Final Report
Heavy-duty On-Road Vehicle Inspection and Maintenance Program
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Abstract

The implementation of an enhanced heavy-duty (HD) Inspection and Maintenance (I/M) program could be a critical element in ensuring the emissions performance of heavy-duty vehicles (HDVs) over their full useful life. The objective of this study was to evaluate and assess alternatives for a more comprehensive HD I/M program that could be implemented in California. The study incorporated a literature review, a prototype pilot study, analysis of the pilot study data, and recommendations.

A pilot study with 47 vehicles and 51 repairs was conducted where emissions were measured before and after repair. Vehicles were recruited based on the check engine light being on indicating that the engine control module (ECM) had identified a repair or maintenance need in one of the 22 categories targeted for the study. The results showed that nitrogen oxides (NOx) reductions of greater than 80% were found for 43% of the 30 miles per hour (mph) tests and 28% of the 50 mph tests after repair, with the highest emitters showed greater than 80% NOx reductions under all conditions. For the full fleet of vehicles recruited with the check engine light on, the fleet average NOx emissions reductions were 75% at 30 mph and 46% at 50 mph. For the vehicles with the diagnostic malfunction DM1 malfunction indicator light (MIL) on pre-repair, showing the vehicle had an active diagnostic trouble code (DTC) indicating an emissions-related malfunction in addition to having the check engine light on, the fleet average NOx emissions reductions were 81% at 30 mph and 53% at 50 mph. For both of these scenarios, Navistar trucks not equipped with selective catalytic reduction (SCR) and vehicles where the DM1 MIL was on post-repair were excluded.

The pre-repair opacity snap acceleration values were 5% or less for all but 8 vehicles. Of the 8 vehicles with pre-repair opacity readings that were above 5%, 6 vehicles showed reductions in opacity to below the 5% level for the post-repair tests. Fleet average reductions of 43% in opacity were found for both all vehicles with the check engine light on pre-repair and for vehicles that also had the DM1 MIL on, excluding the Navistar trucks and the vehicles where the DM1 MIL was on for the post-repair test. Particulate matter (PM) mass measurements during the 30 and 50 mph tests were low, and could not be adequately measured by some of the PM instruments. Solid particulate number (PN) and PM instruments showed greater sensitivity in measuring at such low PM levels than the I/M grade PM mass measurements. Although a DPF was replaced on one vehicle, the other vehicles did not appear to have catastrophic DPF failures. It is suggested that further studies be conducted to better understand potential PM-related repair benefits for 2010+ vehicle technologies.

Analysis of more extensive two-year repair records indicated that 26% of the 2010+ vehicles had their check engine light on upon arrival at the repair facility. Based on estimates from the pilot study, is estimated that approximately 62.5% of vehicles recruited with the check engine light on, also had the DM1 MIL on. This would represent approximately 16% of the 2010 in-use fleet based on the average mileage of 522,000 miles for the vehicles found in the repair records. It should be noted, however, that this does not necessarily represent the fraction of check engine lights and DM1 MILs on in the on-road HDV fleet, as vehicles needing repairs would be preferentially found at repair facilities.

The average repair costs per vehicle were $1,803 for vehicles with check engine lights on and $2,037 for vehicles with the DM1 MIL on, with a range from $250 to approximately $8,660. The most costly repairs were primarily those associated with the replacement of major parts, such as

diesel particulate filter (DPF), selective catalytic reduction (SCR) catalyst, turbocharger, or injector doser, while less expensive repairs included those that were sensor replacements.

Based on a review of the potential methods, we propose that a revised HD I/M program incorporate both OBD and tailpipe methods, in a manner that is cost effective and that provides cross confirmation between the different methods. This could include OBD as the primary methodology for HD I/M, with the possibility of using telematics kiosks to the extent that such technology is available. The HD I/M program could also include roadside monitoring with a remote sensing device (RSD)-like system to capture any vehicles that might be missed in an OBD-only HD I/M program and for the portion of the fleet not equipped with full OBD systems starting with 2013 model year engines. Finally, mini-portable emissions measurement systems (mini-PEMS) could be used on a more limited basis to verify RSD emissions readings in identifying high emitters and as a check on the OBD effectiveness. The gas-phase mini-PEMS showed good potential for identifying high NOx emitters in the pilot study, but the different PM/PN mini-PEMS did not show consistent trends between instruments. Additional study is suggested to identify a suitable PM/PN mini-PEMS for this application.

Overall, the testing results suggest that a HD I/M program will provide significant and tangible emission benefits and can be an integral component of California's ability to meet federally-mandated ambient air quality standards, and CARB's overall air quality, sustainable freight, and climate goals.

Acronyms and Abbreviations

BAR ....California Bureau of Automotive Repair
BC ....Black Carbon
Bhp-hr ....Brake Horsepower-Hour
CAA ....Clean Air Act
CARB..California Air Resources Board
CC ....Cubic Centimeter
CDPHE ....Colorado Department of Public Health and Environment
CFR ....Code of Federal Regulations
CH_4 ....Methane
CO ....Carbon Monoxide
CO_2 ....Carbon Dioxide
CPC ....Condensation particle counter
CTP ....Continuous Test Program
CRC..Coordinating Research Council
CUEDC ....Composite Urban Emissions Drive Cycles
CVN ....Calibration Verification Number
DDV ....Durability Demonstration Vehicle
DPF ....Diesel Particulate Filter
DRI...Desert Research Institute
DTC..Diagnostic Trouble Codes
ECL ....Emissions Control Label
ECM...Engine Control Module
EDAR...Emission Detecting and Reporting
EF_{BC} ....Black Carbon Emission Factors
EF_{NOX} ....NO_X Emission Factors
EGR..Exhaust Gas Recirculation
ERG..Eastern Research Group
FEAT..Fuel Efficiency Automotive Testing device
GHG...Greenhouse gases
GVWR ....Gross vehicle weight rating
HC ....Hydrocarbon
HD..Heavy-duty
HDET...Heavy-Duty Emissions Tunnels
HDIUT ....Heavy-Duty In-Use Testing
HDV...Heavy-Duty Vehicle
HDVIP ....Heavy-Duty Vehicle Inspection Program
HEAT...Hager Environmental & Atmospheric Technologies
H.E.R.O.S. ....High Emitter Repair or Scrap program
HTCC...High Temperature Co-Fired Ceramic
ICCT ....International Council on Clean Transportation
I/M..Inspection and maintenance
IoT..Internet of Things
iPEMS...Integrated Portable Emissions Measurement System
KW/t...Kilowatts per Ton
LD ....Light-duty

LiDAR..Light Detection And Ranging
LLSP ....Laser Light Scattering Photometry
LPG..Liquified petroleum gas
LPR..License Plate Reader
MAHA ....Maschinenbau Haldenwang GmbH & Co. KG
MEL..Mobile Emissions Laboratory
METAS...Swiss Institute of Metrology
MIL ....Malfunction Indicator Light
Mph..Miles per Hour
MY ....Model Year
NCEM..Compact Emissions Meter
NDIR...Nondispersive Infrared
NO..Nitric Oxide
NO_2 ....Nitrogen Dioxide
NOx..Oxides of Nitrogen
NPET..Nanoparticle Emissions Tester
NRNM..Non-road Mobile Machinery
NTE..Not-to-Exceed
O_2 ....Oxygen
OBD ....On-Board Diagnostics
OEM..Original Equipment Manufacturer
OHMS ....On-road Heavy-duty vehicle emissions monitoring system
OIS ....OBD Inspection System
PAMS..Portable Activity Measurement System
PEAQS ....Portable Emissions AcQuisition System
PEMS ....Portable Emissions Measurement System
PEPA...Portable Emission Particle Analyzer
PM..Particulate Matter
PM10..Particulate Matter with a size up to 10 microns
PN ....Particle Number
PPM..Parts per Million
PSIP..Periodic Smoke Inspection Program
R^2 ....Coefficient of Determination
RDE..Real Driving Emissions
RSD..Remote Sensing Devices
SAE ....Society of Automotive Engineers
SCAQMD ....South Coast Air Quality Management District
SIM ....Subscriber Identification Module
SCR..Selective Catalytic Reduction
SHED ....Streamlined Heavy-Duty Emissions Determination
TEOM ....Tapered Element Oscillating Microbalance
THC..Total Hydrocarbons
TM&M..Tampering, mal-maintenance, and control component malfunction
TRUE ....The Real Urban Emissions project
USC..United States Code

USEPA .... United States Environmental Protection Agency
VID .... Vehicle Information Database
VIN .... Vehicle Identification Number
VSP .... Vehicle Specific Power
Whp-hr .... Wheel Horsepower-Hour

Executive Summary

Emissions from on-road heavy-duty (HD) vehicles are major contributors to poor ambient air quality in California. HD vehicles (HDVs) and engines have been the subject of progressively more stringent emissions regulations over the past several decades, with the latest generation of regulations requiring exhaust aftertreatment for the control of both nitrogen oxides (NOx) and particulate matter (PM) emissions. Despite these significant reductions, on-road HDVs with gross vehicle weight ratings (GVWRs) of greater than 14,000 lbs. are still projected to represent 24% of NOx and 10% of PM tailpipe emissions statewide from all mobile sources in 2025 based on EMFAC2017 estimates. Although turnover to newer trucks meeting more stringent emission standards is reducing emissions, it is also important to ensure that the emissions from these vehicles do not significantly deteriorate over the course of their full operating lifetime. California's existing heavy-duty vehicle inspection program comprises the roadside Heavy-Duty Vehicle Inspection Program (HDVIP) and the fleet Periodic Smoke Inspection Program (PSIP). More recently, CARB has put forth and is in the process of implementing new opacity limits of 5% for diesel particle filter (DPF)-equipped HDVs for both the HDVIP and PSIP (CARB, 2018a). While these programs provide some important benefits in maintaining emission levels of HDVs, they do not include inspections for NOx emissions and NOx aftertreatment systems from the in-use fleet, nor do they incorporate the use of on-board diagnostics (OBD). In order to better ensure that modern diesel engines are maintained and repaired to continue to meet emissions performance requirements in-use, California is now in need of a more comprehensive heavy-duty vehicle inspection and maintenance program (HD I/M).

The objective of this study was to develop, evaluate, and assess options for a more comprehensive HD I/M program for vehicles over 14,000 pounds GVWR, and to provide recommendations for the implementation of a full-scale program. This effort included a literature review, and a demonstration and evaluation of a prototype HD I/M program. The pilot study included measuring pre- and post-repair emissions for 47 vehicles at a local repair facility with a suite of instruments that included OBD scans, chassis dynamometer measurements with a number of mini-portable emissions measurement systems (mini-PEMS), as well as measurements with an Emissions Detecting and Reporting (EDAR) remote sensing device and a Portable Emissions AcQuisition System (PEAQS). The pilot study results were evaluated in terms of the emissions reductions obtained from the repairs and the cost of the repairs. The study results can be used by the CARB to help inform staff as it considers developing a comprehensive HD I/M program as part of its broader policy efforts to meet federally-mandated ambient air quality standards and CARB's overall air quality, sustainable freight, and climate goals.

A summary of the results of this study are as follows:

Literature Review

The main emphasis of the literature review was to evaluate potential methodologies and instruments that could be utilized for a HD I/M program and propose a framework for the prototype HD I/M study that was conducted as part of this project. A summary of the main features and costs of different methodologies is provided in Table ES-1 below.

Table ES-1. Summary of Main Features of Various I/M Methodologies

Methodology	Pollutants	Ease of Use/Test time	Initial Capital Costs*
Repair grade chassis dyno with I/M grade analyzers	NOx, PM, THC, CO, CO_2	Requires reporting to station location, 30 minutes to 1 hour for set up and actual testing	$170k for dynamometer with installation and I/M grade analyzers
1065-compliant PEMS	NOx, PM, THC, CO, CO_2	Requires mounting PEMS and driving truck, several hours to a full day	$100k to $120k for gas-phase $200k to $220k for gas-phase + PM
Mini-PEMS (sensor-based or solid PN)	NOx, PM, THC, CO, CO_2 for full system or a PM/PN only system	Testing under idle or snap acceleration conditions could take 10 minutes. Tests that require driving with mini-PEMS could be longer and prohibitively inconvenient	$30k to $50k
Remote Sensing Devices	NOx, PM, THC, CO, CO_2	Test conducted while truck is driven by and could be unmanned	$20k to 200k and upwards depending on complexity of set-up
OBD – repair station scan	Monitors system components related to NOx, PM, and HC emissions	10 to 20 minutes to conduct and record scan	OBD incorporated onto truck
OBD – kiosk system (physical connection)	Monitors system components related to NOx, PM, and HC emissions	Cable to download data from truck	Capital costs for a kiosk would be ~$50k with another ~$50k for installation
OBD – remote transmission methods	Monitors system components related to	Wireless transmission to a designated database	$50-$100 per unit for dongle

	NOx, PM, and HC emissions		Minimal costs for Wi-Fi data transmission
OBD – remote continuous monitoring	Monitors system components related to NOx, PM, and HC emissions	Data transmission through a cellular network	~ $17 per month per vehicle beyond the cost of the dongle

* Note that the capital costs reflect the costs for the purchase of major pieces of equipment. The actual per test cost would be considerably less than that and would depend on many factors, including the volume of the testing, the specifics of the testing requirements, and other items.

A summary of the results of this literature review portion of the study for the different methods is as follows:

Tailpipe Emissions Measurements

Tailpipe emission measurement methodologies that were evaluated included chassis dynamometer emissions measurements, portable emissions measurement systems (PEMS), and remote sensing devices (RSD).

- Dynamometer testing represents one of the most intensive methods that could be utilized for a HD I/M program, and it provides the best potential to correlate with laboratory grade emission measurements. However, the implementation of a dynamometer based inspection system that could service the full population of trucks in California, and the burden that would be associated with pulling vehicles out of service to go to such facilities on an annual basis make this option impractical for a full HD I/M program implementation.
- PEMS can include both fully 1065-compliant PEMS, which represent laboratory grade measurement accuracy, and smaller mini-PEMS that are designed to provide quality measurements without meeting full regulatory requirements. PEMS that are 1065-compliant meet the most stringent specifications, as spelled out under 40 Code of Federal Regulations (CFR) 1065, which are the requirements that PEMS must meet for in-use regulatory testing. The cost and level of intrusion on the HDV operator is still an issue with fully 1065-compliant PEMS, with the capital costs ranging from $100,000 to $120,000 for a gas-phase PEMS, and from $200,000 to $220,000 if a PM PEMS is also included. Mini-PEMS can be more readily deployed and are considered as a possible method to validate high emissions identified from other methods. Costs of mini-PEMS can vary from $30,000 to $50,000 for a more complete sensor-based type of mini-PEMS with the ability to measure multiple components or designed to meet a traceable metric, such solid PN.
- RSD/On-Road Heavy-Duty Vehicle Emissions Monitoring System (OHMS)/PEAQS-like systems have the advantage of being non-invasive, having the ability to capture the emissions of vehicles as they are driven by the owner/operator under real-world conditions. As such, these systems do not require that trucks be taken out of service in order to perform such testing. Such systems could be deployed at weigh stations or other suitable locations, and could also provide a methodology for evaluating emissions of vehicles that are not equipped with OBD or to cross check the emissions of vehicles equipped with OBD.

Capital costs for such systems could range from $100,000 or more depending on the complexity of the system design.

On-Board Diagnostics (OBD)

Full OBD systems have been required on heavy-duty engines/vehicles staring with the 2013 model year. OBD monitors all emissions critical devices and systems, stores diagnostic trouble code(s) (DTCs) and illuminates a malfunction indicator light (MIL) when a problem is detected, as required by CARB's regulations.

- A key advantage of OBD is that the vehicle's emission control system is continuously monitored as the vehicle is driven under real-world conditions.
- An OBD I/M test could be relatively quick, convenient to the owner operator, and cost can be considerably less than dynamometer or PEMs-based alternatives for the full fleet.
- The OBD system itself is already integrated into the engine design for 2013 and newer model year engines. Therefore, the only owner-related costs for an OBD-based HD I/M would be those associated with the visit to the repair station, centralized or decentralized inspection facility, or a kiosk, resembling a "drive up" ATM in size, with a physical connection.
- OBD can also be remotely monitored using telematics, which would allow the I/M program to be administered with little intrusion for the owner operator. Upgrading the OBD to remote OBD could be done for less than $100.
- With a remote OBD system, the OBD scan could be performed by a kiosk or other some other roadside antenna through a wireless local area network (Wi-Fi). Data transmission cost would be minimal in this case. Alternatively, OBD scan data could be transmitted on a continuous basis through a cellular network. This option would allow for the OBD system to be queried at any time, regardless of time or location. The costs of data transmission for continuous monitoring would be approximately $17 per vehicle per month.

Pilot Study Results

A pilot study was conducted to evaluate methods of emissions measurement that might be used in an HD I/M program, emissions reductions from repairs, and repair costs. The exploratory pilot program consisted of testing 47 vehicles before and after repair on a chassis dynamometer at two independent repair facilities (45 vehicles were tested at one main repair facility, and 2 vehicles were tested at the other repair facility). Vehicles were recruited on the basis of having the check engine light on upon arriving at the repair facility indicating the need for repair or maintenance in one of the 22 different target categories. The 22 target categories include categories related to selective catalytic reduction (SCR) systems or DPFs and their associated components or sensors, exhaust gas recirculation (EGR), turbocharger, or fuel system-related issues, other sensors, DPF cleans, and other problems. The testing included OBD scans, chassis dynamometer testing with I/M grade emissions analyzers and a number of mini-PEMS, and some RSD and PEAQS measurements before and after the repair.

Emissions Measurements

NOx Emissions

- The pre-repair NOx emissions results measured with a Maschinenbau Haldenwang GmbH & Co. KG (MAHA) analyzer showed that a number of vehicles had NOx emissions higher than 0.20 g/bhp-hr for both the initial 30 and 50 mph tests. The MAHA NOx analyzer is designed for use in a inspection test facility, and as such is not classified as a PEMS or mini-PEMS, and utilizes measurement techniques typical of those used for repair and I/M applications. It should also be acknowledged that the results should not be directly compared to certification standards, which are set for engine dynamometer testing that was not performed in the pilot study.

- The results showed that NOx reductions of greater than 80% were found for 43% of the 30 mph tests and 28% of the 50 mph tests after repair, while the highest emitters showed greater than 80% NOx reductions under all test conditions.
- The mini-PEMS generally were successful in detecting vehicles that showed high NOx emissions for the chassis dynamometer measurements with the I/M repair grade instrument. This suggests the mini-PEMS show the potential for identifying high NOx emitters.
- SCR efficiency calculations were also made based on readings from the inlet and outlet NOx sensors for a subset of 9 vehicles. SCR efficiencies varied from vehicle-to-vehicle, with one engine manufacturer showing SCR efficiencies greater than 75%, and another engine manufacturer having some vehicles with efficiencies higher than 84% and others with pre-repair efficiencies below 70%, including two vehicles with SCR efficiencies below 15% pre-repair. The SCR efficiencies for the two vehicles with very low pre-repair values improved to greater than 90% for most test conditions after repair.

The results for the NOx running exhaust emissions repair benefits for the vehicles in the broader categories having their check engine light on and having the DM1 MIL on pre-repair are provided in Table ES-2. Having the check engine light on is an indication that the engine control module (ECM) has identified a repair or maintenance need in one of the target categories, and this was the criteria for recruiting all vehicles into the pilot study. The subset of vehicles where the DM1 MIL on all had active DTCs indicating an emissions-related malfunction in addition to having the check engine light on. These values include only those vehicles for which the DM1 MIL was off post-repair, which would signify that the vehicle has sufficiently completed what would be the repair process for a HD I/M program. The results also exclude two trucks with Navistar engines that did not utilize SCR aftertreatment, and are estimated to represent only a very small fraction of the fleet by 2025. For the vehicles that were recruited based on the check engine light being on, the fleet average NOx emissions reductions were 75% at 30 mph and 46% at 50 mph. For the vehicles where the DM1 MIL was on pre-repair that fully completed the repair process, the fleet average NOx emissions reductions were 81% at 30 mph and 53% at 50 mph.

Table ES-2 NOx Emission Reductions from Pilot Study

Failure Category	Pollutant	Emission Reduction (30 mph)	Emission Reductions (50 mph)
Check Engine Lights	NOx	75%	46%
DM1 MIL on	NOx	81%	53%

PM Emissions

- The pre-repair opacity values were 5% or less for all but 8 vehicles. Of the 8 vehicles with pre-repair opacity readings that were above 5%, 6 vehicles showed reductions in opacity to below the 5% level for the post-repair tests.

- Fleet average reductions of 43% in opacity were found for both all vehicles with the check engine light on pre-repair and for vehicles that also had the DM1 MIL on, excluding the Navistar trucks and the vehicles where the DM1 MIL was on for the post-repair test.
- PM measurements during the 30 and 50 mph tests were relatively low and could not be adequately measured with some of the PM instruments. Solid PN and PM instruments showed greater sensitivity in measuring at such low PM levels.

