel engines already exhibit CO_2 levels below the 2027 Phase 2 GHG standards, with one engine already meeting a NOx certification level of 0.06 g/bhp-hr as well. Although other engines in this weight class are certified to higher NOx and CO_2 levels, this data point indicates that it is possible to meet the 2024 Phase 2 GHG standards and, at least, a 0.08 g/bhp-hr NOx level without significant changes to the engine and aftertreatment system.

   Figure 8 shows CO_2 versus NOx certification levels for 2019 MY light heavy-duty engines. For these engines emission certification levels are close to the current certification standards for both NOx and GHG. These engines indicate they would need some redesign of the engine aftertreatment system to meet the 2024 Phase 2 GHG standards. Optimization to achieve the 0.05 to 0.08 g/bhp-hr NOx emission levels could also be performed at the same time.

B. Particulate Matter Standards

As shown in Figures 3 to 5 above, most engines currently have PM certification levels well below the current 0.01 g/bhp-hr standard and certify close to 0.001 g/bhp-hr. However, over the last few model years some manufacturers have elected to certify some of their engine families to higher PM emission levels as a result of changes to the diesel particulate filter (DPF) substrate. During a meeting with one of the aftertreatment suppliers, it was confirmed that some engine manufacturers are selecting more porous DPFs to reduce engine backpressure at the expense of higher PM emission rates, albeit still compliant with the current PM standard. Thus, to maintain current robust PM emission control performance at 0.001 g/bhp-hr levels, staff is considering a lower PM standard of 0.005 g/bhp-hr. This change is feasible with existing DPF aftertreatment systems and would assure that the best DPF technologies continue to be utilized for the maximum control of PM emissions.

C. NOx Emission Standard on Low Load Cycle

As described above, two of the tasks of the Stage 2 project are the development of the LLC and optimization of the EAS on this cycle. The development of candidate LLCs and baseline testing on the LLCs has been completed. Baseline tailpipe NOx emissions on the preferred LLC for two engines were 0.8 g/bhp-hr and 1.5 g/bhp-hr[23] while the corresponding engine-out emissions were 3.2 g/bhp-hr and 4.2 g/bhp-hr. Since both engines have similar SCR systems, staff believes the large difference in emissions between the two engines is primarily due to differences in engine-out emissions and system calibration.

Assuming a NOx baseline of 0.8 g/bhp-hr NOx on the LLC (as already demonstrated with today's technology), staff believes NOx emissions can further be reduced through engine calibration changes aimed at reducing engine-out NOx and increasing exhaust temperatures. Marginal exhaust temperature profile improvements can make significant differences by allowing urea dosing and SCR NOx conversion during an increased fraction of the duty cycle. Such NOx optimization strategies could be incorporated together with the changes to be made to meet the GHG standards in a single engineering effort. Staff believes a NOx standard of 1 to 3 times the proposed FTP standard is feasible on the LLC in 2024. As discussed above, SwRI has demonstrated in the Stage 1 project NOx reductions of about 50 percent on the OCTA cycle and 66 percent on the NYBC through engine calibrations that reduced engine-out emissions and increased exhaust gas temperatures. Staff does not plan to propose a CO_2 emission cap on the LLC for the 2024 through 2026 MY engines.

D. Heavy-Duty In-Use Testing

An assessment of the current HDIUT program using the NTE methodology shows that the vast majority of driving conditions is not evaluated and goes un-checked for in-use compliance.[24] This is due to the numerous exclusions incorporated in the NTE procedures,[25] including those for intake manifold temperature and aftertreatment exhaust temperature, the NTE control area, and the requirement for a continuous 30-second operation for a valid NTE event. The limitations and inadequacies of the current NTE methodology has compelled staff to pursue a MAW approach similar to the method used currently in Europe (Euro VI(D)).[26] Euro VI(D) does not have most of the data

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[23] Heavy-Duty Low NOx Program Workshop - Low Load Cycle Development Presentation. January 23, 2019 (https://www.arb.ca.gov/msprog/hdlownox/hdlownox.htm) (See Appendix 4 for slides)
[24] Bartolome, C., et al., 2018. "Toward Full Duty Cycle Control: In-Use Emissions Tools for Going Beyond the NTE", 28th CRC Real World Emissions Workshop, March 18-21, Garden Grove, CA
[25] 40 CFR § 86.1370 - Not-To-Exceed test procedures
[26] COMMISSION REGULATION (EU) No 582/2011, May 25, 2011 (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02011R0582-20180118&from=EN)
COMMISSION REGULATION (EU) 2018/932, June 29, 2018

exclusions included with the NTE method, enabling evaluation of a much greater fraction of collected in-use data. Figure 11 shows a comparison of the current NTE method, a possible version of an improved NTE method, and a modified Euro VI(D) method using the FTP rather than Europe's World Harmonized Test Cycle as the defined work window. The bar charts clearly show the superiority of the modified Euro VI(D) method in its ability to capture more of the test time and NOx emissions for evaluation compared to either of the NTE methods. Furthermore, staff will likely propose to use the same conformity factor and percentile pass criteria as used with Euro VI(D). For a passing test, Euro VI(D) requires the 90^{th} percentile of windows be less than the in-use threshold, which is the product of the conformity factor and the FTP emission standard (1.5 x FTP Standard).

Staff is also considering an alternative compliance path using NOx sensor data collected using the On-Board Diagnostic's (OBD) REAL monitoring system. This option is contingent on NOx sensor technology development being able to monitor emissions at low NOx levels as well as monitor emissions over the whole duty cycle of heavy-duty vehicles operations. Manufacturers need to institute such a strategy under a pilot program before replacement of the manufacturer-run HDIUT program for the 2027 MY engines.

Unlike the Euro VI(D) that specifies the mix of route operation (rural, urban, highway), staff plans to propose that the vehicle be driven on its regular fleet route. Additionally, a manufacturer would have to submit the test plan, including but not limited to, test location, operation type (regional, line haul, etc.), and time of year testing will be conducted. Also, to ensure the results are not biased by fleets that happen to have an unusually high portion of low load operating conditions, staff plans to propose that a manufacturer may invalidate any test day with over 50 percent of windows at or below the 10 percent power threshold, the same as with Euro VI(D). However, manufacturers would need to continue to perform testing until they obtain valid testing results.

Staff believes implementation of the modified Euro VI(D) methodology with an in-use threshold of 1.5 x FTP standard for engine MYs 2024 through 2026 is technically feasible. Although engines certified in Europe today are complying with current Euro VI(D) requirements using aftertreatment technologies that are similar to those currently used in the U.S., these engines are meeting an in-use threshold that is over 4 to 7 times higher than the proposed CARB in-use threshold (0.51 g/bhp-hr in Europe versus 0.075 to 0.12 g/bhp-hr in U.S.). As a result, staff believes manufacturers will need to do additional calibration and potentially aftertreatment hardware improvements to meet the more stringent CARB in-use threshold. Staff understands that there are certain cycle conditions that arise from real world testing and absent in the prescribed cycle of Euro VI method to be challenging from an emissions control perspective. Technical assessment and provisions for these specific operations will be ongoing to ensure feasible compliance and control for the 2024 MAW implementation.

(https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R0932&from=EN)

Another challenge is complying with the Phase 2 GHG standards while meeting the modified Euro VI(D) in-use threshold. In Europe, heavy-duty vehicle GHG standards have been developed but are not currently being implemented. Not faced with the constraint of GHG standards, European manufacturers have reported that compliance with the current Euro VI(D) in-use threshold results in an increase in CO_2 emissions during sustained low-load operation. As a result, staff believes U.S. manufacturers may need to do additional calibration and potentially change engine hardware to meet both the Phase 2 GHG standards and the modified Euro VI(D) requirements.

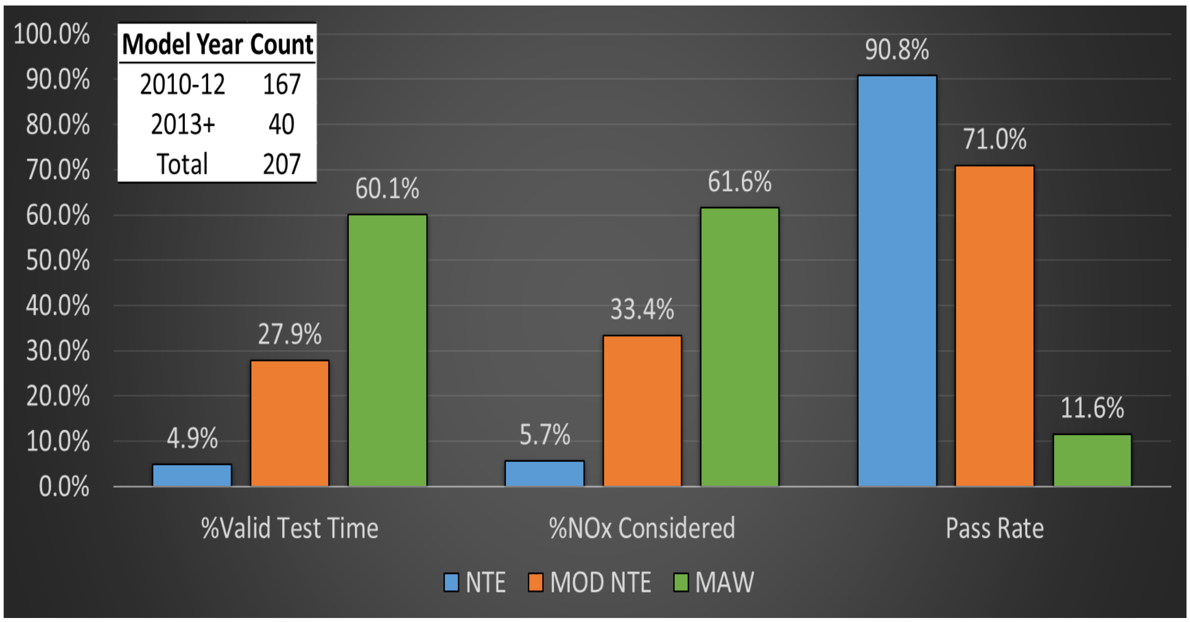


Figure 11 Method Comparison: MAW Captures More of Test Time and Emissions on HDIUT data set

E. Vehicle Technologies that Benefit NOx Emission Reductions

As discussed in previous workgroup meetings, staff also plans to recognize vehicle technologies that would provide NOx emission reductions over the engine certification cycles. Staff plans to work with manufacturers as well as with U.S EPA to develop a testing method for crediting these technologies. Such technologies may include stop-start systems, hybrid technologies, and others.