In comparing between the different instruments that were used for the measurement of PM and PN, the results were more complicated than for the NOx instrument comparisons. In particular, the opacity, PM mass, and PN measurements generally did not show a strong correlation for measurements on different test vehicles. This is likely due in part to the low PM levels that were found for the test vehicles and the small sample size. The opacity measurements were also done under snap accelerations, whereas the other instruments measured under steady state or idle conditions. Also, the fact that the PM instruments measure different characteristics of PM (mass vs. number), different properties (total vs. solid PM), and different particle size ranges, can influence comparisons between instruments. Most of the PM instruments were generally light weight, easy to use, and had short warmup times. It is suggested that a more systematic study may be needed to better understand the types of instruments that would be most appropriate for identifying PM failures for DPF-equipped vehicles, although other studies have suggested that PN may be the best metric for this application.

Although a DPF was replaced on one vehicle, the other vehicles did not appear to have catastrophic DPF failures. It was also difficult to quantify PM repair benefits because the DPF is often still capable of physically capturing excess PM even if a PM-related repair failure is present. The impact of repairs on soot loading and regeneration frequency and improved maintenance in preventing more catastrophic failures was also not evaluated. It is suggested that further studies be conducted to better understand potential PM repair benefits for 2010+ vehicle technologies.

Other Emissions (THC, CO, and CO_2)

- THC emissions were generally low and fell within a narrow range, but did not show consistent reductions in post-repair emissions.
- CO emissions were also low, and while some vehicles showed reductions in CO emissions after repair, these reductions generally represented very small changes on an absolute level.
- Although some differences in CO_2 emissions were seen between pre- and post-repair testing, the changes in CO_2 emissions could be due to changes in the dynamometer loading, which precluded the characterization of more precise changes in fuel economy.

Repair costs

The repair costs from the pilot study ranged from $250 to approximately $8,660, depending on the extent of the repair needed. The most costly repairs were primarily those associated with the replacement of major parts, such as the DPF, SCR catalyst, turbocharger, or injector doser. Less expensive repairs included those that were sensor replacements or recalibration of the ECM. Based on the pilot study vehicles, the average repair cost per vehicle for a heavy-duty I/M is estimated to be $1,803 for vehicles with check engine lights on and $2,037 for vehicles with the DM1 MIL on pre-repair.

In terms of failure rates in future heavy-duty fleet, an analysis was performed on a repair record database obtained from the main repair facility for a two year period. This analysis indicated that

26% of the 2010+ vehicles, which had an average mileage of 522,000 miles, had their check engine light on upon arrival at the repair facility. The corresponding percentages of check engine lights being on were 27% and 24%, respectively, for 2010 to 2012, and 2013 and newer trucks. Based on estimates from the pilot study, is estimated that approximately 62.5% of vehicles recruited with the check engine light on also had the DM1 MIL on. This would represent approximately 16% of the 2010 in-use fleet at 522,000 miles. It should be noted, however, that this does not necessarily represent the fraction of check engine lights and DM1 MILs on in the on-road HDV fleet, as vehicles needing repairs would be preferentially found at repair facilities.

Recommendations

Based on a review of the potential methods, it is proposed that a revised HD I/M program incorporate both OBD and tailpipe methods, in manner that is cost effective and that provides cross confirmation between the different methods.

OBD as the Primary Methodology of HD I/M

HD OBD systems were designed in anticipation of statewide HD I/M program. Phased in beginning with 2010 model year engines, OBD is required on all 2013 and newer model year heavy-duty vehicles, which will represent approximately 75% of the fleet by 2025. OBD has the ability to monitor all emissions critical components, while the vehicles are in service under "real world" driving conditions. An OBD-based test could be relatively quick, convenient to the owner operator in comparison to other options, and the test costs and burden to the owner can be considerably lower than dynamometer or PEMS-based alternatives. The implementation of telematics OBD could provide further benefits in terms of the ease of carrying out a HD I/M program.

Given that the state owns and operates 51 weigh stations strategically positioned at 37 locations throughout the state and that CARB staff already uses the weigh station infrastructure, in conjunction with the California Highway Patrol, for roadside heavy-duty vehicle testing, it is suggested that site-based OBD information collection systems be installed at these locations. In much the same manner that light-duty kiosks have been established in some states for periodic inspection of the fleet, trucks could be automatically scanned when passing through or by the weigh stations. The cost per transaction (communication from the vehicle to the reader) is relatively low per vehicle and would not represent additional owner/operators cost or inconvenience given existing requirements to visit the scales. Alternatively, data could be monitored continuously through transmissions through a cellular network, although subjecting vehicle owners to continuous monitoring could be more difficult to implement from a practical standpoint.

Coupling of an OBD-based HD I/M with roadside monitoring with a remote sensing methodology

It will be important to have a validation testing element as a supplement to OBD within a comprehensive HD I/M program. It is suggested that one component of a HD I/M program include the implementation of RSD/OHMS/PEAQS-like systems. The advantages of RSD/OHMS/PEAQS-like systems include the fact that the devices are non-invasive, and have the ability to capture emissions of vehicles as they are driven by the owner/operator under real-world conditions. To eliminate the need for trucks to report to a centralized facility, RSD/OHMS/PEAQS-like systems could be set up at truck weighing stations or other locations where there is a high incidence of HDV traffic throughout the state. Such a system that can be operated at a low cost and largely unmanned for extended hours could be key for this implementation. One disadvantage of RSD/OHMS/PEAQS-like systems is that they only evaluate over the limited operating conditions that occur while the HDV is passing through the system. This could lead to conditions where some high emission failures could be missed, while the HDV might also be operated in a manner that might trigger high emissions that would not otherwise be seen under typical operations.

A comprehensive HD I/M program with OBD as the primary methodology, remote sensing and mini-PEMS for validation testing

Although the coupling of OBD with remote sensing will provide for a relatively comprehensive HD I/M program, there are some conditions that may still require additional resolution beyond what could be captured in a pure OBD + RSD program. This could include situations where high emissions don't trigger the OBD MIL and are also not detectable at the limited conditions evaluated by RSD. This could also include situations where an issue is identified under conditions utilized for RSD testing that would not be found under typical operating conditions. Mini-PEMS could be used on a more limited basis to verify emissions readings or the effectiveness of RSD in identifying high emitters. Mini-PEMS could be utilized at weigh stations or in fleets similar to the PSIP for this purpose, and could provide significant advantages in sensitivity compared to current opacity testing. This could be similar to the solid PN instruments that are being used in Europe under Swiss Regulation 941.242 for non-road equipment. Such testing would need to be designed so that it could be completed in a short period of time (~10 minutes), under conditions that do not require the instrument to be mounted on the vehicle (such as idle or snap accelerations), and by operators that do not have significant training. As the results of the pilot study did not show consistent trends between the different PM/PN mini-PEMS, additional study in this area is suggested to identify a suitable mini-PEMS for this application. It is expected that over the next 8 years that mini-PEMS technology will continue to improve, and that such mini-PEMS could be able to provide sufficient accuracy to distinguish between failing and non-failing vehicles in this capacity.

Chassis dynamometer and fully 1065-compliant PEMS methods were also considered in this capacity, but would likely be more burdensome in terms of the need for vehicles to be taken out of service to report to a centralized location, the more extensive requirements in terms of setting up and conducting the testing, and the greater capital costs associated with the test equipment. Additionally, an extensive network of chassis dynamometers would need to be established throughout the state to fully service the vehicles. The feasibility of establishing such a network and the associated testing costs would need to be investigated further to determine the feasibility of implementing a chassis dynamometer-based HD I/M program. Chassis dynamometer and 1065-compliant PEMS would, however, continue to play an important role in terms of in-use surveillance testing and in-use regulatory testing of manufacturer trucks.

Overall Conclusion

Overall, the testing results suggest that a HD I/M program will provide significant and tangible emission benefits and can be an integral component of California's ability to meet federally-mandated ambient air quality standards, and CARB's overall air quality, sustainable freight, and climate goals.

1 Introduction

Emissions from on-road heavy-duty vehicles (HDVs) are major contributors to poor air quality in California. Although HDVs with gross vehicle weight ratings (GVWRs) of greater than 14,000 lbs. represent a relatively small portion of the total population of vehicles on the road, (only two percent by count), they produce a disproportionate amount of the emissions generated from on-road motor vehicles. The problem is complicated by the large number of heavy-duty vehicles, registered in other states that travel in and out of California transporting various goods. HDVs and HD engines have been the subject of progressively more stringent emissions regulations over the past several decades. This has led to significant reductions in emissions from newer diesel engines over the years, with the latest generation of regulations requiring exhaust aftertreatment for the control of both oxides of nitrogen (NOx) and particulate matter (PM) emissions. This includes diesel particle filters (DPFs) for PM reduction and selective catalytic reduction (SCR) for NOx reduction. Despite these significant reductions, on-road HDVs are projected to still represent 24% of NOx and 10% of PM tailpipe emissions from all mobile sources in 2025. As trucks represent only 8% of greenhouse gas (GHG) emissions from motor vehicles, this suggests that the fuel-specific emissions of NOx and PM are substantially above the motor vehicle fleet average.

While engines meeting the newest emissions standards continue to penetrate into the in-use fleet, it is also important to ensure that the emissions from these vehicles do not significantly deteriorate over the course of the lifetime of the vehicle. This is important because heavy-duty engines tend to have relatively long lifetimes, both in terms of years of service as well as miles of travel or hours of engine life. Inspection and maintenance (I/M) programs can be important measures in preventing excessive emissions from in-use vehicles. Although I/M programs for light-duty vehicles have been extensively implemented throughout the United States (U.S.), I/M programs for heavy-duty vehicles are more limited in number and in scope. Most HD I/M programs focus predominantly on controlling smoke or opacity emissions (Texas A&M Transportation Institute, 2013; NYSDEC 2008, 2013; St. Dennis et al., 2005). California's existing heavy-duty vehicle inspection program comprises the roadside Heavy-Duty Vehicle Inspection Program (HDVIP) and the fleet Periodic Smoke Inspection Program (PSIP). (ARB, 2015). The HDVIP and PSIP have been in place since the late 1980s. The HDVIP requires HD trucks and buses to be inspected for excessive smoke and tampering, and engine certification label compliance. These inspections can be administered at various locations, including weigh stations and border crossings, and include Snap and Idle testing with a smoke meter to measure the opacity of the exhaust. The PSIP requires diesel truck and bus fleet owners to conduct their own annual smoke opacity inspections, and repair those vehicles with excessive smoke emissions to ensure compliance. There is also an Emissions Control Label (ECL) Inspection Program that requires all vehicles operating in the State to have an ECL showing that the engine met the required federal emission standards applicable for the model year of the engine. Newer trucks are also subject to in-use testing with portable emissions measurement systems (PEMS), although this testing is only for a very small portion of the actual vehicles that are out on the road and not over the full lifetime of the vehicle. More recently, CARB has put forth, and is in the process of implementing, new opacity limits of 5% for DPF-equipped HDVs for both the HDVIP and PSIP (CARB, 2018a). While these programs provide some important benefits in maintaining emission levels of HD vehicles, the existing programs do not include significant controls for NOx emissions and NOx aftertreatment systems from the in-use fleet. In order to better ensure that in-use engines continue to meet emissions performance requirements, California still needs a more comprehensive HD I/M program.

Given the importance of controlling in-use emissions from heavy-duty trucks, there has been increased emphasis on studies characterizing in-use emissions. These include chassis dynamometer studies, PEMS studies, as well as studies conducted with mobile trailers, such as the UC Riverside, Mobile Emissions Laboratory (MEL) (Durbin et al., 2007; Johnson et al., 2010, 2009, 2008; Khan et al., 2012; Miller et al., 2014; West Virginia University 2003, 2004). While these studies provide valuable information on in-use emissions, the number of vehicles that can be tested utilizing these more comprehensive laboratory techniques is relatively limited. There have also been a number of studies designed to characterize emissions from larger populations of vehicles, and in particular heavy-duty vehicles, using a variety of techniques, including remote sensing (Burgard et al., 2006; Bishop et al., 2012; Envirotest Canada, 2013; Stanard et al. 2012), tunnel or probe studies (Dallmann et al., 2012; Kuwayama et al., 2013; McDonald et al., 2014), and more recently studies utilizing tents that vehicles are driven through (Bishop et al., 2013, 2015; Texas A&M Transportation Institute, 2013). Several of these studies have suggested that such techniques could provide value if implemented in a HD I/M program. A Texas A&M Transportation Institute study suggested that using a tent, or On-road, Heavy-duty Emissions Measurement System (OHMS) potentially in combination with remote sensing and/or chassis dynamometer testing could be beneficial in I/M applications, while a study in Vancouver suggested the possible benefits of using remote sensing for an I/M program. Other methods that have been investigated for HD I/M include the use of chassis dynamometers (Chernich, 2003) or the use of On-Board Diagnostics (OBD), as this becomes more readily implemented into the in-use HD fleet.

Although these studies have suggested the potential benefits of using a variety of different methods in an enhanced HD I/M program, a number of questions must be answered before these methods could be implemented in a full scale I/M program, including the cost effectiveness of such a program, and how effective the program might be in identify high vs. low emitters and in reducing the emissions of high emitters. Another difficulty in developing an I/M test is that the emissions of the vehicle can vary with the way in which the vehicle is operated, its duty cycle (Clark et al., 2002), and the thermal condition of the engine and aftertreatment (Clark et al., 2011). Moreover, the exhaust aftertreatment can cause the instantaneous emissions to be less strongly related to the immediate engine behavior than was the case for older engines. Also, while light-duty I/M protocols are comparatively mature in the U.S., they address primarily gasoline vehicles that employ stoichiometric combustion. Equipment failures or deterioration leading to high emissions levels for light-duty vehicles are well understood and differ substantially from high emissions causes in diesel vehicles. So, while some light duty measurement methods and I/M philosophies could translate to HD diesel vehicles, it is important to consider the differences between LD gasoline and HD diesel vehicles in developing a HD I/M program.

The objective of this study is to develop, evaluate, and assess options for a more comprehensive HD I/M program prototype for vehicles over 14,000 pounds gross vehicle weight rating (GVWR), and provide recommendations for the implementation of a full-scale program. The study results may help inform the design of a more comprehensive HD I/M program that the staff of the California Air Resources Board's (CARB or Board) is considering developing for implementation in the post-2020 timeframe. A future comprehensive HD I/M program would be a component of CARB's broader efforts to meet federally-mandated ambient air quality standards, and CARB's overall air quality, sustainable freight, and climate goals.

2 Literature Review

2.1 Approach

For this portion of the project, light-duty (LD) and HD I/M programs in the U.S. and worldwide were evaluated to assess their applicability to an improved HD I/M program in California. This included identifying features of LD I/M programs that may be transferable to a HD I/M program, and a summary review and assessment of the previous studies. The literature review also evaluated all aspects of developing HD I/M programs, including in-use fleet characterization, pollutants to be measured and by what method(s), diagnosis and repairs, test methods and test cycles. The literature review expanded upon the methods presented and discussed below, and developed and presented results of data analyses for each HD I/M method considered, included a discussion on the pros and cons of each method, and justified the inclusion or exclusion of each method from the HD I/M program prototype.

As part of the literature review, research performed and data collected during the conduct of past programs was compiled and presented. The main emphasis of the literature review was to summarize the possible HD I/M methods, and lay out the framework for a prototype HD I/M program that could be evaluated as part of this project. The International Council on Clean Transportation (ICCT) has recently completed a comprehensive evaluation of HD I/M methodologies and this provided key information for the literature survey to be performed in this study. The Texas Department of Transportation has also recently completed a heavy-duty diesel I/M pilot program which included an assessment of OBD, opacity measurement, idle testing, ASM testing, IM240 testing, RSD, PM filter sampling and chassis dynamometer testing using PEMS. Additionally, HD I/M programs being conducted in California as well as other states were also evaluated. Other states that have some form of HD I/M program include Arizona, Colorado, Connecticut, Maine, Nevada, New Jersey, New York, Oregon, Vermont and Washington. HD I/M programs are also in various stages of development at locations outside of the U.S., including Mexico, Canada, Hong Kong and Australia. The literature review built on this information as well as other studies. A summary of some studies that were primarily evaluated in the development of the literature review is provided below, in the form of an annotated bibliography:

- "Heavy-Duty Diesel Vehicle Inspection and Maintenance Study" (Weaver & Klausmeier, Radian, 1988)

This was an early study that provided the ground work for CARBs current inspection programs. This study included an evaluation the different types of tampering and malmaintenance issues that might be found for heavy-duty trucks, estimates of their potential impact on HDV emissions, and then model to determine the amount of excess emissions that could be captured by a inspection program. As part of this study, emissions test procedures were developed that could be used to identify high emitting HDVs that included a Periodic Inspection and Maintenance Test and a Roadside Opacity Check. Results of this study indicated that an inspection program based on in-use smoke opacity testing and anti-tampering inspections was the most cost effective, which led in part to California's current inspection program. This study is not discussed extensively in the literature, as these procedures have largely been implemented, but provided a good historical context.

- "Air Pollution from Motor Vehicles – Standards and Technologies for Controlling Emissions" (The World Bank, 1996)

The World Bank in collaboration with the United Nations Environment Programme developed a handbook that presented a state-of-the-art review of vehicle emission standards and testing procedures applied in I/M program. They examined four inspection procedures for HD vehicles: snap acceleration, chassis dynamometer, RSD, and OBD. At the time, they suggested that RSD be utilized on roads to catch the high-emitters and direct them to the facilities for chassis dynamometer tests. Finally, they suggested that in the near future OBD would be further developed and more prevalent in the HD vehicle fleet.

- "Proposed Diesel National Environment Protection Measure Project 2, Emissions Performance Testing of 80 In-Service Diesel Vehicles, Evaluation & Correlation of Short Test Protocols" (Parsons Australia, 2000)

This was a project conducted by Parsons Australia Pty Ltd under contract to the National Environment Protection Council Service Corporation I Australia, over the period August 1999 to May 2000. The main part of the study was the testing of 80 vehicles on a chassis dynamometer over drive cycles designed to represent real-world conditions. Dynamometer-based short tests with transient acceleration segments perform much better than unloaded or steady state tests in estimating "real world" emissions of all regulated pollutants. They also evaluated and compared different methods for measuring PM in an I/M setting.

- Development of a Chassis Based Inspection and Maintenance Program for Heavy-Duty Diesel Powered Vehicles, 13th CRC On-Road Vehicle Emissions Workshop, San Diego, CA (Chernich et al., 2003)

CARB evaluated the potential of using chassis dynamometer testing in an inspection and maintenance program as part of their State Implementation Plan measure M17 (Chernich, 2003). The program envisioned portable dynamometers setup at roadside locations where trucks would be pulled over to undergo a short dynamometer test. A total of 91 vehicles was tested over a sequence that included a power curve test, a 60 mph steady-state test at three loads, an idle test and a snap acceleration test.

- "Heavy-Duty Vehicle Chassis Dynamometer Testing for Emissions Inventory, Air Quality Modeling, Source Apportionment and Air Toxics" (Coordinating Research Council (CRC) E55/E59, 2007)

The E-55/59 program was one of the largest chassis dynamometer studies of heavy-duty vehicle emissions to date, with an objective of improving the emissions inventory in California. The studied utilized a variety of in-use cycles representing city driving, cruise cycles, and a high speed cruise cycle. The project was conducted in four phases (denoted 1, 1.5, 2 and 3) and examined 75 vehicles ranging from pre-control model years to those equipped with EGR engines, between September, 2001 and June, 2005. High emitting vehicles were identified and subjected to repair and retest.

- "Heavy-Duty Diesel Inspection and Maintenance Pilot Program" (Texas A&M – Texas Department of Transportation, 2013)

This study describes a pilot study to evaluate options for a HD I/M for the Dallas-Fort Worth area. The study was conducted over a 2 week period at a weigh station in Texas on the I-45. The pilot study included a SHED-based system along with PEMS. As part of the pilot study, the HDV traffic through the weigh station was characterized, and comparisons were done between different measurement methods, and the SHED system was evaluated for HD I/M or screening purposes.

- "Recent Development of On-Board Vehicle Emissions Measurements in Hong Kong" (Hong Kong Environmental Protection Department, 2013)

The Hong Kong Environmental Protection Department has been conducting extensive PEMS testing in order to better understand vehicle emissions under conditions representative of Hong Kong driving. Up to March of 2014, they had conducted tests on approximately 200 vehicles, and found that, except for private cars, the emissions measured by the PEMS were generally higher than the corresponding emission standard for the vehicle.