F. Changes to the Durability Demonstration Procedures:

Staff discussed potential revisions to the durability demonstration procedures for heavy-duty diesel engines in the January 23, 2019 workshop (see appendix 3). These changes would require the manufacturers to age the EAS to full useful life as part of the certification program.

Since the January 23, 2019 workshop, staff has also discussed other possibilities for durability demonstration with U.S. EPA. As a result, CARB staff is currently considering providing manufacturers three options for demonstrating EAS durability for the 2024-2026 MY period. These options are described below:

1. Full UL aging of the EAS on an engine dynamometer using either standardized engine certification cycles (FTP, RMC-SET), or the engine cycles generated from the Phase 2 Greenhouse Gas Emission Model (GEM) using the worst case vehicle/engine combination (worst case would be the vehicle configuration that yields the highest cycle-average power level for each engine family). Manufacturers would need to determine the highest cycle-average power level for both FTP/SET or GEM scenario, and choose the scenario with the highest cycle-average power level. Details regarding the engine dynamometer pathway selection process, the required aging hours, and the sequence of aging cycles are shown in Appendix 3.

2. In the January 23, 2019 workshop, staff also presented an option for HHDD engines that would require aging the EAS for ½ UL on an engine dynamometer, followed by ½ UL aging of the aftertreatment system using the Develop an Accelerated Aging (DAAAC) Protocol. The engine dynamometer aging cycle would be determined similar to how it was determined in option 1. The intent of this option is to reduce the number of aging hours required for the durability program by introducing accelerated aging for a portion of the program. This option would require periodic submittal of NOx sensor data to CARB in order to validate the results from the DAAAC protocol.

3. Based on discussions between CARB and U.S. EPA, both agencies plan to jointly work with EMA to come up with an accelerated EAS aging protocol for all primary intended service classes of heavy-duty engines. Detailed information regarding the feasibility and the development timelines for this protocol is not available at this time, but staff is interested in development of an accelerated aging protocol that would represent real-life aging of the EAS. Since this option would focus on accelerated EAS aging, staff anticipates that periodic NOx sensor reporting would be a requirement under this option.

Although the durability demonstration proposal increases the cost and the length of the durability demonstration program to individual manufacturers from its current baseline values, staff believes that the new requirements are cost effective and would not cause major disruptions to the product development cycle. Staff has already performed a preliminary cost analysis and will include the additional costs due to the new durability requirements in the final program cost study.

In terms of additional aging hours and product development timelines, option 2 would require manufacturers to dedicate approximately 5,500 hours for the durability demonstration program. This is comparable to the 4,000-hour durability program that several off-road compression-ignition manufacturers are currently performing to satisfy CARB's durability requirements. Staff believes that a 5,500-hour durability program would take approximately one year to complete and would not adversely impact product development.

The requirement to submit NOx sensor data (using REAL or other metrics) by manufacturers would be instrumental in development of a new alternative durability program for the 2027 and subsequent MY products, when the useful life values are planned to be increased for all heavy-duty primary intended service classes.

G. Warranty and Useful Life Periods

In June 2018, CARB adopted amendments to the California on-road heavy-duty diesel vehicle and heavy-duty engine warranty regulations to lengthen existing warranty periods, allow maintenance provisions to better reflect the longevity and usage of modern vehicles, and explicitly link the heavy-duty OBD system to the definition of a warranted part. These amendments will be effective with the 2022 MY. However, these "Step 1" lengthened warranty periods, as well as the currently defined useful lives, still fall short of reflecting the real-world longevity of modern heavy-duty vehicles. Accordingly, staff intends to propose increased useful live and lengthened "Step 2" warranty period amendments, for these vehicles and engines, to be effective with the 2027 MY. Staff has no plans to revise the warranty and useful life periods for the 2024 through 2026 MY engines.

VII. Feasibility of Standards

A. Technologies for 2024-2026 MY Standards

Table 4 lists some of the technologies that may be employed to meet the 2024-2026 MY standards. These enabling technologies are either currently commercially available or planned to be implemented by some manufacturers in the next one to two years.

Table 4 – List of Technologies for the 2024 – 2026 MY Engine Standards

Engine calibration strategies	Increased EGR, post-injection, increased idle speed.
Aftertreatment system strategies	Increased catalyst size, improved SCR catalyst (high cell density and high porosity substrates), better urea injection control, heated dosing, and twin SCR systems in one box with dual dosing.
Engine hardware	EGR cooler bypass, turbo bypass, charge air cooler bypass.

The various engine hardware bypasses, split SCR systems, and heated dosing may be driven mainly by the need to meet the low load cycle standard, the in-use standards, and idling standard and not necessarily by the need to meet the FTP or RMC-SET standards.

Some of the above strategies may increase GHG emissions when incorporated in current engines, as was observed in the Stage 1 Low NOx program. However, since these engines are going to be re-designed and optimized to meet the 2024 GHG emission standards, NOx optimization strategies could also be incorporated together with the changes made to meet the GHG standards in a single engineering effort, minimizing GHG emissions impacts.

B. Technologies for 2027 and later MY Standards

Meeting the 2027 MY engine standards will require optimization of the 2024 MY technologies plus additional technologies such as those listed in Table 5.

Table 5 – List of Technologies for the 2027 and Later MY Engine Standards

Engine calibration strategies	2024 MY strategies plus optimization.
Aftertreatment system strategies	Further optimization of 2024 MY strategies plus advanced catalysts such as SCR coated on filter, twin SCR systems with light-off SCR close-coupled to the engine and dual dosing, better urea injection control, etc.
Engine hardware	2024 MY engine hardware strategies plus cylinder deactivation, stop-start systems, early exhaust valve opening, etc.

VII. Heavy-Duty Low NOx Implementation Timeline

Figure 12 below shows implementation phases of the various elements included in the Heavy-duty Low NOx Omnibus Rulemaking as well as implementation of the various phases of the Phase 2 GHG requirements. The implementation dates to meet the low NOx requirements discussed in this white paper have been designed to coincide with the implementation dates to meet the Phase 2 GHG standards. This would provide manufacturers the opportunity to implement NOx optimization strategies together with the changes to meet the MY 2024 and 2027 Phase 2 GHG standards.

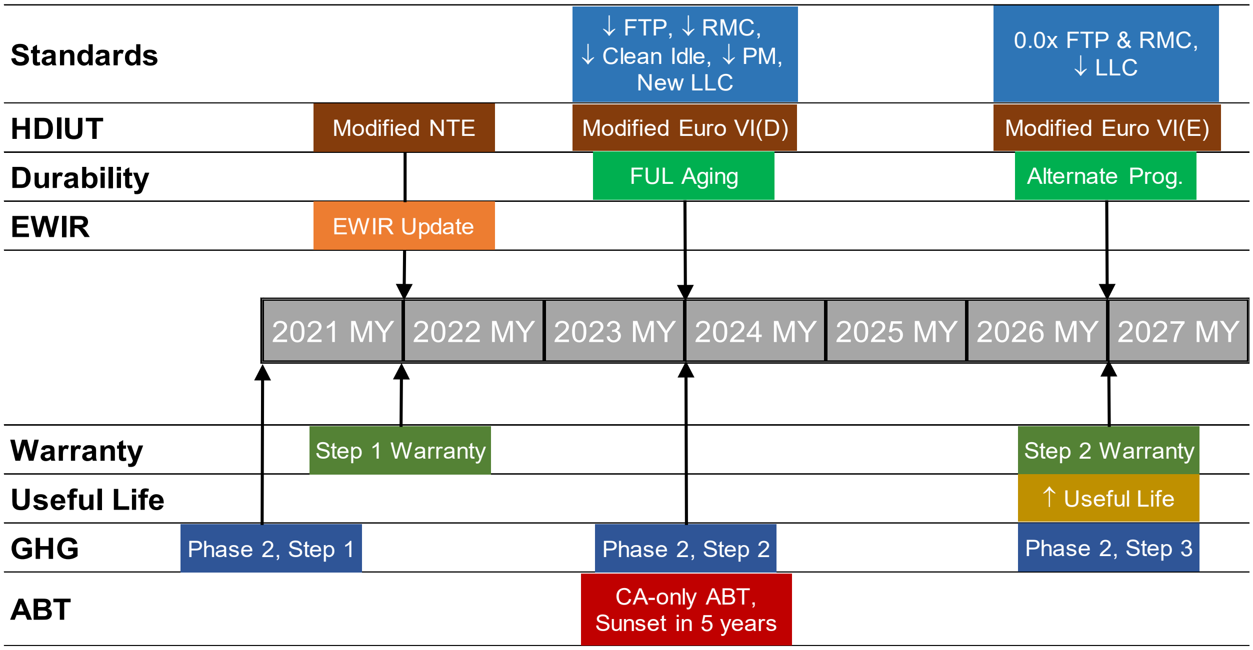


Figure 12 CARB Heavy-Duty Low NOx Rulemaking Implementation Timeline

VIII. What will the cost of compliance with the proposed requirements be?

Staff understands that manufacturers will incur costs to comply with the proposed requirements discussed above. Based on preliminary estimates, CARB staff believes that the MY 2024 provisions described in this white paper could be met at a cost effectiveness of less than $3/pound NOx. The $3/pound NOx estimate is well within the cost-effectiveness of previous rulemakings adopted by CARB.

CARB has contracted with the National Renewable Energy Laboratory (NREL) to help estimate compliance costs associated with the Heavy-Duty Low NOx program. NREL is currently in the process of collecting cost data; the results are expected to become available by May 2019. Once these results are available, staff plans to seek further input from industry and refine the cost-effectiveness assessment.

XI. Conclusions and Next Steps

It is staff's intent that this white paper will help provide clarity in addressing engine manufacturers' concerns and uncertainties with regard to lead time and potential regulatory requirements impacting their MY 2022 through 2026 products.

Staff plans to continue to engage the engine manufacturers, EMA, and other stakeholders to listen and address their concerns, and share any information that becomes available from the various research projects currently in progress. Staff will also continue to hold workgroup meetings and workshops to reach out to stakeholders, nongovernmental environmental organizations, trade associations, and the public.

Attachments

Appendix 1a – Heavy-Duty In-Use Testing (HDIUT) Presentation

Appendix 1b – Compliance report checklist for MAW Euro VI(D)

Appendix 2 – Emission Warranty Information Reporting (EWIR) Presentation

Appendix 3 – Durability Demonstration Program (DDP) Presentation

Appendix 4 – Low Load Cycle Development (LLC) Presentation

Appendix 1

CALIFORNIA AIR RESOURCES BOARD

HEAVY-DUTY LOW NO_x PROGRAM WORKSHOP

JANUARY 23, 2019

HEAVY-DUTY IN-USE TESTING (HDIUT)

MOBILE SOURCE CONTROL DIVISION

CALIFORNIA AIR RESOURCES BOARD

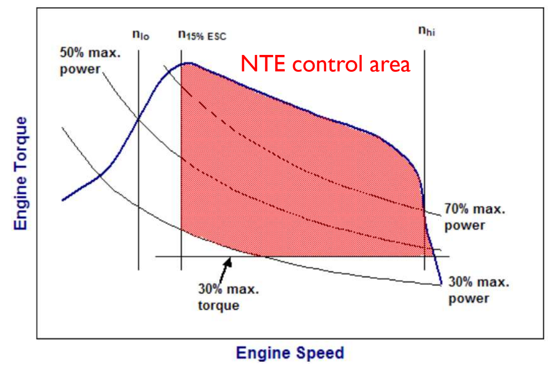
HDIUT: OUTLINE

- Current HDIUT / Not to Exceed (NTE) program
- Problems with current program
- Proposed changes
  - Administrative and Reporting
  - Testing Conditions and Exclusions
  - Full Duty Cycle Control
  - Moving Average Windows (MAW)
  - Pass Fail Determination

2

HDIUT: BACKGROUND

- 2003: Outline of the HDIUT developed by U.S. EPA, CARB, and Engine Manufacturer's Association
- 2005: EPA adopts Manufacturer Run HDIUT
- 2006: CARB adopts HDIUT and national HDIUT pilot year
- 2007: 1st year of HDIUT criteria pollutant enforcement



https://www.dieselnet.com/standards/cycles/images/nte.png

3

HDIUT: CURRENT REQUIREMENTS (40 CFR PART 86 SUBPART T)

	Current CARB & EPA HDIUT
Request for testing	• CARB & EPA Requested
Engine Selection	• 25% of engine families certified
Frequency	• Annually
Driver	• Regular Fleet Driver
Route	• Regular Fleet Route
Method	• Not-to-Exceed
Exclusions	• Ambient, 30% min power, 30% min torque, min-rpm, zero check, AT-temp, cold operations, intake manifold temperature (IMT), engine coolant temperature (ECT), On-Board Diagnostic (OBD) fault code, Engine Manufacturer Diagnostic fault codes, diesel particle filter (DPF) regeneration
Window Validity	• 30 sec continuous operation within NTE control area without entering exclusions operation
Emissions	• Brake specific [g/bhp-hr]
In Use Thresholds	• 1.5 x Std. + PEMS accuracy margin [0.45 g/bhp-hr NO_x threshold]
Pass Determination	• 90% of time weighted valid NTE events must emit at or less than the In Use Threshold

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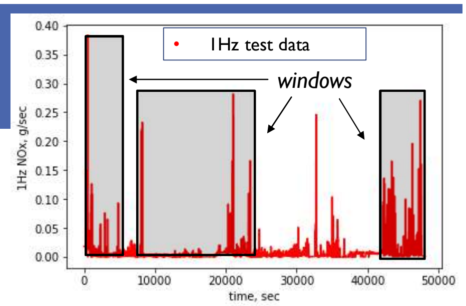
HDIUT: CURRENT ISSUES AND LIMITATIONS

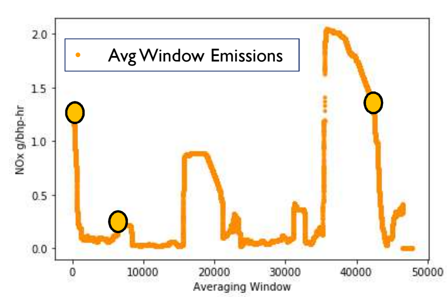
1. Current HDIUT program targets sustained high speed and high load operation for gross NO_x polluting offenses
2. After applying the current exclusions, valid data from testing represents a small fraction of the total test in terms of time (<5%) and NO_x emissions (<6%)
3. 24% of tests pass without any valid NTE events
4. Current HDIUT does not represent the full duty cycle emissions
5. There is a discrepancy in the pass rates observed by the manufacturer (91%) and CARB-run HDIUT(44%) results. (CARB testing: 20 of 36 failed NTE)

5

MOVING AVERAGE WINDOWS (MAW)

- Implemented in Euro VI regulations for In-Use Conformity testing
  - Mass emissions are calculated for subsets, i.e., "windows", of complete data set.
  - Length of windows based on the reference work or CO2 measured over the transient certification cycle [Ref Cycles: WHTC in Europe and FTP in USA]
  - Windows are started at every second of the data set given that there is enough following data to complete a window length
  - 1Hz NOx emissions are averaged over a window (highlighted in grey).
  - Window emissions are reduced to a single point Window Averages.
  - The averaged window emissions are ordered and the 90th percentile window is compared with the emission standard
  - The ratio of the 90th percentile emission to the emissions standard must not be greater than the conformity factor, 1.5





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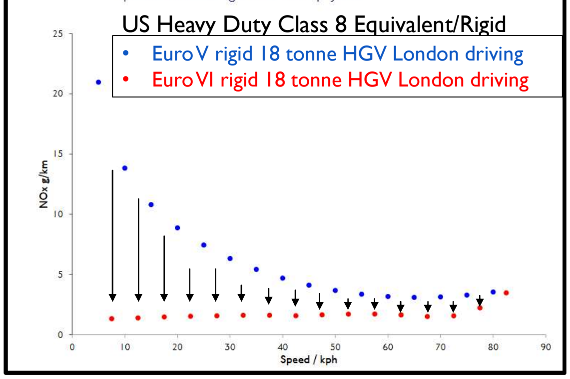
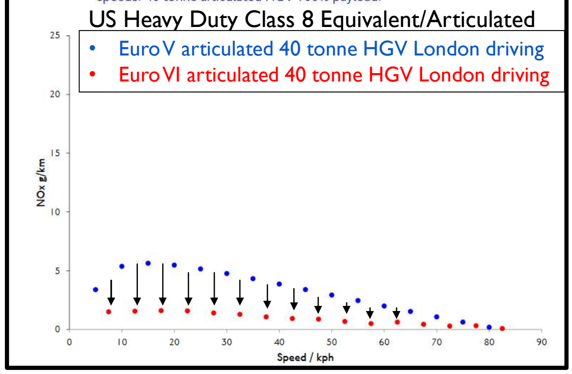
EMISSIONS BENEFITS IN LONDON FROM MAW IMPLEMENTATION

Figure 5 Comparison of Euro V versus Euro VI NO_x emissions over a range of road speeds: 18 tonne rigid HGV 100% payload



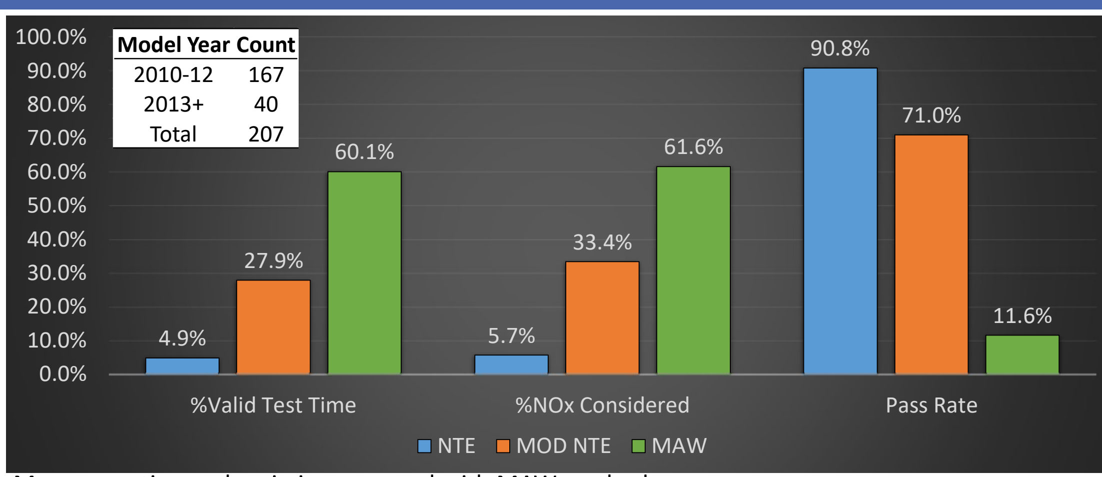
(2015) In-service emissions of Euro 6/VI vehicles. A summary of testing using London drive cycles. Transport for London.