- "Greater Vancouver Regional District Remote Sensing Device Trial for Monitoring Heavy-Duty Vehicle Emissions" (Envirotest Canada, 2013)

Envirotest conducted an assessment of remote sensing method for evaluating HDV emissions for the Metro Vancouver. This study included an RSD system and a prototype OHMS system. During the 55 days of data collection, a net total of 6,012 individual HDVs were measured by RSD including 17% of all class 8 trucks registered in the region. The systems were able to differentiate between emission levels of 2007 & older, 2008-2010, and 2011 and newer heavy-duty trucks.

- "Survey of Best Practices in Emission Control of Heavy-Duty Diesel Vehicles" (The International Council on Clean Transportation – Climate and Clean Air Coalition, 2013)

This report provided an overview of programs that are being conducted throughout the world to identify high emitting HDVs, as well as other issues related to HDV emissions such as retrofits and fuel quality. The study highlights some of the more successful program emission control programs on local, regional, and national levels. Based on this overview, the report provides recommendations of practices for emission control programs that can be implemented on a national and local level.

- "Review of Current Practices and New Developments in Heavy-Duty Vehicle Inspection and Maintenance Programs"; International Council on Clean Transportation; August, 2015.

ICCT reviewed of current practices and new developments in heavy-duty vehicle inspection and maintenance programs. Current I/M programs for HDVs rely on two main testing methods, the free acceleration smoke test and the lug down smoke test. They also evaluated a number of newer measurement technologies and testing methods that could be utilized to improve I/M programs, including the use of OBD, RSD, and the On-road Heavy Duty Vehicle Emissions Monitoring system (OHMS).

One of the most important elements of the literature review was to evaluate potential I/M monitoring techniques. In general, potential HD I/M program monitoring techniques can be broken down into three main categories as follows:

- Tailpipe emissions measurements
    - on-site (e.g., chassis dynamometer)
    - on-board (e.g., portable emissions measurement system [PEMS])
- Plume measurements

  - remotely (e.g., EDAR, Denver University FEAT, the On-road Heavy-duty vehicle emissions Monitoring System [OHMS], and the Portable Emissions AcQuisition System [PEAQS])
- Electronic interrogation
  - on-site (e.g., actually plugging a device into the HD vehicle on-board diagnostic [OBD] system)
  - remotely (e.g., using telematics or cellular communications to remotely query the HD vehicle OBD system)

2.2 Tailpipe Emissions Measurements

The following provides an overview of different tailpipe emissions methods.

2.2.1 On-Site Testing

2.2.1.1 Chassis Dynamometer Testing

Short of certification testing, a chassis based dynamometer test for inspection of heavy-duty vehicles may represent the most accurate alternative. Chassis dynamometer testing is commonly used for the characterization of emissions from heavy-duty vehicles for model and regulatory development (Gautam et al. 2001, 2002, Clark et al. 2004, 2006, 2007, Miller et al. 2013, Carder et al. 2014). A great deal of information also exists on the field use of relatively low-cost, repair-grade, water-brake dynamometers and the development of short cycles such as the AC5080 and the Power-Curve test that have been shown to correlate well with laboratory grade emissions readings and could be practical for larger compliance programs.

The viability of this approach has been proven in the joint research efforts between CARB and Clayton Dynamometers and by Parsons, Australia in their assessment of a roadside I/M test for heavy-duty trucks.

Parsons Australia Pty Ltd conducted a chassis dynamometer study of heavy-duty vehicles under contract to the Australian National Environment Protection Council Service Corporation with cofunding by CARB, over the period August 1999 to May 2000 (Anyon et al., 2000). This included tests over various composite urban emissions drive cycles and seven in-use emissions assessment procedures. A total of 80 heavy-duty vehicles were tested. The study included a dilution tunnel with laboratory grade analyzers for the measurement of standard regulated emissions (NOx, CO, CO_2, HC and O_2), as well as particle instruments covering a range of particulate sizes from around 0.004 microns to over 10 microns, a Laser Light Scattering Photometry (LLSP) instrument capable of measuring particles up to 10 microns (PM10) and a diesel tapered element oscillating microbalance (TEOM) instrument to measure all particles. Smoke opacity measured under a controlled load on a dynamometer showed essentially no correlation with particulate emissions. For particles, the LLSP showed reasonable accuracy and repeatability, and a good correlation ($R^2 = 0.92$) compared to the laboratory PM measurements, but with rugged, simple operation and a price many times lower, potentially opening the door to low-cost, reliable and fast measurements of particulate emissions from diesel vehicles.

Six short tests, plus an on-road visible smoke observation, were included in the tests.
(a) The **D550** is a steady-state test using a constant dynamometer load equivalent to a fully laden vehicle driving up a 5% gradient at 50 km/h.
(b) The **Two-Speed** test is a steady-state test that measures emissions under full-throttle conditions at two calculated speeds.
(c) The **Lug Down** test is performed at full throttle, with the dynamometer load gradually increased to pull back engine speed so that the engine is laboring, or "lugging".
(d) The **DT80** test is an aggressive mixed-mode test, with three full-load accelerations to 80km/h, followed by a steady-state 80 km/h cruise. The test requires the use of a dynamometer with inertia simulation.
(e) The **AC5080** is a new test, developed by CARB that was added to the program. It is a mixed-mode test having two full-load accelerations and two steady-state cruises. It also requires the use of an inertia-simulating dynamometer.

(f) The **Snap-Idle** (or 'Free Acceleration' SAE J1667) test simply involves fully depressing the accelerator pedal while the transmission is in neutral, and measuring the maximum smoke opacity. The test was developed in the USA as a quick test to evaluate smoke opacity without the need for a dynamometer.

A summary showing the comparisons of correlations for the various short cycles with the Composite Urban Emissions Drive Cycles (CUEDC) is provided in Table 2-1 (Anyon et al., 2000). The CUEDC was developed to simulate on-road driving in Australia (Brown et al., 1999). It includes 4 segments representing congested, minor road, arterial road, and freeway/highway driving. Correlations between the "real-world" CUEDC drive cycle and the various short tests ranged from excellent to very poor. Snap Idle, the only non-dynamometer test, proved to be an extremely poor indicator of particulate levels, even though it provided a reasonable correlation with maximum CUEDC opacity levels. The second group (D550, Lug Down, 2-Speed) tests did not prove to be good surrogates for the CUEDC. They were generally poor indicators of particulate emissions, although their NOx and HC results provided a fair correlation with the CUEDC. Only the two transient dynamometer based tests (DT80 and AC5080) delivered good correlations on all pollutants studied. Note, however, that the vehicles being examined did not include aftertreatment, so that the emissions were more directly related to the instantaneous operation (engine torque, speed) than for late model year trucks that are the focus of this study. It should be noted that even for 2010 vehicles using EGR as the primary source of NOx control, the correlations between different pollutants were poorer than those seen in previous studies of older vehicles (Chen et al., 2010).

Table 2-1 Correlation Coefficients of CUEDC emissions *vs* Short Test emissions for HDVs with no Aftertreatment.

	Correlation Coefficient (R^2) for all test results						
Short Tests	Average NOx (g/s)	Average HC (g/s)	Average LLSP (mg/s)	Filter mass (mg)	Average Opacity (%)	Maximum Opacity (%)	Rating 1 - best 8 - worst
AC5080	0.95	0.92	0.70	0.71	0.87	0.80	**1**
DT80	0.90	0.85	0.63	0.58	0.68	0.81	**2**
2 speed torque	0.62	0.72	0.30	-	0.40	0.68	3
DT80 last 10s	0.80	0.74	-0.35	-	0.15	-0.21	4
Lug Down	0.60	0.68	0.22	-	0.26	0.68	5
2 speed power	0.55	0.36	0.12	-	0.15	0.17	6
D550	0.64	0.53	-0.18	-0.23	0.03	-0.23	7
Snap idle	0.47	0.23	-0.02	-	0.29	0.59	8

CARB evaluated the potential of using chassis dynamometer testing in an inspection and maintenance program as part of their State Implementation Plan measure M17 (Chernich, 2003). This evaluation was done in the early 2000s, before DPF and SCR aftertreatment systems were being utilized on HD vehicles. The program envisioned portable dynamometers setup at roadside locations where trucks could be pulled over to undergo a short dynamometer test. Vehicles determined to be non-compliant could be cited and required to be repaired. The cited vehicles would be repaired and retested utilizing an extensive network of water-brake dynamometers located at repair facilities throughout the state. The potential effectiveness of this program was evaluated using a repair grade dynamometer facility located in Stockton, CA. A total of 91 vehicles were tested over a sequence that include a power curve test, a 60 mph steady-state test at 3 loads, an idle and then a snap acceleration tests. A distribution of NOx emissions over the test fleet showed an upward turn at 10 g/wheel horsepower hour (whp-hr), representing approximately 15% of the excess emissions, with 5% of the vehicles having NOx emissions in excess of 12 g/whp-hr. Overall, a total of 42 vehicles were repaired as part of this study, but the vehicles generally did not show large reductions in NOx, with the 6 vehicles with emissions greater than 10 g/whp-hr being repaired, showing a 2.1% reduction in NOx for repairs costing an average of $1,018 per vehicle. In addition, sometimes repairs led to a NOx emissions increase. Additional comparisons were also made in this study using a Semtech D PEMS to show correlation with the instruments at the dynamometer facility.

Perhaps the greatest drawback to the implementation of a dynamometer-based inspection system would be the amount of time that the vehicle would need to be taken out of service for testing. A network of chassis dynamometer facilities that is large enough to service the full population of trucks within California would also be needed. This inefficiency also exists in the light-duty program but is offset somewhat through the exemption of the newest and oldest vehicles from mandatory periodic inspection, with little danger of adversely affecting the program's overall effectiveness. Light-duty vehicles can also be readily serviced in much smaller facilities than would be needed for heavy-duty vehicles. The feasibility of establishing a large enough network of chassis dynamometer facilities and the associated testing costs would need to be investigated further to determine the feasibility of implementing a chassis dynamometer-based HD I/M program. Another potential role for dynamometer testing could be in verifying emissions rather than as a primary screening tool. In considering dynamometer testing as a way to verify emissions, a set dynamometer test cycle would need to be identified where cut points could be established that could readily identify whether the vehicle was a high emitter or if there was a component failure on the vehicle. This would have to account for the fact that emissions can vary in a non-linear fashion with engine load (Chen et al., 2010), are influenced by transient behavior and different transmission hardware in different vehicles, and can be skewed in time by aftertreatment. Looking to the future, heavy duty vehicle drivetrain hybridization will further decouple emissions from actual vehicle activity.

2.2.2 Typical Instrumentation Used for I/M Tailpipe Testing

The type of instruments commonly for I/M testing include I/M grade emissions analyzers that are used in conjunction with chassis dynamometer facilities, as well as opacity meters that are used at either a location such as a weight station or at the base for a fleet operation. This includes some of the instruments used in the pilot study discussed below, so a brief introduction to these instruments is provided here. A summary of some of the characteristics of such instruments is provided in Table 2-2. This includes emissions analyzers from MAHA that were used in the pilot study discussed below and opacity meters. Other PEMS and mini-PEMS instruments are discussed in greater detail below.

Table 2-2 Technical Specifications of Typical I/M Grade Emissions Measurement Instrumentation

Instrument	Pollutants	Measurement Specifications
MAHA MGT5	NOx	0-5000 ppm with 1 ppm resolution
	CO	0-15% with 0.001% resolution
	CO_2	0-20% with 0.01% resolution
	HC	0-2000 ppm with 0.1 ppm resolution
MAHA MPM4	PM	0-700 mg/m^3 with 0.1 mg/m^3 resolution, 100 nm to 10 µm
Opacity Meter	PM	550 and 570 nm light source, particle size 200 nm or greater

Opacity meters are currently one of the most widely applied PM monitoring instruments for I/M applications, due to their relatively low cost and availability. The SAE J1667 snap acceleration procedure is typically used for the opacity measurements in such programs (SAE, 1996). Opacity meters are designed to measure PM based on the optical properties of the exhaust particles. Opacity meters measure the light attenuation of the exhaust between a light source and a receiver in a measuring chamber of a defined length. The light source is typically a green light emitting diode with a spectral peak between 550 and 570 nm or an incandescent lamp with a color temperature in the range of 2800 to 3250 °K, although red light emitting diodes may also be used. The light attenuation is quantified using the Beer-Lambert law, and is characterized in terms of opacity or the specific absorption ("k" in m^{-1}) of the gas. In terms of particle size, 200 nm or greater size particles block green light according to their surface area, but 50 nm particles block only about 15% of their surface area. So, the opacity meter does have sensitivity issues in measuring small particles that are typical of diesel combustion. The correlation between opacity measurements and PM has been studied extensively over the years. A number of earlier studies have shown poor correlations between opacity and PM (Clark et al., 1999; Gautam et al., 2000; McCormick et al.). CARB has conducted some more extensive testing recently to evaluate the potential for opacity to characterize high PM emitters. Karim (2012) evaluated opacity and PM measurements for tests conducted on a 2004 Mack trash truck, an off-road tractor equipped with a 2007 John Deere engine, and a scrapper equipped with a 2000 Caterpillar engine. He found correlation of $R^2 = 0.92$ between the opacity and PM mass with a slope of 100 x PM (g/bhp-hr) for the opacity values. CARB has done additional as part of the development of its EMFAC model and recent update of the opacity regulations. In testing conducted at NREL on two engines, it was found that FTP PM emissions levels of 0.1 g/bhp-hr were equivalent to approximately a 2.8 to 3.2% opacity measurements. CARB (2018) is in the process of implementing stricter opacity requirements of 5% for 2007 and later heavy-duty vehicles for the HDVIP and PSIP. CARB maintains a list of opacity meter manufacturers that have provided statements stating that their opacity meters meet the SAE J1667 requirements.[1]

[1] https://www.arb.ca.gov/enf/hdvip/smokemtr.htm

The MAHA emissions analyzer system is designed for use in a inspection test facility or at a stationary location, and it was used as the primary system for the pilot study. MAHA has a MGT5 five gas analyzer capable of measuring HC, CO, NOx, CO_2, and O_2 called the MGT 5 that is more designed for repair and I/M applications. The instrument measures HC, CO, and CO_2, via infrared spectroscopy and NO and O_2 via electrochemical detection. For PM measurement, MAHA offers a MPM 4. This instrument is based on laser light-scattering photometry and has been designed for use in the mining and non-road applications. This instrument has shown good correlations with PM filter mass measurements at high PM emissions, as shown in Figure 2-1, but has not been extensively tested at the lower PM levels found for DPF equipped vehicles.

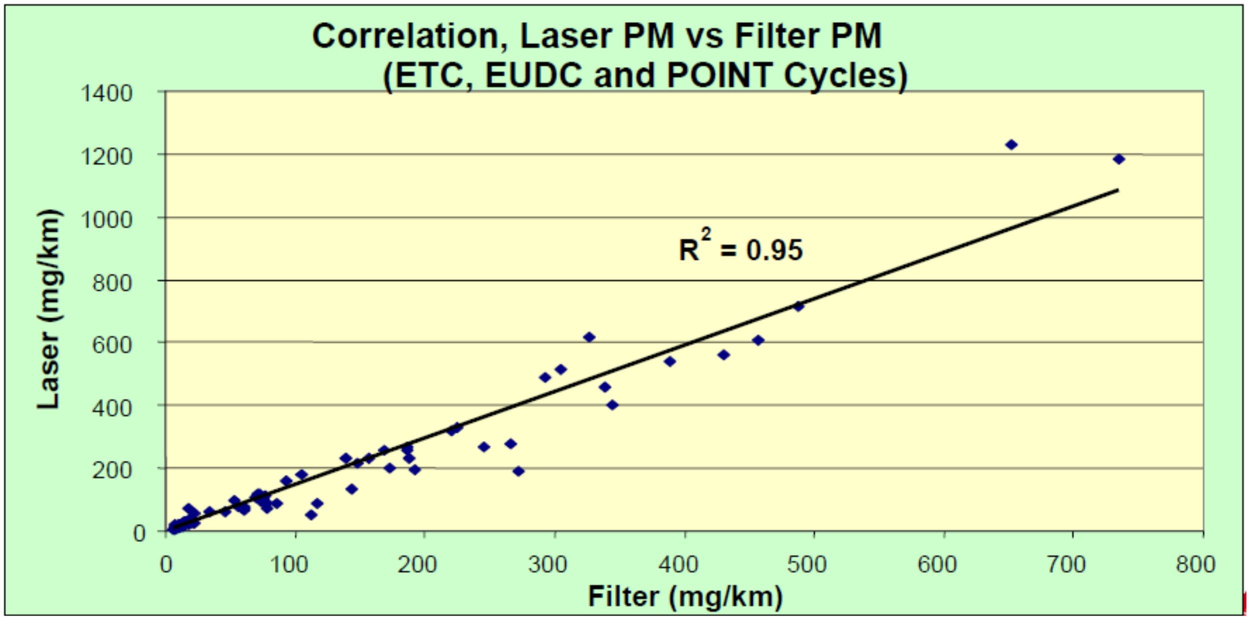


Figure 2-1 Correlation between MAHA MPM4 and Filter based PM measurements in Bangkok (Anyon, 2009)

2.2.3 On-Board Testing

2.2.3.1 <u>1065 Compliant Portable Emissions Measurement Systems</u>

The use of PEMS, either in conjunction with or independent of repair-grade dynamometers have demonstrated sufficient accuracy in pollutant measurement to be considered reliable for use in inspection and maintenance programs. With PEMS, vehicles can be tested at a lower cost than full laboratory based assessments and the portability of these systems allows the test to be performed where the vehicles are, as opposed to the requiring vehicles to report to a test facility (as would be the case for dynamometer-based screening). The most stringent specifications for PEMS are those spelled out under 40 CFR 1065. These are the requirements that PEMS must meet for in-use regulatory testing. This section of the CFR also discusses regulatory requirements for laboratory engine dynamometer testing. The downside of testing with a fully 1065-compliant PEMS is that the PEMS would have to be mounted on the vehicle and the vehicle would need to be driven in a manner that would allow comparisons with predefined cut points. This would provide an added level of inconvenience to the vehicle owner that would make the application of such PEMS in a HD I/M program impractical. The capital costs of fully 1065-compliant PEMS are also relatively expensive compared to the typical costs of I/M repair grade instruments, as the PEMS costs can range from $100,000 to $120,000 for gas-phase only PEMS to $200,000 to $220,000 for a full gas-phase and PM PEMS.

PEMS have been developed extensively for in-use testing and have been incorporated into the regulatory process for heavy-duty vehicles/engines to ensure emissions are controlled over the full range of speed and load combinations commonly experienced in use. The in-use testing requirements were first introduced as part of the 1998 Consent Decrees with heavy-duty engine manufacturers, and do not demand the same test schedule as is used for certification. The regulations require compliance under conditions defined by a not-to-exceed (NTE) control area that includes provisions such as engine load and power greater than or equal to 30%, that the temperature of the aftertreatment system is greater than 250°C, and that the engine remains in the NTE area for 30 continuous seconds (CFR 2007, U.S. EPA, 2004). The accuracy of these instruments was defined through the Measurement Allowance program that included laboratory testing, on-road testing, as well as modeling (Johnson et al., 2008, 2009, 2010, 2011). Brake-specific emissions limits for PEMS are higher than for certification, allowing for real-world variation and allowance for measurement error.

CARB has on-going efforts to evaluate the emissions of heavy-duty trucks under on-road conditions. This includes testing programs being conducted in both Southern and Northern California. For the Northern California studies, Misra et al. (2013, 2016) undertook a study to characterize the in-use emissions of model year (MY) 2010 or newer diesel engines. Emissions from four trucks: one equipped with EGR only, and three equipped with EGR and SCR were measured on two different routes that included a cold start, an arterial, highway driving, and industrial driving with three different payloads in the Sacramento area using a PEMS. Results also showed that for typical highway driving conditions, the SCR technology was effective in controlling NOx emissions, with emissions rates in the range of 0.07 to 0.10 g/bhp-hr. However, under operations where the SCR's do not reach minimum operating temperature, like cold starts and some low load/slow speed driving conditions, NOx emissions were still elevated.

CARB has also been conducting a pilot program in Southern California in preparation for in-use compliance testing pursuant to Title 13, California Code of Regulations, Sections 2111-2140 (O'Cain et al., 2016, Tu et al., 2016). To date, CARB has tested approximately 23 vehicles (O'Cain, 2018). This testing has focused on three engine families. For the three families, 6 of 10 vehicles were found to be noncompliant with the NTE standards for one engine family, with an average NTE emission rate of 0.59 g/bhp-hr, 8 of 10 vehicles were found to be noncompliant for the second engine family, with an average NTE emission rate of 1.02 g/bhp-hr, and 3 of 3 vehicles have been found to be noncompliant for the third engine family. Additional steady state chassis dynamometer and engine testing is also being conducted in conjunction with this testing.

One of the most extensive studies of in-use heavy-duty emissions is currently under way. The project is designed to involve 200 on-road heavy-duty test vehicles used in transit bus, school bus, refuse, delivery and goods movement applications. The study will characterize engines in these applications with different alternative fuels (fossil fuel-based and renewable natural gas, propane, electric and hybrid), conventional and alternative diesel fuels, and a combination of diesel and natural gas fuels, with an emphasis on 2010+ engines. The test vehicles will be split equally between UCR and WVU. The testing will include PAMS testing on 200 vehicles, PEMS testing on 100 vehicles, chassis dynamometer testing on 60 vehicles, and on-road testing of an additional

5 delivery/goods movement vehicles. This study will provide a wide range of important information on in-use emissions, in-use activity, and in-use duty cycles in various applications.

In examining PEMS as a component of a HD I/M program, the main issue is that it is time consuming to install and may require that vehicles be driven over a prescribed route or in a uniform manner in order to assess their emissions accurately. For example, in an analysis performed by ERG for the Hong Kong EPD, professional drivers operated PEMS equipped vehicles over a pre-determined route with a standardized payload. As with dynamometer testing, periodic testing with PEMS would require each vehicle to abandon normal operation and report for testing. Also like dynamometer based testing, all vehicles would have to be tested in order to identify those vehicles most likely to fail. Therefore, like dynamometer based testing, a better use for PEMS might be for the verification of the pass/fail determination of a less sophisticated screening process rather than as the primary method of monitoring the fleet.

2.2.3.2 Mini-Portable Emissions Measurement Systems for Screening

Mini-PEMS are simplified versions of the full 1065-compliant PEMS discussed above. Mini-PEMS are less expensive and easier to operate than full 1065-compliant PEMS, and could also be less expensive than chassis dynamometer testing. Costs of mini-PEMS can vary greatly from $30,000 to $50,000 for a more complete sensor-based type of mini-PEMS with the ability to measure multiple components or designed to meet a traceable metric, such solid PN. On the lower end, hand held condensation particle counters (CPCs) or other technologies are available for $3,500 to $10,000 that can be used as a quick check of PN. On the other hand, reduced measurement accuracy leads to higher measurement error allowances if the standard is set using the mini-PEMS, or the need to conduct a proportion of re-tests with higher grade equipment if the standard is referenced to more complex measurement techniques. Their role in a HD I/M program would likely be more comparable to that of the SAE J1667 Snap-Acceleration opacity test that is currently utilized in California. As such, the test would need to be completed in approximately 10 minutes or so under idle or snap acceleration conditions. The instrument would also need to be operated without requiring it to be mounted to the vehicle or requiring significant training for operators. Mini-PEMS devices are already being used in a similar manner in Europe for I/M purposes as part of the Swiss SR941.242 Regulation, as discussed below. This regulation requires biannual testing of off-road diesel machinery equipped with DPFs for compliance with a particle number limit. A disadvantage of mini-PEMS is that the roadside inspections could require vehicles to be pulled out of service, and could require trained personnel on-site to administer the testing with the mini-PEMS. This would likely be a limitation in implementing mini-PEMS in a manner that could be implemented the entire fleet operating in California, including out-of-state vehicles. Additionally, mini-PEMS sometimes utilize measurement methodologies, such as PN, that may not be directly correlated to the PM mass standards that are used to initially certify the engines. Although PN may be high, most particles are tens of nanometers in size, contributing little mass at the 2.5 or 10 micron levels. Mini-PEMS could, however, be used for verification testing on a subset of vehicles, as discussed in the recommendations, or for a screening test. A summary of the different available mini-PEMS and their measurement specifications is provided in Table 2-3, with a more detailed discussion of the different systems below. Mini-PEMS were also a central part of the pilot study.

Table 2-3 Technical Specifications of the mini-PEMS

Instrument	Pollutants	Measurement Specifications
Pegasor PPS-M	PM	1 µg/m^3 to 250 mg/m^3 with 1 mg/m^3 resolution, >~10 nm
EmiSense PMTrac	PM	0 µg/m^3 to 630 mg/m^3, with a detection limit <0.25 mg/m^3
TSI NPET	Solid PN	1,000-5x10^6 particles/cm^3, accuracy ±10% compared to standard, >~23 nm
Testo PEPA	Solid PN	50,000 - 5,000,000 #/cm^3 with 1 #/cm^3 resolution, 10 to 300 nm
NTK NCEM	NOx	0 – 1,500 ppm
	PM	0.01 to 50 mg/m^3, >~10 nm
	PN	5x10^4 - 1x10^8 particles/cm^3, >~10 nm
parSYNC® PLUS	NO	0 - 5,000 ppm NO, accuracy 0.05 ± 0.01 µA/ppm
	CO_2	0 to 20%, accuracy ±70 ppm, ±5% of reading

2.2.3.2.1 PN mini-PEMS

Several mini-PEMS have been designed to meet the testing requirements for non-road equipment under Swiss Regulation 941.242 (2014), which went into effect in 2014. Under this regulation, all non-road mobile machinery (NRMM) is tested bi-annually to ensure that the DPFs are continuing to function throughout the life of the equipment. The standard is based on solid PN counts. The test itself consist of three measurements at high idle for a period of 5 seconds each. The test itself can be completed in about 45 seconds. The passing limit is that the average of the three solid PN measurements can not exceed 250,000 counts per cubic centimeter (cc). Note that this limit is based on non-road equipment that is often retrofitted with DPFs, and lower limits might be more appropriate for on-highway trucks. For this program, instruments are certified by the Swiss Institute of Metrology (METAS). It should be noted that there is some discussion of modifying the instruments, such as changing the D50 cut point for the PN measurements, or narrowing the temperature requirements for the measurements.

TSI has developed a Nanoparticle Emissions Tester (NPET) that has been used in studies to identify high emitting vehicles (TSI, 2016). The NPET is currently the only instrument officially certified for use in meeting Swiss regulation 941.242. The NPET measures total solid particle number emissions, and can be used with a variety of applications, including buses, construction equipment, and others. This unit is designed to sample raw exhaust directly from the tailpipe downstream of a DPF to evaluate the condition of the DPF for inspection and maintenance or emissions research. The NPET includes a 10:1 diluter with a dryer for the recirculating dilution flow, a catalytic stripper heated to 350C to evaporate, oxidize, and remove volatile particles, and a CPC for counting the particles. The unit has been used in Santiago, Chile to evaluate the effectiveness of DPFs that have been installed on buses. In one testing campaign, five buses were measured on route and with the 40-second official SR 941.242 test with the NPET, as well as with a free acceleration opacity test. Of the five buses tested, all five passed the existing opacity standard of 0.24 m^{-1} (~3% opacity) while only three of the five passed the Swiss standard of 2.5 x 105 cm^{-3}. Additionally, one of the buses failing the Swiss test, had opacity reading very similar to those passing the Swiss test. The NPET has also been utilized for measurements of a DPF-equipped John Deere 6068TF275 diesel engine stationary generator.

The Testo Portable Emission Particle Analyzers (PEPA) is a particle number instrument designed for vehicle type approval in Europe. The PEPA measures the number concentration and diameter of nanometer sized particles in the size range 10 – 500 nm. The instrument is based on a diffusion charging technology and uses electrical charging to count particles. The unit also incorporates a PMP-compliant volatile particle remover. The instrumentation is compact, easily portable and provides on-line response. Due to these properties it is a suitable technology for particle number concentration measurements in non-laboratory settings. It is battery operated and therefore appropriate for on-board and field measurements.

Handheld particle counters is another level of instrumentation that could be considered for an HD I/M application. Such particle counters have been developed for monitoring ambient air, clean rooms, or for health studies on individuals. Such, monitors can be very inexpensive, with prices below $1,000, to higher quality monitors that might range to $3,500 to $10,000. From an I/M perspective, such particle counters could potentially be used to characterize particle number counts at idle, high idle, or perhaps even under a snap acceleration condition. The particle counter would need to be traceable to some standard, which could be challenging given that particle number measurements can be quite variable during different types of operation, and it would have to be designed to handle raw exhaust. So, it is expected a higher end particle counter would be needed for a regulatory HD I/M applications. Handheld particle counters based on condensation particle counter (CPC)-based technology would be one example of such a technology.

2.2.3.2.2 PM mini-PEMS/Sensors/opacity

Pegasor has developed a PM sensor that is being used in a variety of applications (Saukko et al., 2016). The Pegasor PPS-M is a PM sensor module. The operation of the PPS-M sensor is based on electrical charging and detection of the charged aerosol particles. The design combines a sheath air-assisted corona charger with an ejector pump. Clean air is ionized via a positive corona needle and mixed with the sample, charging the particles. The positively charged particles enter and escape a Faraday cup creating a net total charge that is proportional to particle concentration. As such, it can be used to measure particle mass and number concentration. The sensor can be used as an independent module, but has also been integrated into a more complete PEMS system. Systems that incorporate the Pegasor PM sensor include the NTK system, the SEMTECH CPM system, and the Control System unit from Italy.

EmiSense has developed sensors for particulate matter measurements making use of high-temperature co-fired ceramic sensor elements and other ceramic components. EmiSense is working to improve sensor accuracy and durability while lowering cost by simplifying geometries of ceramic components and improving the signal processing elements of an integrated system for emissions measurement and control. For PM, EmiSense's PMTrac sensor samples PM by extracting exhaust into the sensor electrode region by a venturi tip using exhaust velocity (Bilby et al., 2016). The sensor design uses alumina for an integrated heater and a high-voltage electrical insulator. This helps to provide better long-term durability and lower costs. Naturally charged particles are captured between two electrodes in an electric field. Captured particles break away from the surface of the electrode due to high charge buildup. Electrometer current is an output associated with particle release from the electrode surface. Operating without a sample pump over a wide range of exhaust gas velocities and temperatures, the sensor outputs a real-time signal that is stable even if ash and other contaminants accumulate on the electrodes. Testing at EmiSense and at Southwest Research Institute's Particle Sensor Performance & Durability facility and by UCR (Steppan et al., 2011) indicates the device's output agrees well with reference laboratory instrument results over a wide range of conditions and particulate matter concentration levels.

Other PM sensors include those produced by Electricfil and Stoneridge (Khalek and Permnath, 2016). Both sensors utilize electrodes with a high electric resistance. As soot deposits onto the electrode substrate, a resistance develops across the electrodes. The change in resistance directly correlates to the soot concentration. When the resistance reaches a certain level, the sensor is regenerated by burning the soot off.

2.2.3.2.3 NOx Sensors

The development of NOx sensors has expanded considerably as NOx aftertreatment systems have become more widely implemented on light-duty and heavy-duty vehicles. NOx sensors operate on principles similar to those used for oxygen sensors. The sensors are typically composed of electrochemical cells in two or more adjacent cells. The first chamber is utilized to remove oxygen from the source gas to eliminate the potential for interference by oxygen in the second chamber. The gases that remain after the oxygen is eliminated in the first chamber diffuse into a second chamber. In the second chamber, NOx is dissociated into N_2 to O_2 by a reducing catalyst. The current generated by the dissociated oxygen measured at an electrode in the cell is proportional to the amount of oxygen obtained from the NOx in the gas. NOx sensors are made commercially by Continental and NGK, Bosch, and others.

The potential value of information from the OBD NOx sensor data was demonstrated by a study by Tan et al. (2018). They evaluated the in-use NOx emission rates from the OBD data of 72 SCR-equipped HDDVs. The NOx emission rates were estimated based on NOx sensor measurements. Based on this information, they were able to evaluate NOx emissions as function of exhaust temperature and engine load, and determine the efficiency of the SCR catalyst under different operating conditions. Proposed updates for the CARB OBD regulations for heavy-duty engines will add monitoring of NOx emissions as part of the OBD requirements beginning in model year 2022 (CARB, 2018b).

EmiSense has developed a NOx sensor that uses a planar HTCC alumina insulator and yttria-stabilized zirconia-sensing element capable of 1 to 2 ppm resolution (Bell et al, 2016). EmiSense is targeting a durable NO_x sensor in the price range of current wideband oxygen sensors. Depending on volume, the current price of such oxygen sensors is $30 to $40, versus $100 to $150 for NO_x sensors. They expect major cost savings to come via simplified processing of the sensor geometry, possibly including a transition to dry pressing.

2.2.3.2.4 Combined mini-PEMS systems for NOx, PM/PN, and other pollutants

NTK has developed a small PEMS system called the NTK Compact Emissions Meter (NCEM) (Jiang et al., 2016). The system can be used to measure PM and PN, NOx and O_2, and air/fuel ratio. The system weights about 12 kg and measures 340 mm by 280 mm by 270 mm. It can be set up in approximately 5 minutes. It is powered by a DC12/24V vehicle battery and draws less than 10 Amp to operate. The PM/PN sensor is based on the Pegasor technology. The NOx sensor detects NOx by measuring disassociated O_2 ions from NOx in a second chamber. UC Riverside conducted some comparison tests with the NTK system for both an on-road and marine engine. For the on-road engine, the NTK NOx values were within 20% of UCR Mobile Emissions Laboratory (MEL) results, with the NTK NOx measurements generally being lower than the MEL reference method. PM values were within 70% with PM2.5 for engine dyno test. For the marine engine, NOx emissions showed a good correlation with a CLD-NOx in a bypass mode. PN compared well with CPC results from the marine engine for the catalytic stripper mode. NTK vs CVS PN differences resulted from organic condensation formation in CVS, as the NTK measurement represents a solid PN.

The 3DATX Corporation has developed a smaller size integrated portable emissions measurement systems (iPEMS). The systems are called the parSYNC® and parSYNC® PLUS and are designed to provide a lower cost option to full 1065 compliant PEMS (Ropkins et al., 2016). The parSYNC® and the parSYNC® PLUS both utilize replaceable (patents pending) “Sensor Cartridges” coupled with a multiple miniaturized chambers to obtain real-time PM/PN data for applications in dedicated “pass/fail” lane testing or in a PEMS/PAMS type of field unit. In addition, the parSYNC® PLUS adds a NO/NO_2 (NOx)/CO_2 GasMOD™ Sensor Cartridge. The 3DATX Corporation has also developed a particle generator called the CA/GE™ System that is designed to produce a controlled size-disbursed/distributed aerosol combination of non-toxic particles and vapor in the required size range. This provides a calibration method suitable for verification programs. The parSYNC® has recently been evaluated by researchers at Ford Motor Company (Vu et al., 2018). This included tests on a 2015 gasoline direct injection vehicle over the FTP, US06, and World Harmonized Light Vehicles Test Cycle (WLTC). The PM output from the parSYNC® showed reasonable correlation to PM (measured by a Dekati Mass Monitor) and PN (measured by an Engine Exhaust Particle Sizer) for ‘normal’ drive conditions of the drive cycle. For Phase 4 of WLTC and US06 driving events, the relative response does not correlate well. There were also some baseline zero shifts that were observed that had to be compensated for.

2.2.3.2.5 Mini-PEMS Intercomparison tests

TNO in the Netherlands has evaluated alternative different instruments for possible use in periodic technical inspections for DPF equipped light-duty vehicles (Kadijk et al., 2016; Spreen et al., 2016). This testing evaluated two generations of smoke opacity meters and a hand held total particle counter for a fleet of 213 Euro 5 and 6 light-duty diesel vehicles equipped with DPFs. The smoke meter tests were performed using a free acceleration test, while the handheld PN tests were performed at low idle. The low idle tests were conducted for approximately 15 seconds and were done in triplicate. The results looked at failure rates for opacity absorption k values of 0.1 to 0.3 m-1 (approximately 3 to 10% opacity), and for number concentrations from 50,000 to 250,000 #/cm3. The results are shown in Figure 2-2, where FA-SO denoted free acceleration standard opacity meter, FA-IO represents free acceleration improved opacity meter, and LI-PN represented low idle PN. The results show that PN measurements were potentially more sensitive in identify DPFs failures, as 8.5% of the vehicles were found to have PN counts >250,000 cm^3, where opacity limits between 0.1 and 0.3 m-1 identified between 1.4 and 5.6% of the vehicles as having potential DPF failures. The overall assessment of the different testing results is shown in Table 2-4. The results suggested improved representativeness, accuracy, and repeatability and reproducibility for the PN measurement tests, at a slightly higher cost per test.

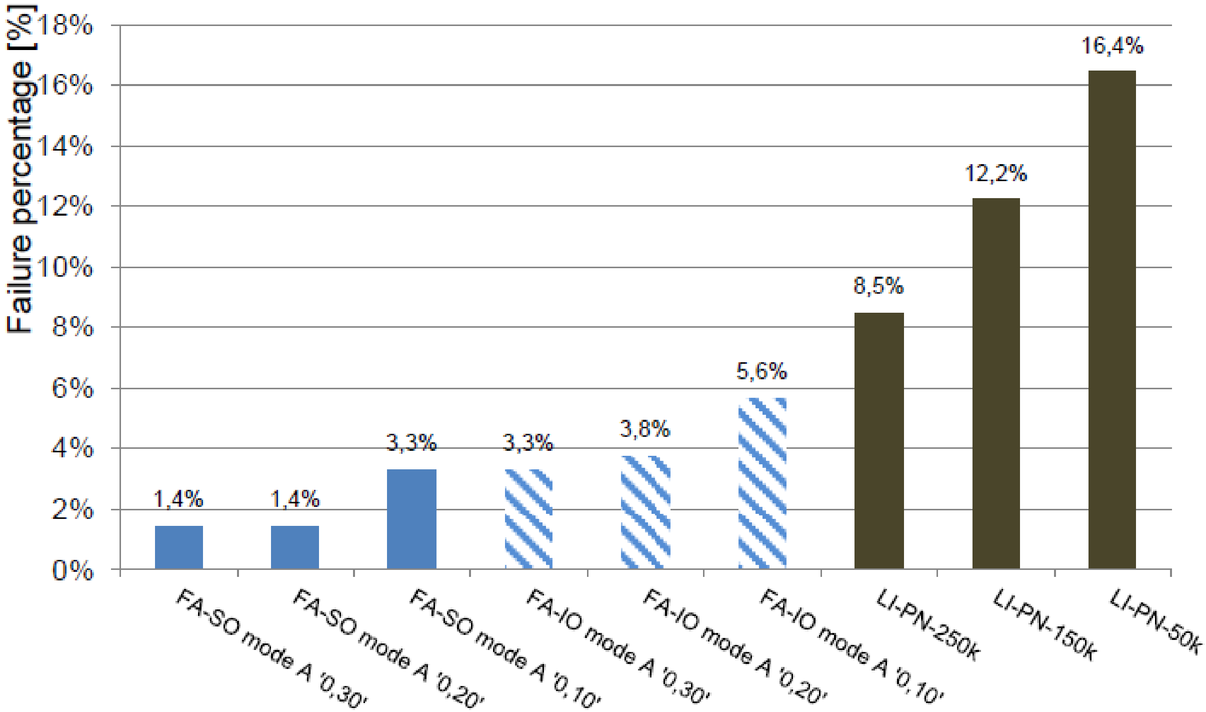


Figure 2-2 Percentages of DPF Failures Based on Different Test Procedures and Limit Values

Table 2-4 Overall Assessment of Parameters for the Different Test Methods

Parameter	Free Acceleration Standard Opacity	Free Acceleration Improved Opacity	Low idle PN
Comment	Current method	Improved 1 'CITA'	Improved 2
Representativeness	+/-	+/-	++
Sensitivity, threshold	--	+/-	++
Accuracy	-	+	++
Reliability	+/-	+	++
Screening performance	--	-	++
Reproducability	-	-	++
Repeatability	+/-	+/-	++
Executibility	+/-	+/-	++
Costs	+	+	+/-
Costs [€/test]	3.30 – 15.00	3.30 – 15.00	3.30 – 28.50
Test duration	+/-	+/-	++
Comfort for tester	-	-	+
Acceptance vehicle owner	+/-	+/-	++
Maturity	++	+	+
Limit values	--	+	++
Limit values	$0.7\ m^{-1}$	$0.10\ m^{-1}$	$250{,}000\ \#/cm^3$

Johnson and coworkers conducted an extensive series of tests as part of the measurement allowance program that included the evaluation of a range of different PM measurement methodologies (Johnson et al., 2010, 2011, 2012; Khan et al., 2012). In one study, three on-highway, heavy-duty trucks with a range of PM emission levels from 0.1 to 0.0003 g/hp-h, and varying compositions of elemental carbon (EC), organic carbon (OC), and sulfate were tested (Johnson et al., 2011). This testing included instruments designed to measure PEMS based on diffusion charging + gravimetric filter, a quartz crystal microbalance, photoacoustic measurements, electric mobility and aerosol impact, and light scattering. The photoacoustic measurement PEMS performed best for the non-aftertreatment system-equipped engine, where the PM was mostly EC, with a linear regression slope of 0.91 and an R^2 of 0.95. The PEMS did not perform as well for the 2007 modified ATS equipped engines, however. The best performing PEMS showed a slope of 0.16 for the DPF-equipped engine with predominantly sulfate emissions and 0.89 for the DPF-equipped engine with predominantly OC emissions, with the next best slope at 0.45 for the predominantly OC engine.