Figure 6 Comparison of Euro V versus Euro VI NOx emissions over a range of road speeds: 40 tonne articulated HGV 100% payload.



(2015) In-service emissions of Euro 6/VI vehicles. A summary of testing using London drive cycles. Transport for London.

METHOD COMPARISON: MAW CAPTURES MORE OF TEST TIME AND EMISSIONS ON HDIUT DATA SET



- More operation and emissions covered with MAW method
- New method would improve real world emissions performance

CHANGES TO THE HDIUT PROGRAM

- **Remove the Following Elements:**
  - Discard the Not-to-Exceed method, NTE control area, operation exclusions, and averaging period
  - Discontinue the use of the PEMS accuracy margin allowance [0.15 g NO_x /bhp-hr]
- **Proposed Changes:**
  - Use the Euro VI MAW based method
  - Window size based on the test engine's work or CO_2 measured on the FTP cycle
  - Incorporate control over higher emitting windows: cold start, low load, idle operation
    - Weighted composite cold start and warm running emissions
- **Additional Reporting:**
  - CARB pre-approves manufacturer's HDIUT test plans
  - Data quality checklist assuring valid and complete test data was collected prior to submittal

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HDIUT: ENGINE FAMILY SELECTION AND TEST PLAN APPROVAL

- **Engine Selection**
  - CARB and EPA will continue to work together in selection of engine families for HDIUT
  - Rules for number of engine families selected annually and over a 4 year average would stay in place
- **Manufacturer test plan must be approved by CARB**
  - Test vehicle to be driven by fleet operator (manufacturer may also do testing with CARB/EPA approval)
  - Test vehicle to be driven over its regular fleet route (or CARB/EPA approved test route)
  - Season, ambient conditions, and other test conditions to be reviewed and require approval by CARB

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HDIUT: COLD START CRITERIA AND DATA EXCLUSIONS

- **Cold Start and Warm Up Conditions**
  - Cold start: engine must start with either:
    - Engine coolant must be less than or equal to 30 deg C
    - Engine coolant must be less than the ambient temperature by 2 deg C
  - Engine warm up must be within the first 15 min from engine start by satisfying either:
    - Engine coolant reaches 70 deg C for the first time
    - Engine coolant stabilizes within plus or minus 2 deg C for 5 minutes
- **Atmospheric Pressure and Temperature Range**
  - Ambient pressure and temperatures outside the current altitude, temperature, and pressure ranges shall be excluded from evaluation
- **PEMS QC Exclusions**
  - Data collected during the periodic instrument zero or drift checks excluded from evaluation

HDIUT: MAW ANALYSIS METHOD

- **Moving Average Windows**
  - Subsets of continuous overlapping windows
  - Incremental averaging rate, 1Hz
  - Window size based on a reference Work or CO_2 mass on the FTP cycle
  - Size of windows shorter than the FTP are also being evaluated at SwRI
  - Window average power must be greater than the threshold power to be valid
    - Initially set power threshold to 10% maximum engine power [Euro VI(d)]
    - Future power threshold reduced to idle operation
- **Emission Metrics**
  - Average brake and CO_2 specific emissions of windows will be reported
  - Emissions at low loads and idle operation require a method other than brake specific emissions
  - CO_2 and fuel rate among other metrics are being evaluated by SwRI

HDIUT: PROPOSED METHOD WITH PHASE IN TIMELINE

Model Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HDIUT Methodology	NTE		Euro VI(d) MAW					Future method		

- 2022 to 2026 MY Engines
  - Based on Euro VI(d)
  - Deviations from Euro VI(d):
    - Real world fleet route and fleet driver
    - Reference window size based on FTP
    - Minimum of 3 hours of valid test data
- Potential changes for the future method (2027+ MY)
  - Weighted cold starts emission inclusion [similar to Euro VI(e)]
  - Expand operation down to idle
  - May have different window size
  - May introduce new emissions metrics

HDIUT: COLD START EMISSIONS [EURO VI(E)]

1. **Calculate the conformity factor for all windows of the test**
   - *CF = [avg window emissions / emissions std]*
2. **Obtain CF_{cold} for the cold portion of the trip**
   - *CF_{cold} = highest CF window value for windows between:*
   - *Engine start and before $T_{engine\ coolant}$ reaches 70 °C*
3. **Obtain CF_{warm} for the warm portion of the trip**
   - *CF_{warm} = The 90th percentile window emissions for windows:*
   - *70 °C ≤ $T_{engine\ coolant}$*
4. **Weight results in following way**
   - The weighted summation of the cold and warm emissions shall not be greater than 1.5
   - Cold and warm start weighing factors will be similar to the composite FTP emissions
   - *$1.5 \geq [0.14\ (CF_{cold}) + 0.86\ (CF_{warm})]$*

HDIUT: FUTURE METHOD SUMMARY

Key:
Previous Requirements
New or updated Elements

	MY 2022-2026	MY 2027+
Testing Request	CARB & EPA	CARB & EPA
Number of Families	25% EFs per year	25% EFs per year
Test Plan	Mfr. Submitted for CARB approval	Mfr. Submitted for CARB approval
Driver & Route	Real world fleet driver and route for a full day or mfr. testing with prior CARB/EPA approval	Real world fleet driver and route for a full day or mfr. testing with prior CARB/EPA approval
Method	MAW Euro VI(d)	TBD
Cold Start	Cold start engine coolant temp. exclusion	Include composite weighting
Exclusions	Extreme ambient conditions & PEMS checks	Extreme ambient conditions & PEMS checks
Window size	Work or CO_2 equivalent on an FTP cycle	TBD
Window Validity	Avg window power at or above 10% Power Threshold	All operation
Test Validity	3 hours valid test data	N/A (all valid operation considered)
Emissions metric	Work or CO_2 specific	CO_2 specific
Emissions Evaluation	90th percentile of valid window emissions	9Xth percentile (TBD) of warm valid window emissions 100th percentile of cold start window emissions
Conformity Factor	$CF_{final} = 1.5$	$CF_{final} = 1.5$
Pass Criteria	$\frac{e_{90th\ percentile}}{e_{FTP\ std.}} \le CF_{final}$	$0.14\ x\ CF_{cold} + 0.86\ CF_{warm} \le CF_{final}$

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HDIUT: NEXT STEPS

HDIUT Tasks	Estimated Completion
1. Low NO_x Workshop: Rough proposal	Jan 2019
2. Low NO_x Workgroup: window size and emissions metrics investigation by SwRI	Feb 2019
3. Draft proposal	Apr 2019
4. Low NO_x Workshop: Draft proposal Draft regulatory language (2022-2026MY)	May 2019
6. Low NOx Board Hearing	Q1 2020

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COMPLIANCE REPORT CHECKLIST FOR MAW EURO VI (D)

The compliance report for analysis using the moving average window method described in Euro VI(D) must include the following items:

- All on-road testing data already required by HDIUT Testing 40 CFR 86 Subpart T
- Engine families' work and CO_2 on the FTP cycle
- Analyzed window data must include: window length, start of window, end of window, window power, measured window size, window emissions HC, CO, NOx, PM, window validity
- Rank the valid window g/bhp-hr emissions and report the 50th, 90th, and 100th percentile of the criteria pollutants

Appendix 2

CALIFORNIA AIR RESOURCES BOARD

HEAVY-DUTY LOW NOX OMNIBUS PROGRAM WORKSHOP

EWIR AMENDMENTS

JANUARY 23, 2019

EMISSION WARRANTY INFORMATION REPORTING (EWIR) AMENDMENTS FOR MANUFACTURERS OF HEAVY-DUTY ENGINES

EMISSIONS COMPLIANCE, AUTOMOTIVE REGULATIONS AND SCIENCE (ECARS) DIVISION

1

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EWIR OVERVIEW

- Manufacturers are required to track and report warranty claims/failure rates
- Warranty reporting is a critical tool for monitoring and assessing in-use performance
- Manufacturers must take corrective action (typically recalls or extended warranties) when corrective action thresholds are exceeded
- Corrective action plans are reviewed prior to implementation to ensure that they will be successful, meet regulatory requirements, and adequately address the in-use issue

3

PROPOSED AMENDMENTS OBJECTIVES

- Add explicit consequences for not addressing in-use warranty issues in an expeditious manner (already allowed by statute)
  - Complying with warranty reporting and corrective action requirements shall be conditions under which the Executive Order is granted
    - Aligns with certain conditions under which PC, LDT and MDV Executive Orders are granted 40 CFR 86.1848-01 (c)
  - Failure to comply with CCR 2143 (corrective action for high failure rates) and warranty reporting requirements may result in revocation of the Executive Order and the manufacturer may be subject to penalties
  - Future Executive Orders may be called into question (e.g. no carryover allowed) if a manufacturer has a history of not meeting conditions under which Executive Orders are issued