Durbin and Pisano (2010) evaluated several PM instruments for a small fleet of light-duty gasoline vehicles that included both low and high PM emitters. The PM instruments evaluated included an MPM4 from Maschinenbau Haldenwang (MAHA), an ETaPS from Dekati, a Dustrak and an EEPS from TSI. The DustTrak, the EEPS, and the MAHA were able to distinguish the three high emitting vehicles from the remaining low emitting vehicles. The DustTrak and the EEPS on average both read lower than the PM filter mass data. The MAHA required a calibration factor since the data was only available in concentration units. A linear regression between the DustTrak and EEPS and the PM mass showed a decent agreement with R^2 of 0.791 and 0.943, respectively, and negative intercepts of -1.384 and -2.797, respectively, due to the lower readings of these instruments compared to the filter mass at low levels. The linear regression between the MAHA and the PM mass showed a decent agreement with an R^2 of 0.852. It should be noted, however, that the PM levels for this study were much higher than those measured in the present work where the trucks were equipped with DPFs and had much lower PM levels. The effectiveness of the MAHA PM measurements at such lower levels was not investigated in the Durbin and Pisano (2010) study.

2.2.4 Plume Measurements Systems

2.2.4.1 Remote Sensing Devices

Remote Sensing Devices (RSD) technology has been around for many years, but has yet to find a significant role to play in California's Inspection and Maintenance system. The advantages of RSD include the fact that the devices are non-invasive, having the ability to capture the emissions of vehicles as they are driven by the owner/operator under real-world conditions. Conventional RSD systems utilize infrared and/or ultraviolet radiation to measure the level of pollutants in the exhaust plume. Capital costs for such systems could range from $100,000 or more depending on the complexity of the system design.

Remote sensing is a technique that has been widely used to characterize emissions from a wide range of vehicles. The University of Denver has been using a remote sensing device called the Fuel Efficiency Automotive Testing (FEAT) device since 1987. This system has been used more extensively for light-duty vehicles (LDVs), but more recently has been adapted for HDVs. Studies conducted with the FEAT to characterize the emissions of HDVs include those conducted in Colorado, at the ports of Los Angeles and Long Beach, and at a truck stop in a more suburban area of LA (Burgard et al., 2006; Bishop et al., 2012; Bishop et al., 2013). Commercial RSD systems have been developed by Opus inspection and by Hager Environmental & Atmospheric Technologies (HEAT). The Opus inspection RSD system, the RSD5000, is a 5th generation of their RSD system based on the original University of Denver design. The HEAT Emission Detecting and Reporting (EDAR) device is a different RSD system that utilizes a laser-based technology to provide a 3-dimensional image of the exhaust.

RSD systems have been utilized in programs that supplement I/M-type programs to identify high emitters, in programs to clean screen vehicles (Borken-Kleefeld, 2013), and as part of 40CFR audit programs of I/M programs. RSD is currently used in Colorado, Connecticut, Rhode Island, Tennessee, Texas and Vermont for clean and/or high emitter screening for LDVs, but not as the sole determinant of pass or fail. A map showing states that have low emitter (i.e., clean screen) programs, high emitter programs, or have conducted RSD studies for different fleet evaluations is provided in Figure 2-3. High emitter programs are designed to identify individual vehicles that have emissions significantly greater than expected, whether due to poor maintenance or intentional removal or tampering with emission control equipment. To the extent that a high number of vehicles from a particular vehicle model are identified as high emitters, this could indicate a more systematic issue with the emissions control system, rather than poor maintenance, and would warrant follow-up testing. The objective of clean screen programs, on the other hand, is to identify vehicles having low emissions with the RSD system that can subsequently be exempted from mandatory inspections that can be.

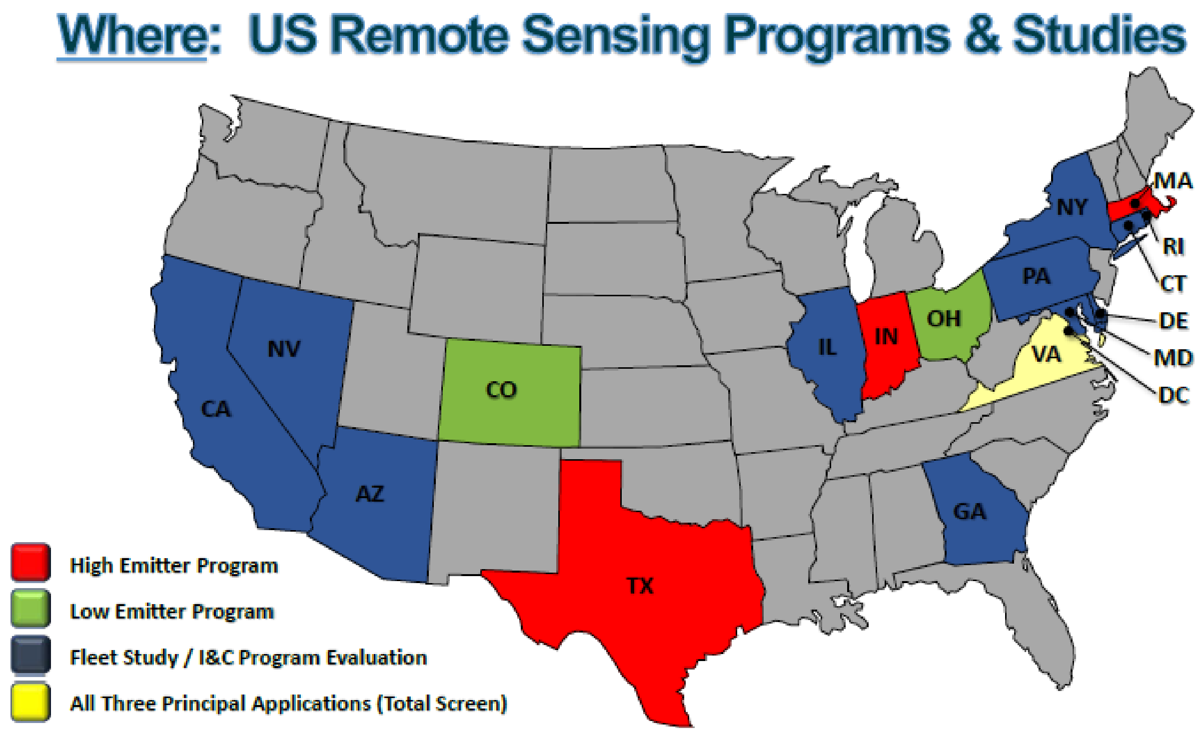


Figure 2-3. Map of U.S. Remote Sensing Programs and Studies (Source: Opus International)

On-road RSD measurements were utilized as part of the South Coast Air Quality Management District's High Emitter Repair or Scrap (H.E.R.O.S) program (McClintok, 2009). Three RSD4500 systems were deployed throughout the greater Los Angeles area from February 2007 through April 2008. More than 949,000 unique vehicles were successfully measured with California plates. From the vehicles registered within the SCAQMD, 25,218 were selected as high emitters potentially eligible for recruitment into the associated H.E.R.O.S. voluntary repair and retirement program. Of these close to 700 were recruited for follow-up inspections at Smog Check Referee stations. Eighty percent (80%) of these high emitters failed the first Smog Check inspection conducted at the Referee stations. Thirty-five percent (35%) exceeded the Smog Check program gross emitter limits, while 37% failed tailpipe or OBD inspection, and 8% were found to be tampered with.

More recently, the U.S. EPA has done extensive analysis of RSD measurements collected in Colorado. Colorado has had an extensive RSD program where between 18-22 RSD systems have been deployed throughout the state, including RSD4000, RSD4500, and RSD5000 systems. The U.S. EPA analyzed nearly 6 years of measurements from this program, which represents over 40 million records and over 10 million unique vehicles. The results have shown that by binning the data from specific vehicle models into vehicle specific power (VSP) bins that vehicle models with particularly high emission levels can be identified. An example showing the differentiation between fleet average RSD emissions and RSD emissions from two individual vehicle groups that are high emitters is provided in Figure 2-4.

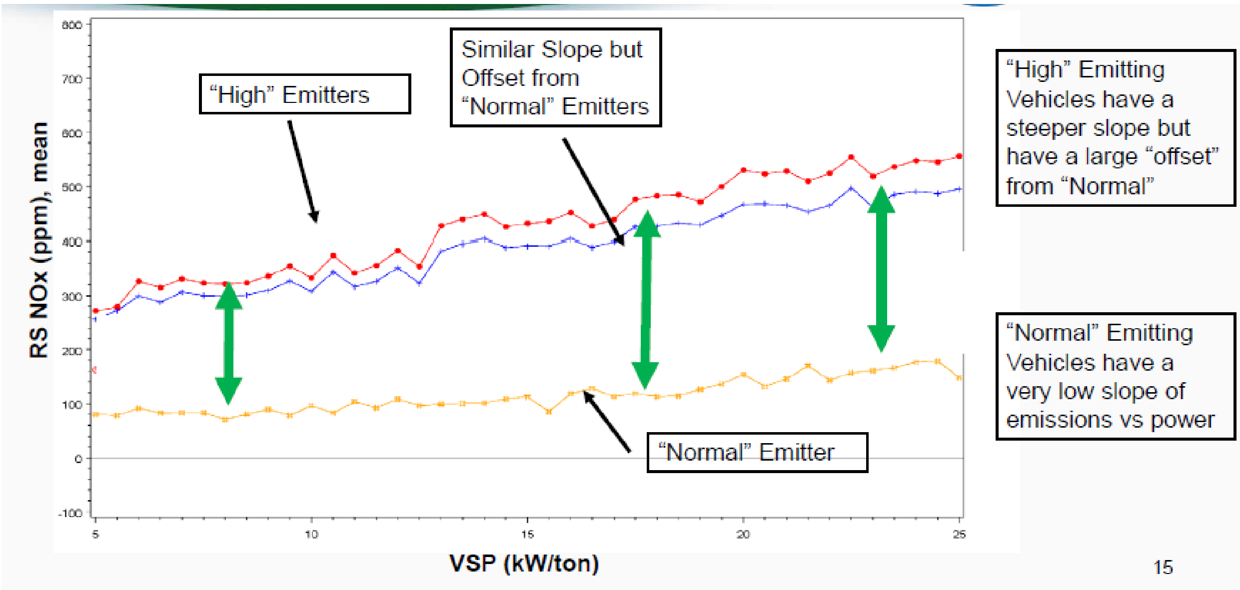


Figure 2-4 Normal and High Emitter Categories based on RSD Measurements

Hong Kong implemented a remote sensing screening program from 2014 to 2016 to identify high-emitting vehicles. The program utilized two remote sensing instruments set up in a series, approximately 10-15 meters apart, that were rotated through over 100 sampling sites. The RSD measurements were compared against predetermined cut points based on different emission standards for different vehicles, and an emission testing notice was sent to the owners of vehicles with RSD measurements above the applicable cut point, requiring additional chassis dynamometer testing. Between 2014 and 2016, approximately 1.3 million remote sensing measurement records representing 311,000 unique vehicles were collected, encompassing 30% of the private car fleet and 100% of the liquefied petroleum gas (LPG) taxi fleet in Hong Kong. A total of 7,236 emission testing notices were issued as part of this program, with approximately 20% of the LPG taxi fleet and 2% of the overall fleet found to be high emitters.

The use of RSD in Europe is continuing to expand. RSD has been deployed in many European countries dating back to the 1990s, including Sweden, the United Kingdom, Spain, France, and Switzerland (Borken-Kleefeld and Dallmann, 2018; Bernard et al., 2018). RSD has been incorporated into the European Real-Driving Emissions (RDE) legislation as a methodology to identify potentially high emitting engine families that would be suitable for more extensive testing under the RDE PEMS testing program. That program requires only requires 5% of engine families to be tested each calendar year, but includes a information gathering and risk assessment component, whereby evaluation methods including RSD, PEMS, OBD, sensors, or warranty records are utilized to identify potentially high emitting families for more extensive testing (Valverde, 2018). Many European cities also have low emissions zones, where older cars certified to older standards are not allowed to enter particular zones in a city. Despite such measures, there is a still an issue with urban NO_2 due to higher NOx emissions from diesel cars. A number of cities are considering a ban of certain or all diesel cars from access to inner parts, for instance: Athens, Hamburg, London, Paris, Stuttgart, Mexico City, and Beijing (Harvey, 2016; Tietge & Diaz, 2017). RSD is also being investigated as a method to characterize, monitor, or enforce such measures.

There are also on-going efforts to establish a larger data pool of RSD data in Europe, under the (CONOX) collaboration (Bernard et al., 2018). The goal is this program is to develop a database sufficiently large enough to determine emissions rates on a per model basis. As of June 2018, the data set consisted of over 700,000 records. The CONOX remote sensing database will be maintained by IVL in Sweden16. Work has also been done to develop a conversion between the remote sensing emission factor unit (gram pollutant per kg fuel) and the unit typically used for regulatory emissions testing (gram pollutant per km driven). A comparison between RSD results converted using this methodology and PEMS results for Euro5 and Euro 6 vehicles shows promising results, as shown in Figure 2-5. There is also work being done within the pan-European CONOX project to recreate RDE test trip or chassis test cycle results from instantaneous emission rates from RSD measurements. The RSD emission rates at a specific engine load, defined by speed and acceleration of the vehicle, are weighted by the speed-acceleration profile for a test trip or test cycle, to provide an estimate for trip or cycle specific emissions.

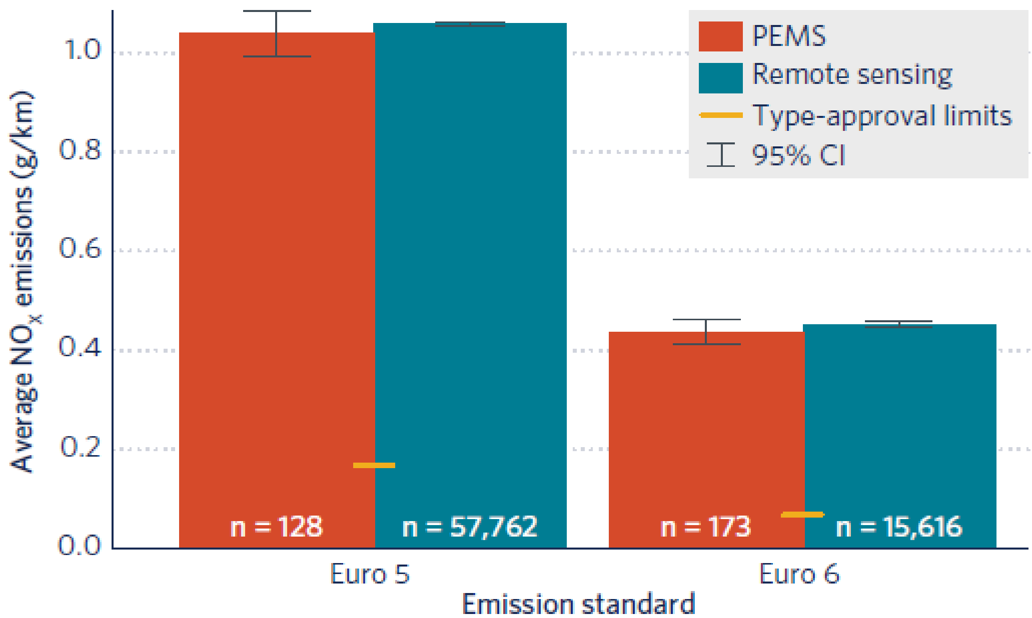


Figure 2-5 Average diesel NOx emissions (g/km) measured from emissions testing campaigns with PEMS and calculated from remote sensing data.

RSD was evaluated as a potential element of California's Smog Check program for LDVs. Eastern Research Group (ERG) conducted a pilot study to evaluate the potential for RSD to improve the effectiveness of the Smog Check program (Burnette et al., 2008). The study focused on evaluating the emission reduction and cost effectiveness of an RSD program that could supplement California's existing I/M program, as opposed to replacing it. This included the potential for RSD to identify vehicles for "clean screening" or for off-cycle inspections. As part of the pilot study from 2004 to 2005, where over 2 million RSD measurements were obtained from 420,000 vehicles. ERG developed models to evaluate the effectiveness of RSD using the RSD measurement data along with California's Smog Check database, known as the Vehicle Information Database (VID). The models analyzed the benefits and costs of targeting vehicles based on RSD measurements alone, RSD measurements used in combination with VID data, and using the use of VID data by itself. The RSD program modeled was large-scale, with the deployment of 50 RSD systems with a goal of collecting approximately 50 million RSD records a year. ERG found that a maximum of about 30% of the statewide fleet subject to Smog Check could be targeted via such a program, due to the requirement that the engine needs to be at a moderate load to get a good reading. The study found that although RSD could be used to identify high emitters, to “clean screen”, or to identify vehicles for scrappage, these programs would not be cost effective. They did, however, find that RSD had the potential to verify emissions reductions for the Smog Check program, as there were differences in vehicle emission levels measured before and after a typical Smog Check inspections on a fleet-wide basis.

There has been a limited number of studies that have compared RSD measurement values with other emissions measurement devices. Vescio et al. (2006) evaluated the correlation between RSD and PEMS measurements during a study of in-use emissions from commercial trucks crossing the US-Mexico border at Nogales, Arizona. A regression analysis of these results is shown in Figure 2-6. The regression shows a fair correlation between the conventional RSD and PEMS measurements of nitrogen monoxide (NO), the main component of vehicular NOx emissions. The data for the different trucks is reasonably close to the linear regression line and the line has a relatively small y-intercept value, suggesting conventional RSD emissions results could potentially be used for screening purposes for NOx for a HD I/M program. The latest version of this RSD system from Opus Inspection (2018) is being used for high emitter or clean screen programs in Colorado, Texas, Indiana, Ohio, and Virginia, as shown in Figure 2-3, and is also being utilized in a high emitter screening program for buses for the Massachusetts Bay Transit Authority (MBTA).

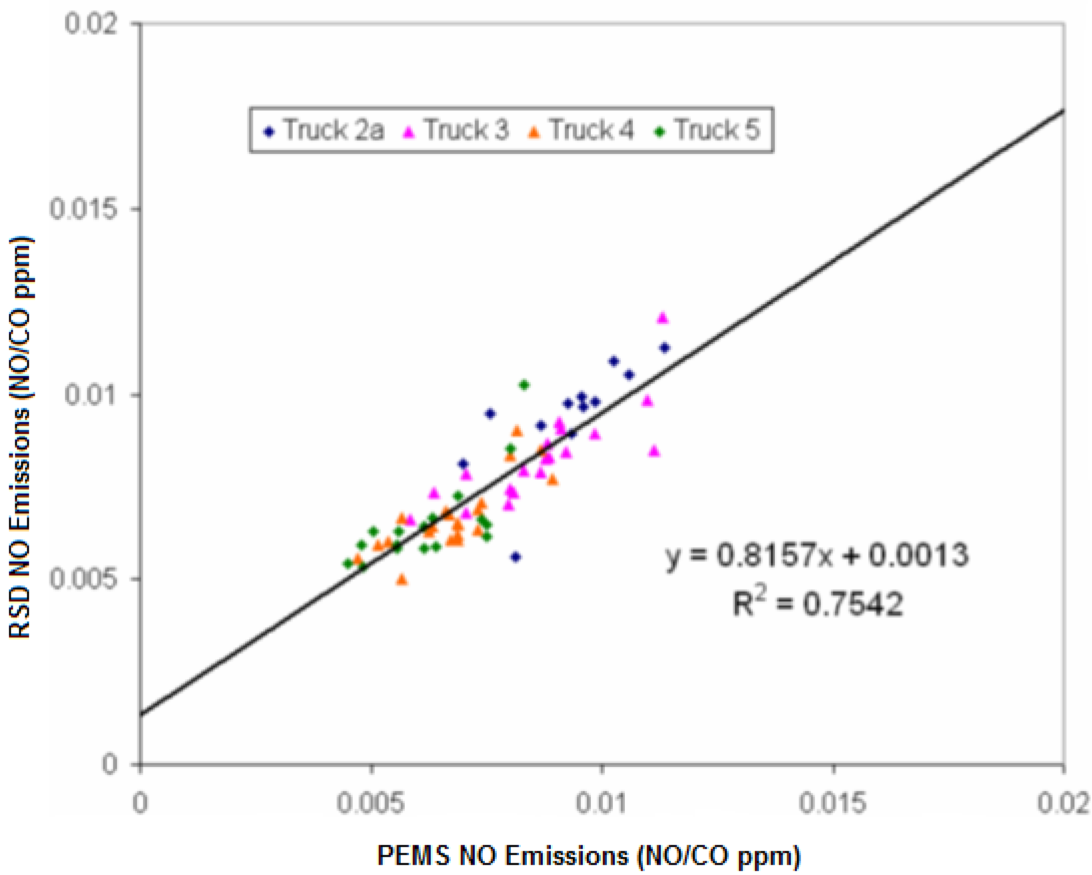


Figure 2-6 Regression analysis for RSD vs. PEMS NO measurements

An emerging technology to conventional RSD is a device offered by HEAT. HEAT was founded in 2009 to develop a new version of RSD. The EDAR device contains a multi-patented system of hardware and software, which allows for a multi spectral 3-dimensional image of the entire exhaust plume of a moving vehicle. The EDAR utilizes laser-based technology as opposed to nondispersive infrared (NDIR) capable of remotely detecting and measuring the infrared adsorption of gases including HC, NOx, PM and CO_2. The technology behind EDAR eliminates the need for calibration, which allows for it to be an unmanned system with one footprint for both heavy and light duty vehicles. The EDAR is designed to be mounted overhead looking down at passing traffic with the capability of capturing the entire exhaust plume regardless of exhaust system orientation. Since EDAR uses remote sensing technology, these units require only periodic maintenance that is performed by a third-party maintenance company. EDAR holds the promise of acting both as an effective screening tool and a means of determining pass/fail emission levels in a heavy-duty I/M system.