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PROPOSED LOWER THRESHOLDS

- Lower thresholds for reporting and corrective action:

	Current	Proposed
EWIR	1% or 25 unscreened claims (whichever is greater)	1% or 12 unscreened claims (whichever is greater)
FIR	4% or 50 unscreened claims (whichever is greater)	4% or 25 unscreened claims (whichever is greater)
EIR	4% or 50 failures (whichever is greater)	4% or 25 failures (whichever is greater)
Corrective Action	4% or 50 failures (whichever is greater)	4% or 25 failures (whichever is greater)

To account for small volume engine families

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PROPOSED CORRECTIVE ACTION REQUIREMENTS

- Recalls shall be required for primary emission control components and computers

Problematic critical emission control components should be corrected immediately

- Extended warranties shall be considered for other emission-related components
- Other emission-related components with warranty rates >=25% will require recall

Warranty rates over 25% are indicative of a systemic problem and will require recall regardless of the component

6

PROPOSED NEED FOR CORRECTIVE ACTION WILL BE BASED ON FAILURE RATES

- Manufacturers must attest to an engine family meeting all emission standards and test procedures at the time of certification
- Statutory authority based on HSC 43106 – Each new engine shall be in all material respects, substantially the same in construction as was certified
- CCR 2147 (Demonstration of compliance with Emission Standards) and CCR 2148 (Evaluation of Need for Recall) shall not apply to 2021 MY and newer heavy-duty engine families

Need for corrective action shall be based solely on warranty failure rates

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PROPOSED ENHANCED WARRANTY REPORTING

- Track and report warranty data throughout the extended warranty period for components for which an extended warranty was issued due to high failure rates, and throughout the warranty reporting period for components replaced under recall

  Will allow CARB to determine whether replacements components are in compliance

- EIRs must include a corrective action implementation date no later than 180 days after the EIR is due

  To ensure that corrective action is taken in a timely manner

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PROPOSED WARRANTY REPORTING VERIFICATION

- Create more robust warranty reporting verification processes
  - Manufacturers shall retain warranty parts that were analyzed for warranty reports throughout the useful life of the engine family

  CARB may evaluate parts to verify warranty reporting

  - Manufacturers shall provide information regarding the number of warranty repairs at each repair station upon the Executive Officer's request

  Will aid in verifying warranty reporting and conducting dealer audits

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PROPOSED CLARIFICATION TO USE GOOD ENGINEERING JUDGEMENT

- HD Test procedures will require manufacturers to use good engineering judgement when investigating failures and generating warranty reports

  Currently expected from manufacturers (clarifying)

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PROPOSED CLARIFYING LANGUAGE/MINOR CHANGES

- Eliminating ambiguity for warranty reporting due dates
- Update contact information for submission of warranty reports

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DATA REQUESTS

- What percentage of warranty claims fall under each warranty?
  - 1. 5 year/100,000 mile warranty
  - 2. Base engine warranty
  - 3. Paid extended warranty
- Emissions data for failed components
  - Test data that quantifies the emissions impact of failed components
- Extended warranty purchase rates, pricing, and coverage descriptions
- Highly encourage manufacturers to share data with CARB
- Data from manufacturers will help better refine EWIR regulations

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Appendix 3

CALIFORNIA AIR RESOURCES BOARD

HEAVY-DUTY LOW NOx PROGRAM PUBLIC WORKSHOP

JANUARY 23, 2019

PROPOSED DURABILITY DEMONSTRATION PROGRAM FOR ON-ROAD HEAVY-DUTY DIESEL-CYCLE ENGINES

MOBILE SOURCE CONTROL DIVISION

DURABILITY DEMONSTRATION PROGRAM (DDP) - BACKGROUND

- The objective of the certification DDP is to:
  - Demonstrate that each certified engine family meets the applicable emissions standards at the end of its useful life (UL)
  - Demonstrate emission related component durability throughout UL (subject to scheduled maintenance intervals)
- DDP is a certification requirement
- For heavy-duty diesel engines, DDP is currently performed by aging the engine and aftertreatment system (EAS) to a portion of the useful life (≈35-50% UL) on an engine dynamometer
- Since EAS is currently aged to a portion of UL, the deteriorated full UL emissions are estimated by linear extrapolation of emissions data from the DDP

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NO PROPOSED CHANGES FOR HEAVY-DUTY OTTO-CYCLE DDP

- The following proposals apply only to engine families that are certified through heavy-duty diesel test procedures
- Engine families certified through heavy-duty Otto-cycle test procedures will continue to use the existing procedures to demonstrate full UL durability demonstration. Adjustments to the useful life period will need to be considered.

PROPOSED DDP PROCESS

- **Goal**
  - Obtaining Deterioration Factor (DF) values that better reflect real world deterioration for EAS at time of certification
- **Method**
  - Standardizing the DDP Process for 2022 and subsequent model year NEW heavy-duty diesel engine families (does not apply to 2022 model year carryover engine families)
- **Elements**
  - Regenerations prior to emissions tests
  - Break-in Period

    (Regenerations and Break-in Period: Applicable to durability & certification engines)
  - Standardized Dynamometer Aging Cycles & Accelerated Aftertreatment Aging option
  - Opportunities for validation of durability via in-use and NOx sensor data in 2026+ MY (Alternate Durability Program Concept)

REGENERATIONS BEFORE OFFICIAL EMISSIONS TESTS

- New preconditioning procedures to minimize the impacts of auto and manual regenerations on emissions test results
  - Need to assure that emission levels have stabilized prior to an official emissions test
- Manual regenerations
  - If used, report in the certification application or durability test results
  - No emissions test allowed until 40 hours of service accumulation after each manual regen event
- Auto regenerations (includes: soot cleaning, ammonia de-crystallization, sulfur removal, hydrocarbon removal, etc.)
  - No emissions test allowed until 10 hours of service accumulation after each auto regen event

BREAK-IN PERIOD

- Initial break-in period is required to assure that emissions are stabilized before an official emissions test is conducted
- Survey of on-road heavy-duty diesel-cycle durability data indicate that the current default 125 hours of break-in period is insufficient for achieving stabilized emissions
- Propose to increase the default break-in period to 300 hours
  - Similar to Tier IV off-road compression-ignition engines
- Manufacturers may propose alternate break-in period as described in §86.004-26(c)(4). Must provide actual emission test results at various intervals to verify that FTP, SET and Low Load Cycle (LLC) stabilized emissions have been reached for each engine family

NEED FOR DDP REVISIONS

- Staff believes that current 35-50% of UL method does not fully represent real life component failures and emission deterioration of EAS
- Need to enhance the process for EAS aging
- OBD regulations (adopted Nov. 2018) defined a standardized process for OBD-aging
  - Objective is to obtain similar OBD system response between laboratory aging and real-life in-use aging
- Certification DDP objectives & compliance evaluation process are different:
  - Demonstrate emission related component durability,
  - Estimate expected deterioration of EAS over UL, i.e. develop DFs

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DDP PROPOSAL

- Goal is to have a program that represents full UL (FUL) EAS aging
- Manufacturers must use standardized DDP process and aging cycles for all certified products
  - For EAS aging on a dynamometer, we propose two possible pathways:
    - Pathway 1 - Use the standardized certification cycles (FTP, SET) for aging
    - Pathway 2 - Use Phase 2 GEM model to create engine aging cycle
    - Select the pathway which yields the highest cycle-average engine power level (CAPL) based on maximum engine power
- An option for using Diesel Aftertreatment Accelerated Aging Cycle (DAAAC*) protocol is proposed for a portion of the durability testing period for HHDD
- Other accelerated aftertreatment aging processes under development may also be considered in lieu of DAAAC (subject to CARB pre-approval)

* https://cleers.org/wp-content/uploads/formidable/3/Bartley_CLEERS2012.pdf

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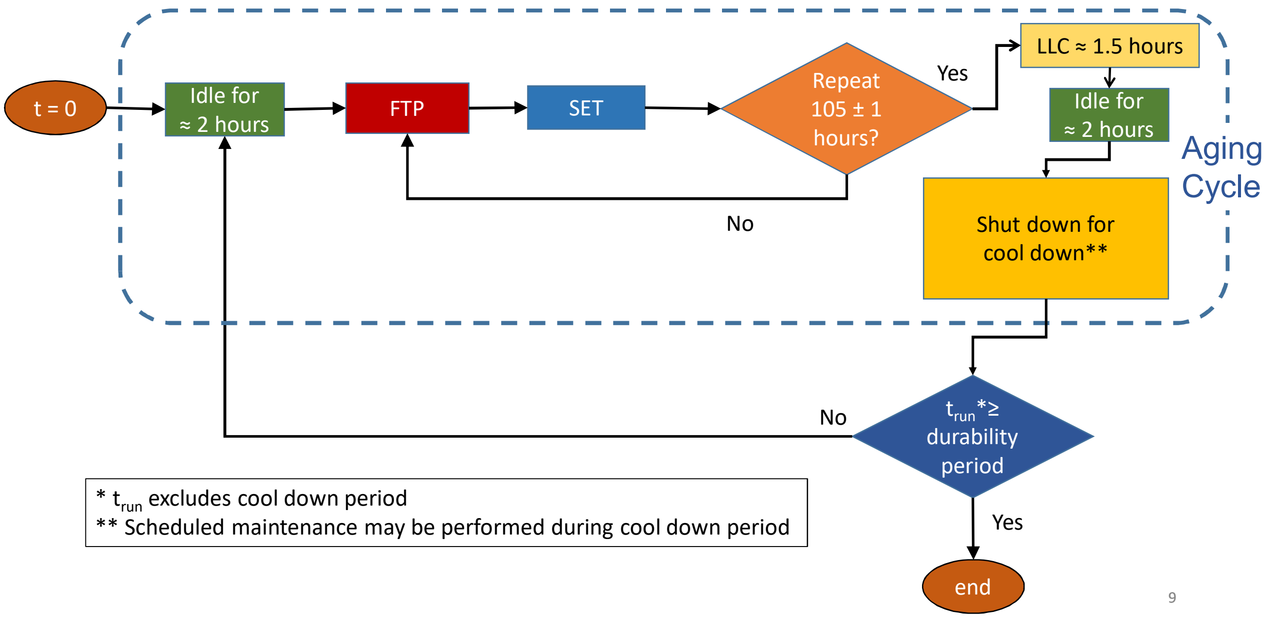
Pathway 1 – Engine Certification Cycles