The EDAR device has been demonstrated in California, Colorado, Utah, Texas and Tennessee, and has been cross compared against PEMS (Hager), other emissions measurement instrumentation (Hart et al 2015), and calibration gases. The EDAR system was utilized in 2014 in Connecticut to satisfy its requirements for on-road emissions testing, as specified in 40CFR §51.351 and §51.371. This requirement includes testing at least 0.5% of the subject vehicle population, or 20,000 vehicles; whichever is less. The EDAR system was deployed in October, and completed 62 hours of testing, over a period of nine days, at eight different locations, resulting in 37,400 measurements (St. Denis et al., 2015). Of these data, 8,130 measurements were excluded for being outside of the allowed Vehicle Specific Power (VSP) limits (3 to 22 kW/t), 1,707 were excluded for unreadable plates, another 2,491 were excluded as commercial vehicles and motorcycles, and 1,816 were excluded as being out of state vehicles. This reduced the valid samples of Connecticut vehicles to 23,256 with valid and complete sample information (speed, acceleration, license plate information and emission measurements), of which 21,396 vehicles were successfully matched with the DMV, with an additional 3,480 excluded due to interfering plumes (emissions from vehicles in adjoining lanes also being measured, etc.) resulting in a final sample of 17,916 vehicles. The survey identified a small percentage of the vehicles as high emitters (1.7% of the final sample), based on exceeding cut-points used in past remote sensing studies (500 ppm HC, 3% CO, 2000 ppm NO). In total, 307 vehicles exceeded at least one of these cut-points. HEAT has finished a study for the state of Arizona, a 3 week trial using their diesel system which detects NO and NO_2 in London and Birmingham, and a 20 day campaign in Paris in June of 2018. The European studies include work done as part of The Real Urban Emissions (TRUE) project (ICCT, 2017). These studies are either being analyzed, or have yet to be publicly released.

In one of the most recent comparisons studies, the U.S. Environmental Protection Agency (USEPA), the Colorado Department of Public Health and Environment (CDPHE), and Eastern Research Group (ERG) evaluated the performance of the EDAR using calibration gases that were released from a specially designed audit truck with its exhaust routed such that it would not be read by the EDAR (DeFries, 2016). A series of 6 audit gases were used containing the following gases and concentration ranges: CH_4 (0 to 209 ppm), propane (31.7 to 6,000 ppmC[3]), NO (40.8 to 502 ppm), which was used as a surrogate for NOx, CO (30 to 50,000 ppm), and CO_2 (11.5 to 14.9%). The vehicle was driven past the EDAR at fixed speeds of 15, 35, 45, and 60 mph while releasing various combinations of the calibrations at a fixed flow rate. Comparisons between the calibration bottle concentrations and the EDAR were then developed to evaluate the linearity, bias, and detection limits of the instrument/measurements. A summary of the average EDAR readings and the standard deviations compared to the challenge gas concentrations is provided in Table 2-5. These results were then used in regression analyses to determine the slope, intercept, and R^2 values compared to the bottle concentrations. For NO emissions, the regression results showed the measured values average about 3% below the bottle concentrations, with an intercept of less than 2 ppm, and a R^2 of 0.998 or larger for all speeds, indicating a small bias, small scatter, and good accuracy. Based on an average standard deviation of around 7 ppm, the detection limit, as defined by 3 standard deviations, is about 20 ppm. For CO, the EDAR showed a slight bias, with regression slopes about 6% high, and low scatter, with R^2 values of 0.996 or larger for all speeds. The detection limits for CO, based on 3 standard deviations, were estimated to be in the range of 50 to 100 ppm depending on speed. For CH_4, the regression slopes for each speed indicate approximately a 4% high relative bias, and the intercepts showed approximately a 19 ppmC low bias. The detection limits for CH_4, based on 3 standard deviations, were estimated to be in the range of 15 to 35 ppmC depending on speed. For propane, the regressions indicated a relative bias of about 4% low and an increasing bias of about 4ppmC3/mph. The R^2 of the data for each speed tend to decrease from 0.99 to 0.93 as the speed increases. The detection limits for propane, based on 3 standard deviations, were estimated to be in the range of 100 to 400 ppmC3 depending on speed.

Table 2-5 Summary of the Precision and Accuracy of the 5 Challenge Blends

Mean ± 1 Standard Deviation
for Bottle CO2 * EDAR molePollutant/moleCO2
(At least 8 replicates at each condition except for Blend B at 60 mph which had 5 replicates)

Bottle Label	Bottle Value NO (ppm)	NO @ 15mph (ppm)	NO @ 30mph (ppm)	NO @ 45mph (ppm)	NO @ 60mph (ppm)
D	41	41 ± 3	39 ± 10	37 ± 4	38 ± 11
C	151	145 ± 4	146 ± 4	149 ± 6	146 ± 10
B	377	360 ± 2	365 ± 8	362 ± 7	365 ± 7
Q	500	480 ± 5			
A	502	488 ± 5	489 ± 5	484 ± 13	489 ± 8

Bottle Label	Bottle Value CO (ppm)	CO @ 15mph (ppm)	CO @ 30mph (ppm)	CO @ 45mph (ppm)	CO @ 60mph (ppm)
D	30	59 ± 57	52 ± 26	60 ± 28	63 ± 33
D*	30	32 ± 4	37 ± 8	36 ± 7	48 ± 6
B	494	509 ± 15	513 ± 16	497 ± 33	477 ± 64
C	1500	1532 ± 27	1507 ± 28	1536 ± 43	1554 ± 124
A	20000	21395 ± 575	21027 ± 507	21021 ± 747	21530 ± 1192
Q	30000	32116 ± 2517			

* After discarding suspected outliers: 2/10 @ 15mph, 3/11 @30mph, 5/10 @ 45mph, 2/9 @ 60mph.

Bottle Label	Bottle Value CH4 (ppm)	CH4 @ 15mph (ppmC)	CH4 @ 30mph (ppmC)	CH4 @ 45mph (ppmC)	CH4 @ 60mph (ppmC)
Q	0	-18 ± 4			
D	24	13 ± 5	2 ± 9	3 ± 3	8 ± 13
C	51	42 ± 4	32 ± 8	27 ± 7	36 ± 7
B	103	96 ± 5	87 ± 8	85 ± 11	89 ± 2
A	209	200 ± 6	192 ± 5	198 ± 14	200 ± 14

Bottle Label	Bottle Value C3H8 (ppm)	C3H8 @ 15mph (ppmC3)	C3H8 @ 30mph (ppmC3)	C3H8 @ 45mph (ppmC3)	C3H8 @ 60mph (ppmC3)
D	32	28 ± 33	60 ± 89	150 ± 93	223 ± 131
C	115	133 ± 36	159 ± 68	263 ± 91	316 ± 104
B	398	428 ± 17	448 ± 123	530 ± 126	744 ± 150
Q	1100	1079 ± 34			
A	1300	1274 ± 36	1305 ± 75	1397 ± 100	1424 ± 128

In another study, the EDAR was compared to measurements from a Semtech D PEMS system. This study was conducted at the University of Tennessee and the National Transportation Research Center at Oak Ridge National Laboratory on a chassis dynamometer using a 2004 Yukon (see Hager). Comparisons of the CO/CO_2, NO/CO_2, and HC/CO_2 are shown in Figure 2-7. Overall, the ratios show a good correlation. The results show the differences in response rates for the two instruments, with the EDAR sampling at a higher sampling rate of 0.025 seconds compared to the PEMS 1.25 second sampling rate. A load on the engine is introduced halfway into the data collection. There are high NO concentrations during the load. The CO and HC dropped as the catalytic converter warms.

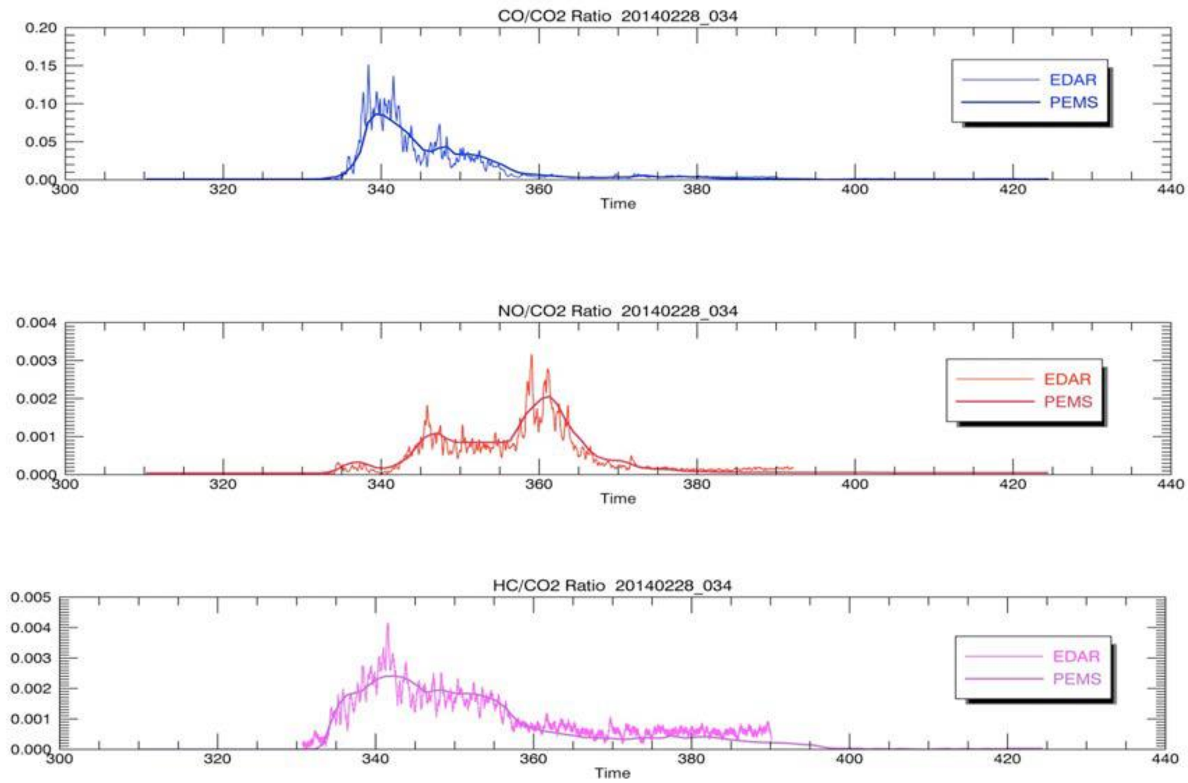


Figure 2-7 Graphs of the ratios of CO/CO_2, NO/CO_2, and HC/CO_2 for both the EDAR device and the PEMS

Additional comparisons were also done in the United Kingdom through a series of tests conducted by the University of Leeds, the University of Birmingham, and King's College London (Ropkins et al., 2018). They conducted two separate studies. In one study, a vehicle was equipped with a PEMS and run through the EDAR under a range of different engine load and gear conditions to provide a broad range of emissions. In the second test, a chase vehicle instrumented with NOx and CO_2 analyzers was run through the EDAR behind a range of different vehicles as a comparison study. For the PEMS study, emissions for 25 runs with the smoothest vehicle trajectories were selected for analysis. In comparing NO/CO_2 ratios for the EDAR vs. PEMS, the results showed a good $R^2 = 0.968$ with a slope of 0.71 for the EDAR. The authors suggested that the low bias could be attributed to the difference in the time resolution for the two measurements, with the EDAR having a resolution of 10 to 100 ms compared to the PEMS time resolution of 1 second. The comparison for NO_2/CO_2 ratios showed a correlation of $R^2 = 0.797$, with a slope of approximately 0.4 for the EDAR. The authors suggested the lower bias for the EDAR could be attributed challenges measuring the more reactive NO_2 molecule. The chase car experiments also showed a good correlation over a broader range of 8 vehicles, with a $R^2 = 0.862$ and a slope near 1. This suggests that the agreement observed in the one vehicle PEMS/EDAR comparison could reasonably be expected for other vehicles in a larger fleet.

The EDAR system was also used for a more extensive two week trial period in Scotland in March of 2017. This campaign include two locations, with 70,318 successful vehicle emissions readings (HEAT, 2017). In general, the results showed that while average emissions of petrol cars declined for increasingly more stringent emissions standards, the average NOx emission values of Euro 4, Euro 5, and Euro 6 diesel cars were significantly higher than standards. Results for high emitters with more than one replicate measurement are shown in Figure 2-8 for NOx. Examples of replicate PM measurements for high PM emitters from this study are presented in Figure 2-9. Overall, the results do suggest that the system has sufficient sensitivity to identify high NOx and PM emitters. The variability from measurement to measurement for the high emitters, as shown in Figure 2-9, suggests that multiple measurements of single vehicle should be made to ensure that high measurements can be confirmed with more than just a single measurement. Note that this variability could be due to the vehicle accelerating through RSD measurement area at different rates, rather than actually large changes in the emissions characteristics of the engine.

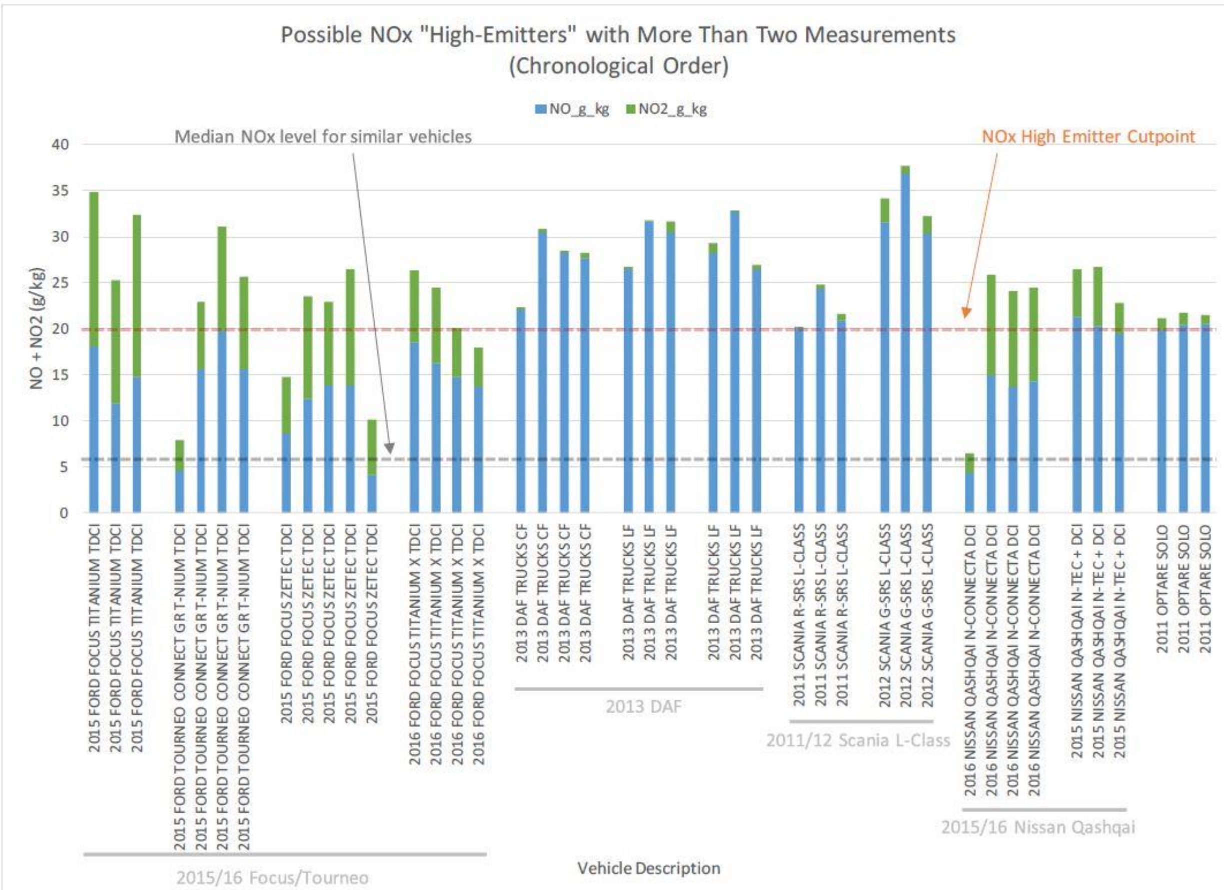


Figure 2-8 NOx "High Emitters" with more than one measurement from EDAR Scotland Pilot Study

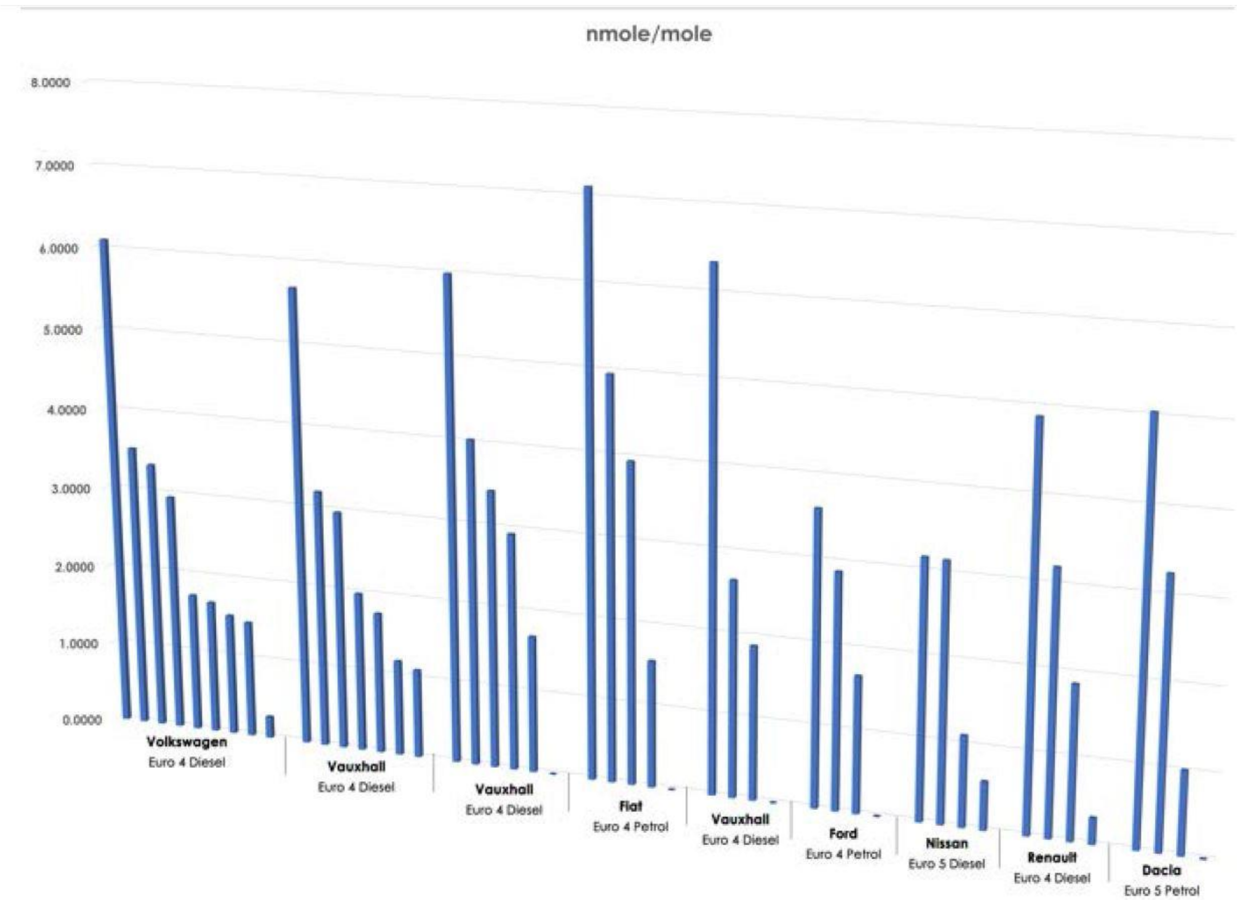


Figure 2-9 Examples of Replicate PM Measurements from the EDAR Scotland Pilot Study

The measurement of PM with an RSD system can be more challenging, as the properties of particles can differ in shape, size, and chemical composition. Elemental and organic carbon are the primary constituents of vehicle PM. Elemental carbon strongly absorbs light in the visible and near visible wavelength range. Organic carbon, on the other hand, is a relatively weak light absorber. The shape of particles can range from more spherical to more aggregate particles, while the size of particles can range from a few nanometers to micron size particles. Chen et al. (2010) evaluated an optical opacity system for a diesel vehicle and a diesel bus in a laboratory setting. The use of opacity measurement systems becomes more challenging for vehicles with lower PM emission rates, however, as the light extension for moderately emitting vehicles may be very small. Stedman and Bishop (2002) utilized a system using a combination of three different opacity measurements to characterize emissions from three light-duty diesel trucks. This included a UV channel with a xenon arc lamp with a bandpass filter at 240 nm, a visible channel using a He/Ne laser with a 632.8 wavelength, and an IR channel using a thermal source with a bandpass filter at 3.9 µm. For the highest emissions points, which would correspond to the high emitters, the results agreed within 20%, with the IR method being lower than the UV methods. Researchers at the Desert Research Institute (DRI) developed a combination system that utilized a UV Light Detection And Ranging (LiDAR) backscattering approach for PM, coupled with a UC transmissiometer (Mazzoleni et al., 2010). This is similar to the approach utilized with the EDAR system. This system was utilized in several field campaigns. The LiDAR approach was found to be more sensitive than opacity methods, and was able to characterize the effects of vehicle model year, type, and fuel, and engine operating conditions on PM from both gasoline and diesel vehicles. More recent comparisons were done in the United Kingdom where a vehicle equipped with a ionization-based PM analyzer was driven through the EDAR system multiple times. For these tests, there was a good correlation between the EDAR and the PM analyzer PM measurements of R^2 = 0.937, with a slope of 0.365 indicating a low bias for the EDAR.