* t_{run} excludes cool down period
** Scheduled maintenance may be performed during cool down period

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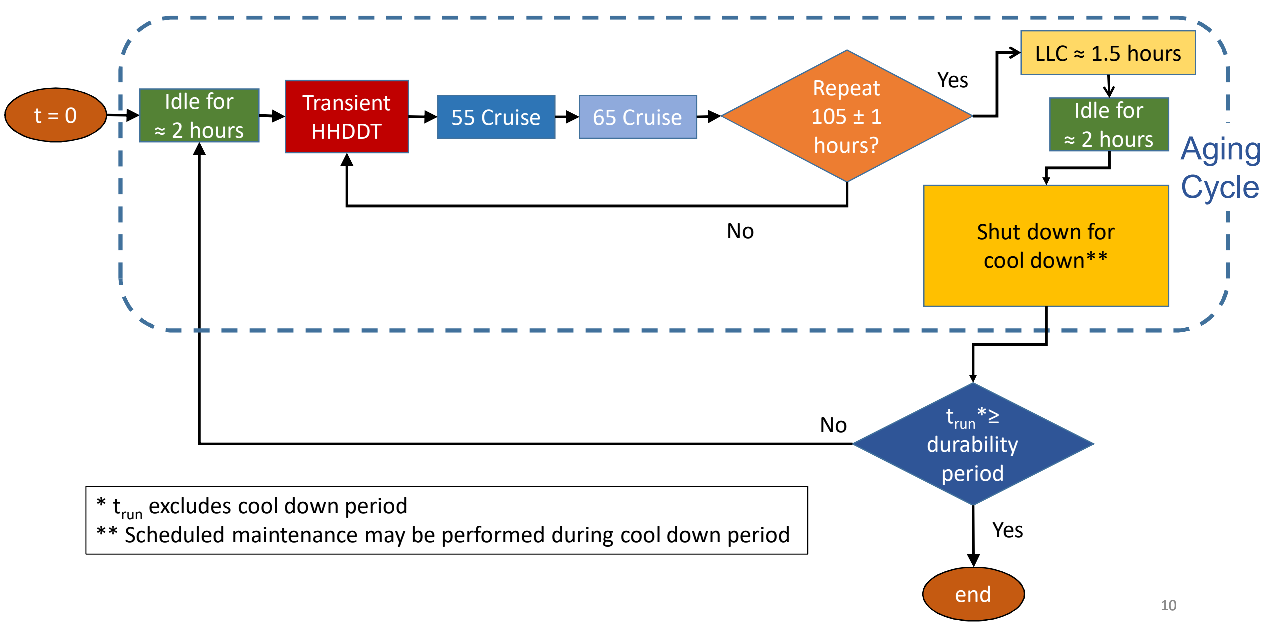
Pathway 2 – Phase 2 GEM Drive Cycles



* t_{run} excludes cool down period
** Scheduled maintenance may be performed during cool down period

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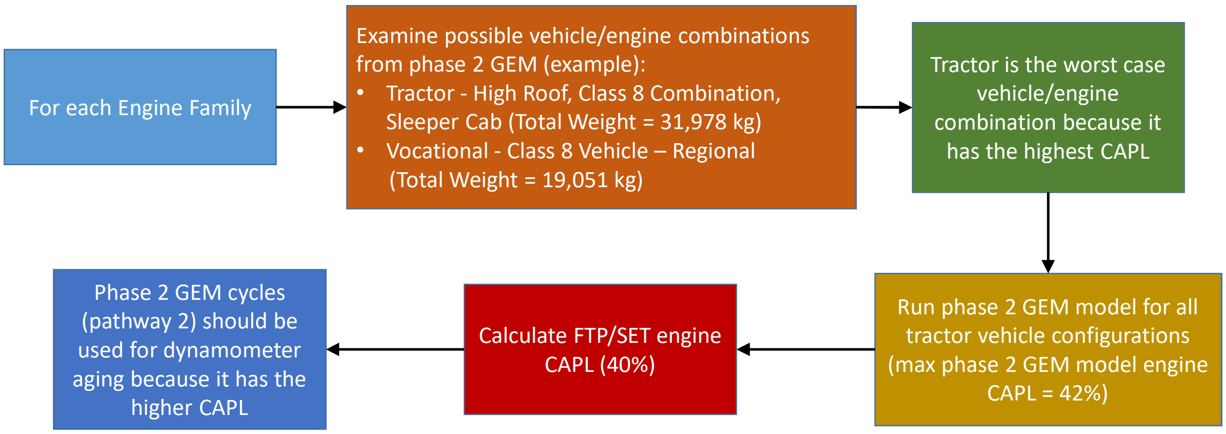
Example – Dynamometer Pathway Selection Process (for illustration purpose only)



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PROPOSED DDP SERVICE ACCUMULATION SCHEDULES

Primary Intended Service Class	Current UL (miles)	DDP Procedures
LHDD	**110,000**	Age EAS on dynamometer to FUL using pathway 1 or 2 cycles **(≈ 2,500* hours)**
MHDD	**185,000**	Age EAS on dynamometer to FUL using pathway 1 or 2 cycles **(≈ 4,200* hours)**
HHDD	**435,000**	Two possible options: • Age EAS on dynamometer to FUL using pathway 1 or 2 cycles **(≈ 9,800* hours)**, or • Age EAS on dynamometer for 4,600 hours using pathway 1 or 2 cycles, and then age aftertreatment only using DAAAC for an additional 500-600 hours (equivalent to ½ UL). Age for 300 additional dyno hours **(≈ 5,500* hours).** This option requires NOx sensor data submittal.

* Service accumulation schedule DOES NOT INCLUDE time required for cool down. Assumes 11 MPH average speed and 1.5 hour duration for LLC (subject to change).

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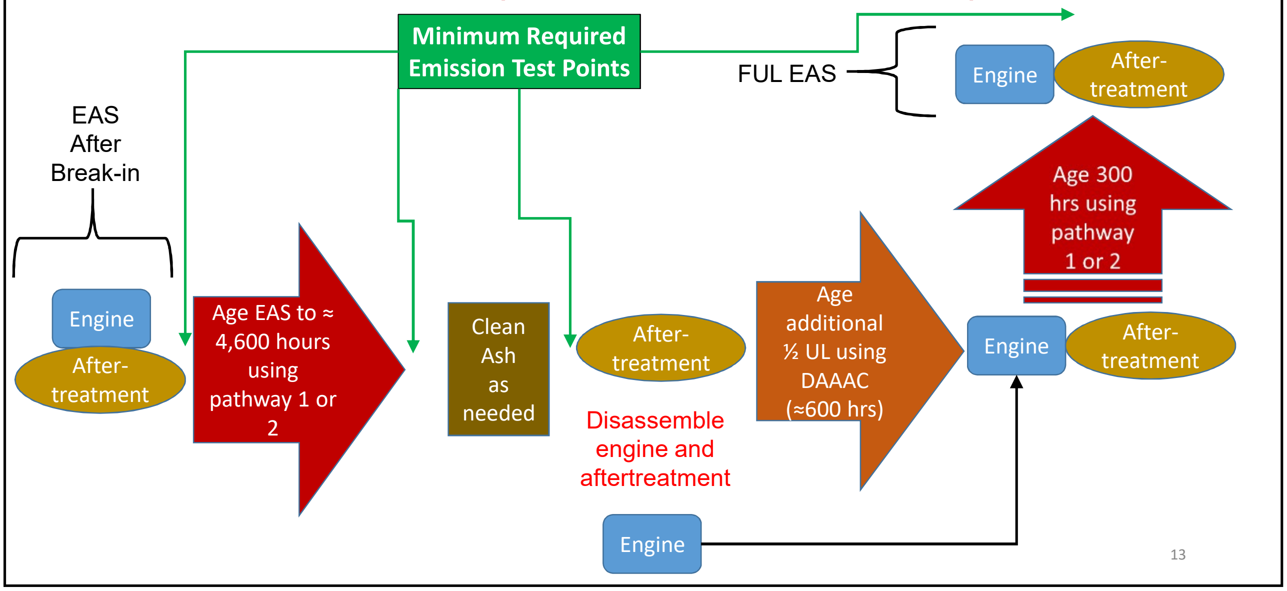
Combined Dyno aging + DAAAC Protocol for HHDD (UL = 435,000 miles)



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ALTERNATE DURABILITY PROGRAM CONCEPT (2026+ MY)

- CARB is considering an increase to UL for all HD primary intended service classes beyond current values starting with 2026 MY
- By 2026 MY, CARB anticipates that a combination of in-use test data, lab aging data, and NOx sensor reporting may lead to the development of an alternate durability program that relies on submittal of NOx sensor reports combined with a shortened lab aging program
- Manufacturers with high emission related component failure rates may not be eligible to use the accelerated aftertreatment aging option or alternate durability program