In evaluating RSD for a heavy-duty I/M program, RSD does not require that trucks be taken out of service in order to perform such testing, as RSD could be located at weigh stations. RSD does suffer from some of the same disadvantages as the SHED variations discussed further below, in that vehicles could only be sampled at a given location, and how consistent the measurements could be is a function of how controlled the operation of the vehicle is as it passes by the RSD. In particular, because RSD captures only a snapshot of emissions, readings may vary widely as a result of external factors including how the vehicle is driven when passing the device, the orientation of the vehicle's exhaust system, and weather conditions when readings are taken. Also, emissions from an engine at a fixed torque and speed may vary depending on the immediate prior history of engine operation. It is also more difficult to determine the VSP for RSD measurements for heavy-duty vehicles, because the load carried by a HDV can vary over a much greater range than typically found for LDVs. RSD would likely be less costly to implement widely than OMHS or SHED, however, and could be set up for more unmanned operation. Owners of vehicles found to have high emissions with RSD could be subsequently notified of the need to fix the vehicle or come in for testing by mail based on license plate readings. The coupling of RSD with another method, such as OBD, that provides monitoring over a greater percentage of vehicle operation could be viable for a HD I/M program.

2.2.4.2 Tunnel/Probe Testing

In addition to RSD measurements, measurements of in-use truck emissions have also been made using measurements in traffic tunnels or freeway overpasses. An extensive series of such experiments has been carried out in the San Francisco Bay area over a period extending back to the 1990s (Dallman et al., 2010, 2011, 2012, 2013, 2014). More recently, sample probes have been implemented in tunnels for the measurement of individual heavy-duty truck emissions. The potential to implement this method at tunnel and freeway overpass locations could provide advantages in terms of provide a wider range of potential noncentralized locations to test at, but it is likely too difficult to provide a traceable link to an individual HD vehicle from an enforcement perspective. As such, a probe technique could be used as a cross check of other methods that might be put in place as part of an I/M program.

CARB has also developed an in-house prototype roadside plume sampling system for HDVs called the Portable Emissions AcQuisition System (PEAQS) (Ham et al., 2017; CARB, 2017a). The full system includes an updraft and downdraft sampling line, lab-grade emissions analyzers for NOx, PM, and CO_2, and a license plate reader. A mid-grade system is also being developed that would include a low cost CO_2 monitor, an aethalometer, and an optional NOx sensor for approximately $20,000. The PEAQS system is designed for multiple uses, including research, regulation development and implementation, air monitoring, fleet characterization, and as an enforcement screening tool to prioritize inspections and investigations. The PEAQS system uses multiple criteria for data validation, including valid pollutant peaks co-aligned with the CO_2 peak, vehicle image captured, and valid vehicle speed. The PEAQS was used in a study in the Fall of 2016 at a California Department of Food and Agriculture Inspection Station in Truckee, CA. A total of 700 HD trucks were measured during this study, including 429 with updraft exhausts and 271 with downdraft exhausts. The emission factor distributions showed that 7.5% and 3.2% for the trucks contributed 50% of the total emissions for NOx and black carbon (BC), respectively.

2.2.4.3 On-Road Heavy-Duty Vehicle Emissions Monitoring System [OHMS]

A modification of the RSD technique, as discussed below, is to incorporate the measurement systems into an enclosure. This allows for more control of the vehicle operation through the enclosure, such that the vehicles are sampled under more uniform conditions. Supplemental analyzers can used to measure PM emissions. Variations of these RSD enclosures have been referred to as SHEDs (Streamlined Heavy-Duty Emissions Determination), Heavy-Duty Emissions Tunnels (HDET) and On-Road Heavy-Duty Vehicle Emissions Monitoring Systems (OHMS). These RSD type enclosures have been evaluated by Envirotest Canada and Texas A&M.

In the Envirotest Canada (2013) study, comparisons were made between tunnel and RSD measurements. A summary of these comparisons is provided in Table 2-6. Overall, there was a reasonably good correlation between the RSD and Tunnel measurements for NOx, particularly for the 2007 and older vehicles. Average RSD PM emissions were 0.4 g/kg higher than the Tunnel measurements across all model years. It was suggested that this may have been a consequence of the operating mode of the vehicles. Heavy-duty vehicle PM emissions per unit of fuel were higher at idle than when engines were under load and those measured by RSD were often operating at a lower average power than those measured through the Tunnel.

Table 2-6 Average Emissions and Observations for heavy-Duty Vehicles in the Envirotest Canada Study

Model Year	Observations	RSD NO g/kg	Tunnel NOx g/kg	NOx Variance (RSD-Tunnel)	RSD PM g/kg	Tunnel PM g/kg	PM Variance (RSD-Tunnel)
2000 & older	6,989	30.5	29.3	1.1	1.2	0.8	0.4
2001-2007	12,768	19.9	20.9	-1.0	1.1	0.6	0.5
2008-2010	3,079	10.9	14.2	-3.3	0.5	0.1	0.4
2011 & newer	2,969	3.6	4.2	-0.6	0.5	0.1	0.4
Total	**25,805**	**19.8**	**20.5**	**-0.6**	**1.0**	**0.6**	**0.4**

As part of this study, Envirotest developed several different variations of high emitter cut-points. One set of high emitter cut-points was intended to identify the worst emitters that could be targeted for mandatory or incentive based repair, replacement or retrofit, and were based on emissions distributions obtained during the study. These cut-points were termed the "conservative" cut-points in the study. The conservative trial cut-points of 24 g/kg (4 g/bhp-hr) NO and 2.4 g/kg (0.4 g/bhp-hr) PM for 2008 and newer vehicles far exceed the standards for these vehicles (0.2 g/bhp-hr for NOx and 0.01 g/bhp-hr for PM). The conservative trial cut-points of 45 g/kg (7.5 g/bhp-hr) NO and 3.6 g/kg (0.6 g/bhp-hr) PM for 2007 and older vehicles were more comparable to the standards, which are 10.7 g/bhp-hr for 1988/1989 engines to 4.0 g/bhp-hr for 1998-2003 models for NOx, and 0.6 g/bhp-hr for 1988-1990 models and 0.1 g/bhp-hr standard for 1994-2006 models for PM. Based on these cut-points, 8% of vehicles measured were classified as high emitters and these vehicles emitted 16% of total PM and 17% of total NO. A second set of cut-points were developed based on 1.5x the engine certification standards with an allowance for RSD variation. Here, the cut-points in g/kg can be divided by 6 to convert to g/bhp-hr. These cut-points are shown in Table 2-7. Based on these cut-points, 26% of vehicles measured were classified as high emitters and these vehicles emitted 42% of total PM and 38% of total NO.

Table 2-7 Standard Based Cut-points from the Envirotest Study

Trial	Model Year Low	Model Year High	NO g/kg Cutpoint	PM g/kg Cutpoint
B	1900	1990	90	6
B	1991	1997	45	2.4
B	1998	2003	36	1.8
B	2004	2007	30	1.5
B	2008	2099	12	0.9

Bishop et al. (2018) also developed an On-road Heavy-duty Measurement System (OHMS) to evaluate in-use emissions of heavy-duty trucks under roadside conditions. This method has been used to measure over 7,075 HDV emissions at the Port of Los Angeles and the Cottonwood weight scales of northern California. The OHMS has also been evaluated in several studies in Texas as a potential tool for a HDDV inspection and maintenance (I/M) program, where the OHMS was compared with PEMS measurements from different trucks(Claus et al., 2018). As part of these studies, the OHMS was also used to identify higher emitters at a Texas weight station. The high emitters identified in this part of the study represented less than 8% of the screened vehicles, but were found to contribute over one fifth of the total NOx emissions.

A Texas A&M (2013) study conducted some comparisons between OHMS and PEMS measurements. These results are presented in Figure 2-10. The SHED data showed a coefficient of determination (R^2) of 0.8081 with the PEMS, but showed a slope of 1.8044 g/kg, indicating the SHED overestimated NOx emissions relative to the PEMS. Poorer correlations were found for CO (R^2 = 0.1835) and HC (R^2 = 0.068) emissions.

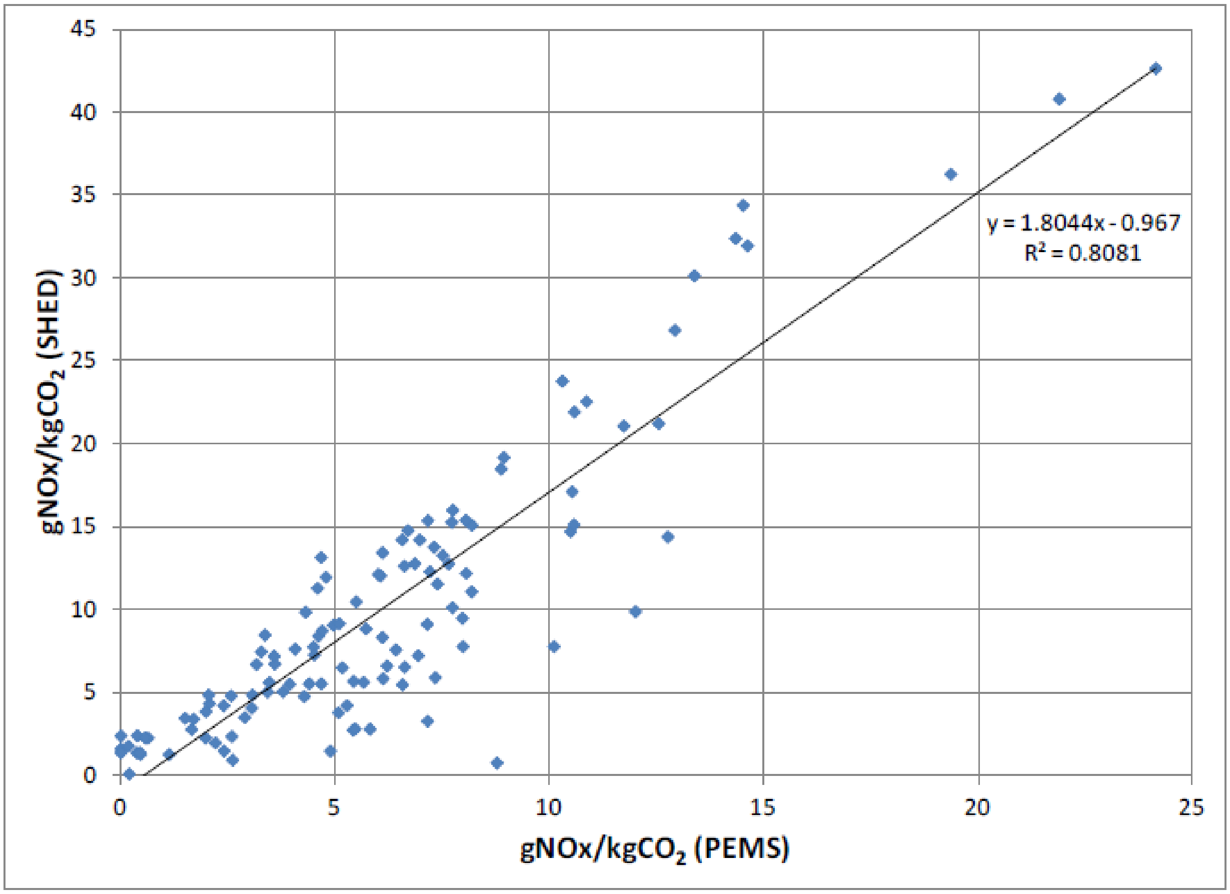


Figure 2-10 Correlation between SHED and PEMS test results for NOx

The OHMS/SHED enclosures design are simple enough that they could potentially be set up at a weigh station, such that vehicles would not need to report to a centralized location. This provides an advantage in comparison with chassis dynamometer or full PEMS testing. On the other hand, the system could still be too costly for widespread implementation if there is the need to erect an enclosure, or if additional analyzers must be used to capture all pollutants of interest. Another limitation is that the vehicles may need to be driven in a uniform manner, which is not defined well by acceleration alone, to ensure the representativeness of the emissions readings.

2.2.4.4 License Plate Readers

An important element of roadside plume measurement methods is obtaining the identity of the vehicle for which the emissions are being measured. This is typically done by capturing the license plate information with an automated license plate reader, or some type of video system that can record freeze-frame images of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The license plate information can be stored electronically such that the license plate information can be incorporated into the emissions database during post-processing. Additional pictures could also be collected of the driver of the vehicle at the time the emissions measurements are made. This would allow the information on the vehicle user (i.e., the driver) to be cross-referenced with information about the vehicle owner or fleet manager who submits the paperwork for the vehicle's registration.

2.3 Electronic Interrogation

Following Volkswagen's introduction of the first automotive on-board computer system with scanning capability in their 1968 fuel-injected Type 3 models, and General Motors' implementation of a proprietary interface and protocol for testing of the Engine Control Module (ECM) on the vehicle assembly line, CARB imposed regulations requiring OBD I to be installed on 1988 and newer model year vehicles. OBD I was designed to monitor components which were considered critical to controlling vehicular emissions, however, the systems were limited. Therefore, more extensive OBD II requirements were subsequently developed to address these shortcomings.

OBD II monitors all emissions critical devices and systems, stores diagnostic trouble code(s) (DTC), and illuminates a MIL when a problem is detected. All 1996 and newer model year gasoline-powered and alternately fueled passenger cars, light and medium- duty trucks are required to have OBD II systems. All 1997 and newer model year diesel fueled passenger cars and trucks are also required to meet the OBD II requirements. Additionally, a small number of 1994 and 1995 model year gasoline vehicles were equipped with OBD II systems.

OBD has become the central methodology for I/M programs for light-duty vehicles throughout the U.S. Nearly every I/M program in the U.S. relies solely on OBD II systems interrogation for vehicles, with the exceptions of California and Colorado. While California and Colorado still require tailpipe testing, many other states that previously operated emissions measurement stations, subsequently closed those operations. Colorado still relies on tailpipe testing exclusively. The California Bureau of Automotive Repair (BAR) requires all model-year 1996 and newer vehicles so equipped to undergo an OBD check as part of the official Smog Check, which includes a visual, functional, and a tailpipe inspection. However, as of March 9, 2015, all 2000 and newer model-year vehicles registered in California are receiving only an OBD II test (BAR-OIS) and a visual inspection. A comparison of Smog Check tailpipe and OBD failure rates is for California presented in Table 2-8. The results show similar failure rates between the emissions and OBD test, with OBD being slightly more sensitive in terms of detecting failures than the emissions test.

Table 2-8 Tabular Data for BAR-97 Initial Tests by Vehicle Model Year

MYR	Initial Tests	Initial Failures	Percent Failure	Emissions Failures (%)	OBD Failures (%)
1996	229,050	54,089	23.61	11.29	13.14
1997	398,326	80,524	20.22	8.61	11.78
1998	376,979	70,026	18.58	7.02	11.52
1999	588,383	84,427	14.35	4.15	9.64
2000	27,516	3,777	13.73	4.75	9.60
2001	32,364	3,996	12.35	3.18	9.54
2002	23,596	2,719	11.52	3.05	8.94
2003	33,559	2,832	8.44	1.97	6.31
2004	21,869	1,791	8.19	1.90	6.08
2005	32,777	1,801	5.49	1.23	4.07
2006	21,135	1,092	5.17	1.28	3.60
2007	30,804	987	3.20	0.69	2.30
2008	14,785	501	3.39	0.95	2.57
2009	14,206	334	2.35	0.53	1.76
2010	3,886	65	1.67	0.77	1.31
2011	5,245	99	1.89	0.69	1.45
2012	3,006	45	1.50	1.00	1.20
2013	2,871	61	2.12	0.87	1.67
2014	2,597	25	0.96	0.35	0.54
2015	2,336	38	1.63	1.46	0.34
2016	509	1	0.20	0.00	0.00

Note: Data for OIS in this report is shown from the BAR-OIS go-live date of March 9th through December 31st.

Heavy-duty engines have traditionally lagged behind light-duty cars and trucks in the use of electronic engine and advanced emission controls. Increasingly more stringent certification standards passed by CARB and the U.S. EPA have resulted in HD manufacturers' reliance upon emissions aftertreatement, including SCRs and DPF. In 2005, CARB adopted California Code of Regulations, title 13, section 1971.1, which established comprehensive OBD requirements for 2010 and subsequent model year heavy-duty engines and vehicles (i.e., vehicles with a gross vehicle weight rating greater than 14,000 pounds), referred to as heavy-duty OBD. The Board updated the HD OBD regulation in 2009 and adopted HD OBD-specific enforcement requirements (California Code of Regulations, title 13, section 1971.5). Finally, as part of the 2009 update, the Board aligned the HD OBD II requirements for medium-duty vehicles. The U.S. EPA also required

OBD for HD vehicles starting in 2010, which is important for out-of-state vehicles. OBD for heavy-duty engines were phased in beginning with 2010 model year engines and required for all 2013 and newer model year heavy-duty engines.

2.3.1 On-Site OBD

2.3.1.1 Overview

With respect to inspection (the "I" in I/M) and the detection mal-performing vehicles, OBD has the advantage over dynamometer and PEMs-based testing given that the vehicle's emission control system is monitored continuously while being driven under real-world conditions. Therefore, the development of representative drive cycles test or the establishment of standardized routes becomes unnecessary. The determination of exceedances of emissions limits are intrinsic within OBD which eliminates the need to establish model-year and vehicle weight specific pass/fail cut-points. Essentially, these cut points are already an integral part of the MIL trigger requirements. Although familiar with engine malfunctions resulting in excessive smoke, mechanics may have little or no experience in efficiently and effectively repairing heavy duty engines based upon emission readings alone. With respect to maintenance (the "M" in I/M), the fact that OBD stores and reports trouble codes that offer valuable diagnostic and repair information could abbreviate the learning curve.

Although an On-Site OBD based I/M inspection strategy shares the same disadvantage as conventional I/M, i.e., the need to monitor the entire fleet in order to detect the malfunctioning sub-fleet, the test itself is quick, convenient to the vehicle owner/operator, and the per-test costs are projected to be considerably lower than dynamometer or PEMs based alternatives.

On-site OBD inspections could be conducted at repair facilities, centralized or decentralized inspection facilities, similar to many LDV I/M programs, or at kiosks. For LDVs, self-service kiosks are being used in Oregon (2018a), Ohio (2018), and Maryland (2018). The kiosks utilize a physical connection with the OBD connector to perform the OBD scan. The kiosks allow for 24/7 self service, with an option for manned operating hours where assistance in performing the test can be provided. In this application, no additional communication hardware or software, as the test is performed through a physical connection with the kiosk querying the vehicle. The test can be performed relatively quickly and cheaply. For LDVs, these states charge between $10 and $14 for a test, which includes about $5 per test going to the state to fund the program (Certificate Fee). The real estate footprint for the kiosks is also smaller than that for a repair station or dedicated inspection station. The number of locations that would need to be set up to service the HDV fleet would need to be determined, and an adequate network put in place throughout the state. Typical OBD kiosks for LDVs are shown in Figure 2-11.