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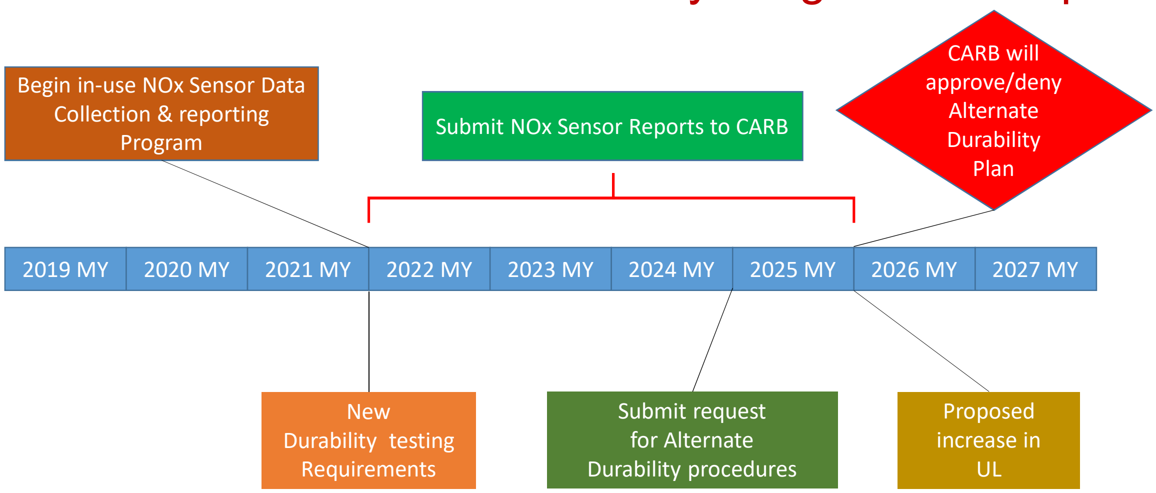
Timeline – Alternate Durability Program Concept



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Appendix 4

CALIFORNIA AIR RESOURCES BOARD

HEAVY-DUTY LOW NOx PROGRAM WORKSHOP

JANUARY 23, 2019

LOW LOAD CYCLE DEVELOPMENT

MOBILE SOURCE CONTROL DIVISION

CALIFORNIA AIR RESOURCES BOARD

OBJECTIVE

- Current engine certification cycles (HD-FTP and RMC-SET):
  - Do not account for sustained low load operations
  - Too short to adequately test for active thermal management of aftertreatement system
- Objective is to develop a new Low Load Cycle (LLC) that:
  - Is representative of real-world urban tractor and vocational vehicle operations that are characterized by low engine loads
  - Has average power and duration adequate for demonstrating that hardware and controls needed to deal with low load challenges are present and functional
  - Has emission standard that balances the need for NOx emission reductions and any associated GHG emission impacts
- Work performed under Stage 2 of the Low NOx Demonstration program by SwRI (with support from NREL)

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LOW LOAD CYCLE DEVELOPMENT STEPS

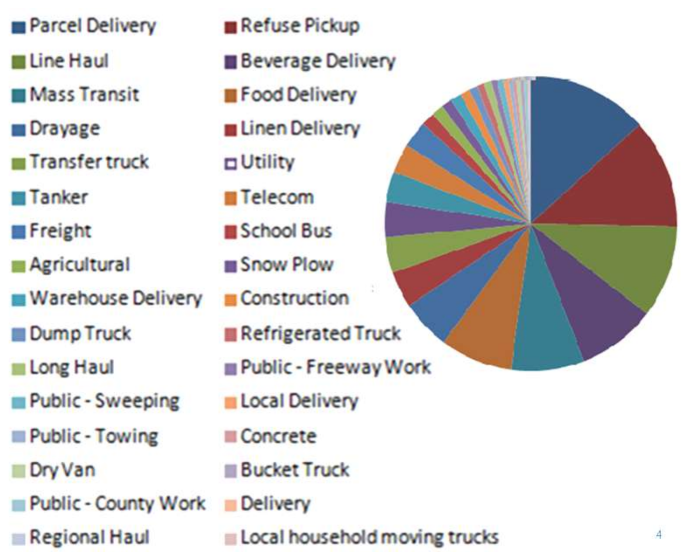
1. Development of Low Load Vehicle Profiles (NREL) ✓
2. Translation of Vehicle-Based Profiles to Engine-Based Ones (SwRI) ✓
3. Testing of Low Load Engine Profiles (SwRI) ✓
4. Development of Candidate Low Load Cycles (NREL / SwRI) ✓
5. Testing of Candidate Low Load Cycles (SwRI) ✓
6. Selection of Final Low Load Cycle (CARB / SwRI) – In Progress

ANALYSIS OF VEHICLE ACTIVITY DATA

<u>Source Datasets</u>

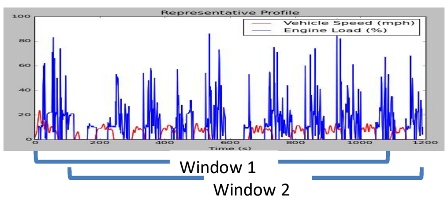
Fleet DNA + CARB HDDV Activity Data

- 751 vehicles
- 25 Locations across the US (predominantly in CA)
- 55 Fleets
- 44 Vocational Designations
- ~600+ GB of raw data

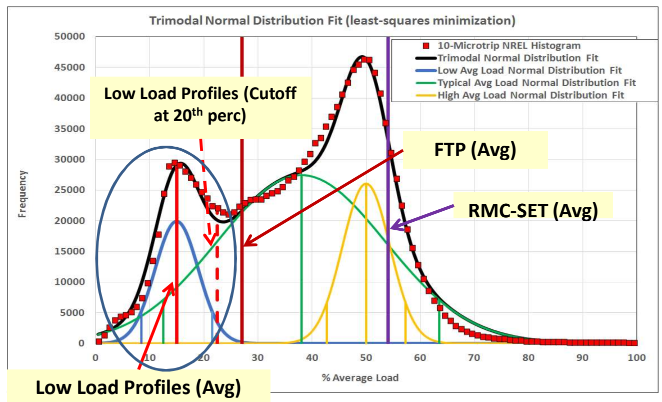


DEVELOPMENT OF LOW LOAD VEHICLE PROFILES

- Data analyzed using moving windows of 10 microtrips



- ~1.25 million windows (profiles) obtained
- Only profiles with average loads below 20% were further considered for constructing the LLC



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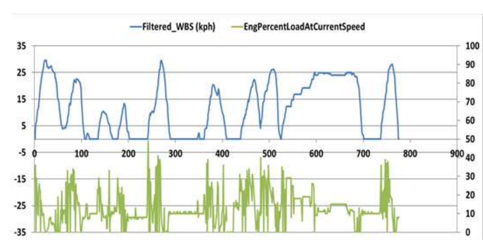
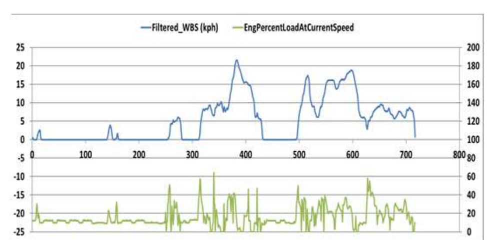
CLUSTERING AND SELECTION OF REPRESENTATIVE PROFILES

- K-means clustering applied to the population of profiles to identify groups with similar characteristics
  - A total of 3 clusters were identified
- To identify most representative profiles, results for each cluster were ranked based on their distance to cluster center
- Starting with profiles closest to cluster center, profiles examined for behavior and final suitability for testing
- Profiles with outlying behavior removed from list





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BASIC EMISSION CONTROL CHALLENGES

- An effective Low Load Cycle will test all three of the following challenges:
  - High Load-to-Low Load Transition
    - Drive to work-site then lower load work or idle period
    - How long can system maintain performance and manage heat during prolonged cool-off?
  - Sustained Low Load
    - Repeated short transients separated by idle (delivery, refuse, transit bus, drayage)
    - Can system maintain heat levels long-term?
  - Low Load-to-High Load Transition
    - Long downhill grade transition to uphill (Tractor)
    - Long idle transition to highway work
    - Can system handle abrupt increases in engine-out emissions?

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SUMMARY OF REPRESENTATIVE PROFILES

Profile	Vehicle	Cluster	Length	Avg % Speed	Avg % Torque	Repeats in SwRI Test Runs	Class	Chassis	Engine	Trans	Gears	Vocation
1	v9892	0	800	26.9	6.9	4	8	4x2	Volvo D13	AMT	12	Food Service
2	v11660	0	1295	21.4	6.6	3	8	6x4	Mack MP8-415C	MT	13	Drayage
3	v075	0	1130	26.3	7.4	3	8	6x4	Mack MP8-415C	AMT	10	Drayage
4	v11815	1	1949	11.5	8.8	3	8	6x4	Cummins ISX 15	MT	13	Transfer Truck
5	v11646	1	904	15.9	10.7	4	4	4x2	Cummins ISB 6.7	AT	6	Parcel Delivery
6	v073	1	1410	33.8	18.1	3	8	6x4	Mack MP8-415C	AMT	10	Drayage
7	v9892	1	1616	27.0	10.6	3	8	4x2	Volvo D13	AMT	12	Food Service
8	v11660	5	615	16.2	3.5	4	8	6x4	Mack MP8-415C	MT	13	Drayage
9	v11806	5	1810	7.5	6.8	3	8	6x4	Cummins ISX 12	AMT	10	Transfer Truck
10	v11817	5	739	15.3	7.7	4	8	6x4	Cummins ISM 11	AMT	10	Transfer Truck

❖ Load data broadcast by engines not sufficiently accurate for use directly to create engine cycle, so used Phase 2 Greenhouse Gas Emissions Model (GEM) simulation model to translate vehicle-based profiles to engine-based ones

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INITIAL CANDIDATE CYCLES

- Five primary types of events were observed in the low load profiles:
  - Sustained low load
  - Long idle
  - Motoring/short idle cooling
  - Post-cooling breakthrough (high load segments)
  - Mid-speed cruise-motoring
- Initial candidate cycles were constructed to include one example of each of the 5 types of events
- Did not always use the entire profile if the key segment could be completed in a shorter time

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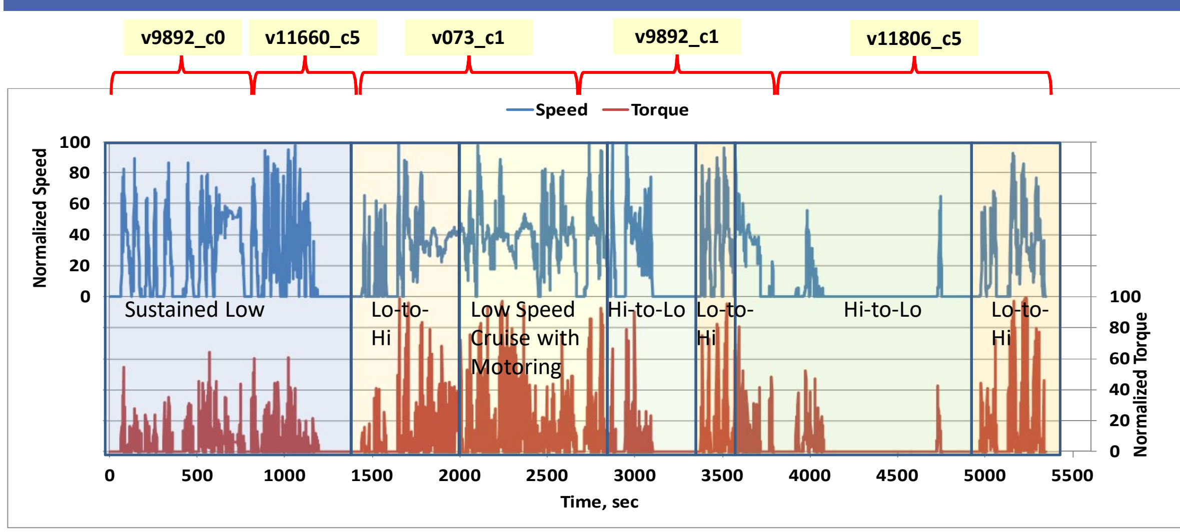
EXAMPLE CANDIDATE CYCLE



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OTHER CONSIDERATIONS

- Preconditioning procedure to bring engine to temperature and warm aftertreatment
  - 1 FTP + 20 min soak
- Longer duration for long idle segment?
  - Not productive, no change in results
- Longer or shorter sustained low load segment?
  - Pro: countermeasure for higher thermal inertia systems
  - Con: longer cycle time
- Longer or shorter mid-speed cruise/motoring segment?
  - Pro: bridges space from rest of LLC to FTP in terms of power, covers upper corner of low load space
  - Con: inclusion does raise overall temperatures, but minor effect, also longer cycle time

FINAL CANDIDATE CYCLES

- LLC Candidate #7 – 90 min
  - 30 min sustained low load segment
  - Retains v073 mid-speed cruise/motoring segment
- LLC Candidate #8 – 81 min
  - 30 min sustained low load segment
  - Shorter v073 mid-speed cruise segment for breakthrough only
- LLC Candidate #10 – 70 min
  - 20 min sustained low load segment
  - Shorter v073 mid-speed cruise segment for breakthrough only

Currently favored by CARB Staff (Candidates #7 and #8)

LLC Candidates – Test Results on Engine E

Candidate	Duration [min]	Conversion efficiency [%]	Engine Out NOx [g/bhp-hr]	Engine Out NOx [g NOx/kg CO2]	Tailpipe NOx [g/bhp-hr]	Tailpipe NOx [g NOx/kg CO2]
#7	90	74	3.2	4.4	0.8	1.1
#8	81	77	2.9	4.1	0.7	0.9
#10	70	69	3.2	4.3	1.0	1.3

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PLANNED LLC REQUIREMENTS

- LLC standard will be based on:
  - SwRI Stages 2 and 3 calibration test results
  - Potential GHG emission impacts
  - Could be a standalone standard or combined with other test requirements
    - e.g., incorporate idle test within the LLC test (to reduce testing burden)
- Conformity factor for LLC and in-use testing requirements:
  - May be same or different, depending on SwRI LLC optimization results
- May include a CO_2 emissions cap
- Preliminary proposal on LLC standard /CO_2 cap: March 2019 workgroup Meeting

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Backup Slides

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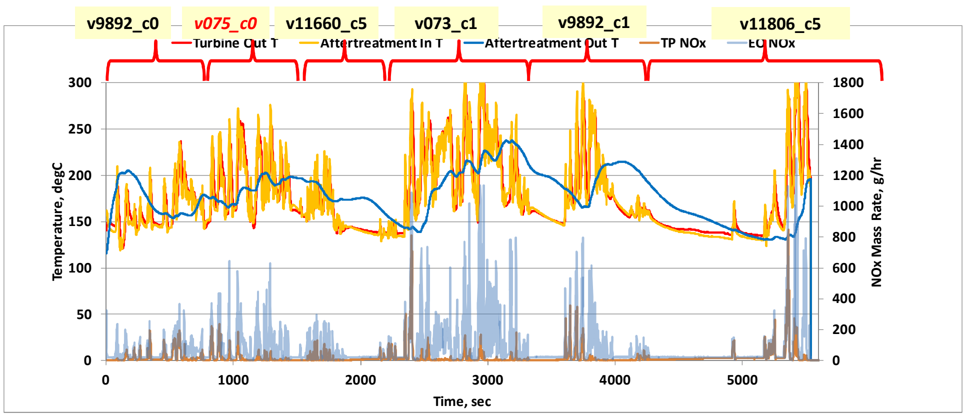
LLC Candidate 7 – Test Results on Engine E



- Overall 74% conversion
- EO NOx (g/hp-hr / g/kgCO2) = 3.2 / 4.4
- TP NOx (g/hp-hr / g/kgCO2 = 0.8 / 1.1

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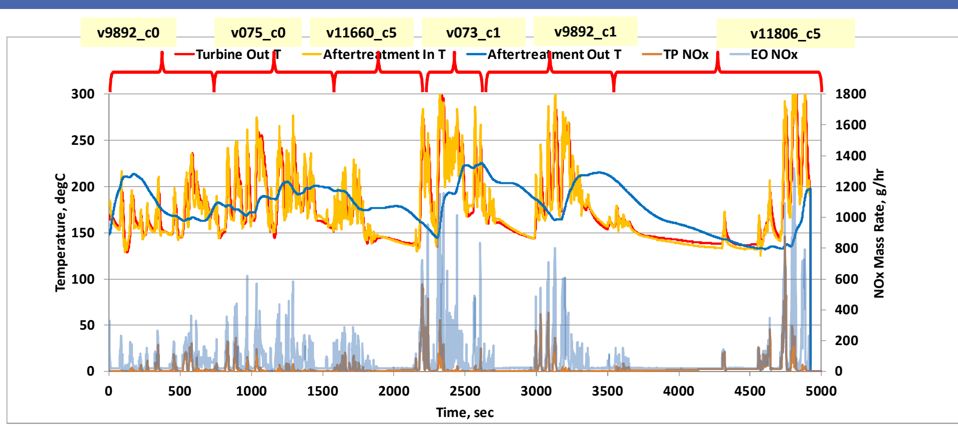
LLC Candidate 8 – Test Results on Engine E



- Overall 77% conversion
- EO NOx (g/hp-hr / g/kgCO2) = 2.9 / 4.1
- TP NOx (g/hp-hr / g/kgCO2 = 0.7 / 0.9

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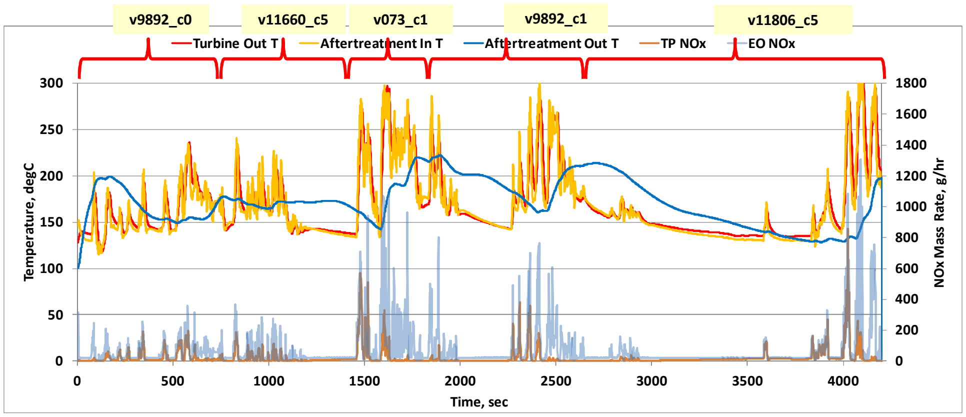
LLC Candidate 10



- Overall 69% conversion
- EO NOx (g/hp-hr / g/kgCO2) = 3.2 / 4.3
- TP NOx (g/hp-hr / g/kgCO2 = 1.0 / 1.3

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