Figure 2-11 Kiosk utilized for OBD scanning of LDVs

2.3.2 Remotely Monitored OBD

2.3.2.1 Remote OBD

CARB and the US EPA have long recognized that if a vehicle is inspected periodically (biennially in the case of California vehicles subject to Smog Check), mechanical failures can and do occur between inspections resulting in increased tailpipe emissions and a reduction in the overall benefits of the program. Although OBD has the advantage of continuously monitoring emissions critical systems in normal operation, in a site-based program, vehicles must still be taken out of service periodically in order to query the on-board computers. The longer the interval between inspections, the greater the risk of undetected or unaddressed failures. This is especially true of heavy-duty trucks which accumulate mileage at a rate over 10 times that of passenger cars.

As an alternative to traditional periodic inspection, OBD systems capable of utilizing cellular or Bluetooth technology would allow remote monitoring of the fleet on a continuous or semi-continuous basis without the vehicle needing to be pulled out of service, which could also shorten the interval between detection and repair.

The concept of remote OBD (often referred to as OBDIII) was first introduced by CARB in 1994 at the Convergence Conference on Transportation Electronics in Dearborn, Michigan. A severe limitation at that time was the lack of communication infrastructure. Therefore, CARB initially demonstrated a system capable of remotely detecting the state of a vehicle's MIL using radio transponders designed for automated toll taking. In a subsequent research project, CARB partnered with Hughes Telematics and Sierra Research in order to demonstrate a system capable of transmitting the vehicle's identification number (VIN) and stored trouble codes via email. CARB staff collaborated with Network Car (later Network Fleet) in the development of a remote fleet monitoring system and in 2012. Network Fleet was acquired by Verizon as part of a $612 million purchase of Hughes Telematics.

Remote OBD has seen widespread implementation by the insurance industry. Progressive Insurance's "Snapshot", Allstate's "Drive Wise", State Farm's "Drive Safe and Save", Esurance's "Pay per Mile" and Nationwide's "Smartride" programs offer discounts to drivers willing to install a device that interfaces with their vehicles' OBD system. These devices record and transmit information regarding driving habits including the number of miles driven, as well as accident-causing factors like hard braking and acceleration, idle time, and night-time driving. Although the exact number of vehicles equipped with such devices is unknown (customer's typically opt in and out of the program at 90 day intervals), hundreds of thousands of vehicle owners have participated in these and similar programs. It is important to note that these insurance discount programs are not offered in the state of California due to legal restrictions.

Another industry that is taking advantage of remote OBD technology is fleet telematics. Telematics is an amalgamation of the words 'telecommunications' and 'informatics,' that refers to "the use of wireless devices to transmit data in real time back to an organization". Real-time information such as vehicle location, speed and mileage is being used by companies to increase productivity, reduce costs, optimize routes, detect maintenance requirement as well as enhance driver and fleet security. The fleet management market size is estimated to grow from $9.54 billion in 2016 to $27.90 billion by 2021, at a compound annual growth rate of 23.9% during the forecast period. Fleet management services and solutions are being offered by companies such as Samsung, Intel, Volvo, Verizon, AT&T, TomTom, Vodafone, Telefonica, IBM and CISCO (Baipai, 2017).

BAR has administered a remote OBD inspection program, beginning in 2002, which is still ongoing. There were 14,131 vehicles in a recent download of the data. The Continuous Testing Program (CTP) was established under the authority granted by Health & Safety Code Section 44024, which required BAR to investigate and research new technologies for possible implementation into the Smog Check Program. In order to encourage participation, BAR exempted participants from biennial Smog Check requirements. At the beginning of the program, BAR was able to find only two companies that had developed equipment capable of collecting and transmitting OBD fault codes and only one, Network Fleet had the resources to develop a system meeting BAR's requirements. More recently, the Oregon Department of Environmental Quality (2018b) has incorporated telematics devices into its vehicle inspection program through a device sharing network with private businesses and for vehicle owners that utilize telematics devices for continuous monitoring for turn-by-turn navigation, road-tolling, usage-based auto insurance, and other applications.

In April of 2002, CARB awarded a grant to Network Fleet to conduct a study to evaluate the effectiveness of continuous monitoring on 710 high-mileage taxis operating in the Los Angeles area. CARB subsequently expanded the study to include participants in the San Francisco Bay Area. Like heavy-duty vehicles, it is not unusual for a taxi to accumulate 200,000 miles per year compared to 15,000 miles per year for a comparable privately owned passenger car. The study found that 54% of the participating vehicles had reported DTCs at some point during the period of evaluation.

In 2008, the U.S. EPA studied the viability of remote OBD and issued a report entitled "Transitioning I/M – Options for Inspection and Maintenance in the OBD dominated Fleet." The report indicated that remote OBD systems represent a viable strategy for the reduction of inspection cost and increased convenience within inspection programs. Table 2-9 provides estimates of the potential cost savings for a periodic vs. remote OBD program. In September of 2010, the U.S. EPA published "Recommended Guidance for Remote OBD I/M Programs." States that follow the new EPA Guidance with respect to remote OBD are be able to claim credit for additional emission reductions in the vehicle inspection programs.

Table 2-9 Lifetime Inspection and Convenience Costs of Periodic I/M vs. Remote OBD

		Periodic OBD	Remote OBD	Savings
Test/Install Cost	Low	$12 Billion	$4 Billion	$8 Billion
	High	$12 Billion	$5 Billion	$7 Billion
Convenience Cost	Low	$9 Billion	$1 Billion	$8 Billion
	High	$17 Billion	$2 Billion	$15 Billion
Total Cost	Low	$21 Billion	$5 Billion	$16 Billion
	High	$29 Billion	$7 Billion	$22 Billion

• Assumes 100% of I/M vehicles switch to Remote OBD • Costs analyzed over the life of a static fleet (10 years) • Savings occur in both test costs and convenience costs • Total of $16-22 billion in savings over 10 years

Low cost (<$100/unit) aftermarket devices are currently available that can interface with the vehicle's OBD system, allowing either the passive inquiry for any stored trouble codes, or the active reporting by the system when a change in state occurs (codes stored or cleared). These devices also allow OBD systems to be randomly queried as a means of detecting tampering with or removal of the devices. Most of these aftermarket units come equipped with GPS systems allowing program administrators to determine a vehicles location at the time when the MIL is illuminated. This option is invaluable with respect to trucks in interstate operation and in the refinement of CARB's on-road emissions inventory.

The disadvantages of this approach include tampering with, or removal of the OBD devices and the related costs of telecommunications. There is also the potential for fraud or the transmission of false data. Section 203 (a)(3)(b) of the Clean Air Act (CAA), 42 U.S.C. Sec. 7522(a)(3)(b), prohibits the manufacture, selling, or installation of any device that bypasses, defeats, or renders inoperative a required element of the vehicle's emissions control system. Emissions-related vehicle repairs or modifications that change the vehicle from a certified to a non-certified configuration are considered tampering. This applies to both vehicle owners and repair facilities and is, therefore, a Federal offense. Overriding the OBD system through the use of high-tech defeat devices or non-certified computer chips, for example, would also be considered tampering.

Technicians can also try to circumvent an OBD only inspection for a given vehicle by collecting data from a surrogate vehicle on which no malfunctions are present, a practice known as clean coding. This presents a problem only if fault code(s) and readiness data are downloaded. In this instance, the system that processes the information cannot verify that the data came from the vehicle for which the inspection was intended. This practice is analogous to "clean piping" where emissions are measured from a vehicle other than the one that is represented by the technician as being tested. The capture of additional fields beyond the minimum data elements should be adequate to minimize or eliminate such practices.

In USEPA's 2010 Recommended Guidance for Remote OBD I/M Programs, it is acknowledged that tamper resistance measures should be taken to deter inappropriate manipulation of the data before it is received by the Remote OBD Link. "Code clearing" refers to the practice or occurrence of extinguishing the MIL and erasing stored information prior to inspection. This can occur by connecting a commonly available diagnostic tool to the vehicle's data port, or by disconnecting the battery for a period of time. Stored readiness indicators are reset to not-ready when on-board fault information is cleared.

Frequent code clearing may indicate an attempt to hide an active fault(s). This practice can be detected through analysis of the readiness indicators over time. Frequent readiness state changes from ready to not-ready is indicative that code clearing is occurring or that the vehicle has a malfunction affecting the proper operation of its OBD system. Criteria can be established for the purposes of detecting when OBD information is cleared routinely, or with unusually high frequency. This could include failing vehicles where the OBD readiness monitors are found to be "not ready".

Unauthorized reprogramming of the on-board computer may be detected by comparing stored Calibration Verification Number (CVN) values with known correct entries for a given calibration ID number (Cal ID). It should be noted that there are vehicle calibrations from aftermarket companies that are not considered to be emission-related tampering. These changes can alter the CVN and possibly the Cal ID, but should not be the sole basis for rejecting a vehicle subject to Remote OBD inspection. The program administrators will need to maintain a list of OEM Cal ID and CVN data along with acceptable aftermarket values.

Alterations to the data reported by the OBD link can also occur through the reprogramming or replacement of the link. Defeat device detection can be achieved through sophisticated use of information available to the on-board computer. Periodic random collection of additional real time engine parameters (e.g., coolant temperature, engine speed, calculated load, etc.) can provide for effective detection of such devices.

Another potential issue with OBD is that it has been shown for light-duty vehicles that some vehicles can emit excessive levels of pollutants without illuminating the MIL (Klausmeier and Durbin, 2005). HD OBD regulation allow for some situations where high emissions might be found that would not trigger the MIL on. This could include situations where the sensor or other components may not be up to full operating temperatures or conditions. This could also include conditions where the DPF is regenerating, which could lead to increased emissions that would not trigger the MIL. Such conditions were investigated extensively as part of the OBD regulatory development process, but perhaps could also be evaluated under real world conditions as well.

As stated earlier, when the concept of a remote OBD inspection system was first introduced in the early 1990's, a limitation to widespread implementation was the lack of a communication infrastructure capable of efficiently and cost effectively handle the task of monitoring California's on-road fleet. Advances in telecommunications achieved since that time have all but rendered this issue moot. In recent discussions with a major telecommunications company, it was suggested that a large scale remote OBD monitoring system could best be addressed using the "Internet of Things" (IoT).

The term IoT first emerged in 1999, and is currently used to describe everything from intelligent thermostats to fridges that order milk when you have run out. It is what happens when sensors, cheap wireless chips and ubiquitous internet connectivity collide: devices can talk to each other, making it easier to control and automate tasks and collect data. Most OBD II aftermarket devices utilize third party SIM cards providing a unique identification (email, telephone number) to each device. In discussing the transmission of a 256K byte block of information from 100,000 vehicles every 14 days, the cost of $1/vehicle-month was not considered unreasonable.

Bluetooth dongle technology can be used as an even more cost effective alternative to the internet or cellular networks with respect to gathering OBD data. Bluetooth is a global wireless communication standard that connects devices together over a certain distance. It is built into billions of products on the market today and connects the Internet of Things. Bluetooth dongle devices use radio waves instead of wires or cables to connect to a phone or computer. A Bluetooth product contains a tiny computer chip with a Bluetooth radio and software that makes it easy to connect over short-range, ad hoc networks. Class 1 Bluetooth devices transmitting at 100mW, have a standard range of approximately 100 meters or 328 feet. Costs of Bluetooth dongle devices range between $50 and $100. Opus Inspections (2018) has a commercially available remote OBD system that meets the US EPA guidance for continuous monitoring. This system is shown in Figure 2-12. States conducting continuous monitoring according to the guidance document will be able to take credit for additional air quality improvement.

Figure 2-12. Remote OBD System from Opus Inspections

U.S. truck makers are already incorporating remote OBD into their trucks. Companies like Peterbilt Motors Co. and Kenworth Truck Co. are factory-installing entire “truck computer systems” into their products to provide a single platform upon which to incorporate a variety of digital services, including telematics offerings now typically installed separately with their own hardware. The current list of manufacturers with whom Telogis partners to build in this technology is Ford Motor Co., GM, Volvo Trucks, Mack Trucks, Hino Trucks (the commercial division of Toyota), Isuzu and Manitowoc Cranes—with more to come.

Renault Trucks announced in 2018 the launch of the first LCV OEM telematics system – ‘Renault Trucks Vantelligence, powered by Verilocation’, a new, turn-key fleet management program, specifically designed to provide operators with the same levels of data and fleet performance for LCV vehicles as HGVs. Ram Telematics powered by Verizon Connect will be available in 2018 on new Ram trucks and can also be installed on select 2015 model year and newer light-duty, heavy-duty and chassis cab trucks. Ram Telematics will also be available on Ram ProMaster and ProMaster City commercial vans later this year.

With a remote OBD system, the OBD scan could be performed by a kiosk or other some other roadside antenna through a wireless local area network (Wi-Fi). Data transmission cost would be minimal in this case. Because vehicles equipped with Wi-Fi Bluetooth systems must come within close proximity to a receiver, the logistics associated with ensuring adequate coverage of the light duty fleet was considered a major obstacle to implementation. Some states have investigated the use of Bluetooth receivers in stationary kiosks and requiring vehicles to periodically drive past to have their OBD systems queried. Although more convenient and cost effective than traditional inspections, the motorist is still required to report to a specified location and is aware of when the vehicle is being queried. Giving the motorist the latitude to drive past the kiosk at their discretion may lead some to clear any existing DTCs prior to inspection. Unlike light-duty vehicles, heavy-duty trucks are required to stop at certain locations such as weigh stations, border crossings and terminal gates, such that relatively few Bluetooth readers would need to be installed to provide coverage of both the intra and interstate truck fleet.

Alternatively, OBD scan data could be transmitted on a continuous basis through a cellular network. This option would allow for the OBD system to be queried at any time, regardless of time or location. As with wireless OBD, the vehicle is equipped with dongle, but in this instance the dongle would have a SIM card installed. This was the methodology evaluated in BAR's CTP program. The cost estimates for different transmission options were obtained from typical costs for the ongoing BAR CTP program. The costs for transmission for that program are $16.95 per vehicle per month for the OBD II and CAN service, $12.95 per month for the non-powered assets, and $32.95 per month for the OBD II and CAN services that require a satellite modem. So, it is estimated that the costs of data transmission service for a remote OBD program would be approximately $17 per vehicle per month for continuous monitoring. Another potential strategy would be to develop a cell phone application that could connect with the remote OBD dongle via Bluetooth. The cell phone could then transmit the OBD information over the truck driver's cell phone network with no additional transmission charges. One issue with continuous monitoring is that vehicle owners may object to continuous monitoring, as was found in the Oregon remote OBD program for LDVs, which could make this option more difficult to implement in practice.

2.4 Literature Review Summary and Recommendations

Many methods are available that could potentially be incorporated into a HD I/M program. The main emphasis of the literature review was to summarize the possible HD I/M methods, and lay out the framework for a prototype HD I/M program that could be evaluated as part of this project. Potential HD I/M program methods evaluated include those incorporating tailpipe emissions measurements, such as chassis dynamometer, the On-road Heavy-duty vehicle emissions Monitoring System (OHMS), portable emissions measurement systems (PEMS), and remote sensing devices (RSD), and those incorporating On-Board Diagnostics (OBD), includes remote OBD applications using telematics or cellular communications. Based on a review of the potential methods coupled with our experience in the area, we propose that a revised HD I/M utilizes OBD as the primary method of failure detection. The OBD implementation could be coupled with a relatively non-invasive technique remote sensing devices, roadside pullovers, or other monitoring systems such as a Portable Emissions AcQuisition System (PEAQS), to provide a validation testing element to the I/M program and to identify any HDVs that emit excessive levels of pollutants without illuminating the MIL. Mini-PEMS could also play a smaller role in the I/M program for roadside pullover validation tests. A summary of the main features and costs of such systems is provided in Table 2-10. A summary of the advantages and disadvantages of each system is provided below. These methodologies are also evaluated in greater detail in the pilot study discussed in the next section.

Table 2-10 Summary of Main Features of Various I/M Methodologies

Methodology	Pollutants	Ease of Use/Test time	Capital Costs
Repair grade chassis dyno with I/M grade analyzers	NOx, PM, THC, CO, CO_2	Requires reporting to station location, 30 minutes to 1 hour for set up and actual testing	$170k for dynamometer with installation and I/M grade analyzers
1065-compliant PEMS	NOx, PM, THC, CO, CO_2	Requires mounting PEMS and driving truck, several hours to a full day	$100k to $120k for gas-phase $200k to $220k for gas-phase + PM
Mini-PEMS (sensor-based or solid PN)	NOx, PM, THC, CO, CO_2 for full system or a PM/PN only system	Testing under idle or snap acceleration conditions could take 10 minutes. Tests that require driving with mini-PEMS could be longer and prohibitively inconvenient	$30k to $50k
Remote Sensing Devices	NOx, PM, THC, CO, CO_2	Test conducted while truck is driven by and could be unmanned	$20k to 200k and upwards depending on complexity of set-up
OBD – repair station scan	Monitors system components related to NOx, PM, and HC emissions	10 to 20 minutes to conduct and record scan	OBD incorporated onto truck
OBD – kiosk system (physical connection)	Monitors system components related to NOx, PM, and HC emissions	Cable to download data from truck	Capital costs for a kiosk would be ~$50k with another ~$50k for installation
OBD – remote transmission methods	Monitors system components related to	Wireless transmission to a designated database	$50-$100 per unit for dongle

	NOx, PM, and HC emissions		Minimal costs for Wi-Fi data transmission
OBD – remote continuous monitoring	Monitors system components related to NOx, PM, and HC emissions	Data transmission through a cellular network	~ $17 per month per vehicle beyond the cost of the dongle

* Note that the capital costs reflect the costs for the purchase of major pieces of equipment. The actual per test cost would be considerably less than that and would depend on many factors, including the volume of the testing, the specifics of the testing requirements, and other items.

2.4.1 Tailpipe Emissions Measurements

Several different tailpipe emissions measurement methods were evaluated.

2.4.1.1 Chassis Dynamometer Testing

Chassis dynamometer measurements provide the potential for more comprehensive emissions readings but also have some significant disadvantages in terms of cost and convenience. Dynamometer testing is typically conducted in the field using repair-grade dynamometers using short cycles such as the AC5080 and the Power-Curve test. The greatest drawbacks to the implementation of a dynamometer based inspection system is the need to bring HD vehicles to a centralized location for testing, which would add a significant burden to HD vehicle owners, and developing a network of dynamometer facilities that would be adequate to service the full population of trucks in California. Thus, considerably more test set up time would be required compared to other methods. The feasibility of establishing such a network and the associated testing costs would need to be investigated further to determine the feasibility of implementing a chassis dynamometer-based HD I/M program.

2.4.1.2 Portable Emissions Measurement Systems

The use of PEMS, either in conjunction with or independent of repair-grade dynamometers have demonstrated sufficient accuracy in pollutant measurement to be considered reliable for use in Inspection and Maintenance programs. PEMS testing can be less costly than full laboratory based emissions testing, but the use of fully 1065-compliant PEMS would likely be more costly and time consuming in terms of setup compared to repair-grade chassis dynamometer testing. On-vehicle installations of a PEMS device would also require that the vehicle be driven over a prescribed route or in a uniform manner in order to accurately assess emissions. Finally, the capital cost for full 1065-compliant PEMS, ranging from $100,000 to $120,000 for a gas-phase PEMS and from $200,000 to $220,000 for a PM PEMS, would also be a limitation.

Mini-PEMS provide cost and ease of use advantages over full 1065-compliant PEMS. It is expected that over the next 8 years that mini-PEMS technology will continue to improve and that mini-PEMS could provide sufficient accuracy to distinguish between failing and non-failing vehicles. Trucks would still need to be taken out of service to perform the test for some period of time. This amount of downtime could be limited to a road-side pullover type of test, although this could still disrupt a driver’s ability to fulfill his delivery schedule. Mini-PEMS could be utilized at weigh stations or in fleets similar to the PSIP for this purpose, and could provide significant advantages in sensitivity compared to current opacity testing. This could be similar to the solid PN instruments that are being used in Europe under Swiss Regulation 941.242 for non-road equipment. Such testing would need to be designed so that it could be completed in a short period of time (~10 minutes), under conditions that do not require the instrument to be mounted on the vehicle (such as idle or snap accelerations), and by operators that do not have significant training. An important issue in that regard would be to ensure that mini-PEMS measuring pollutants that are not currently included in certification testing, such as particle number, can be correlated to cut points that could identify whether the vehicle was a high emitter. A limitation of mini-PEMS/PEMS systems is that they will not detect failures until the failures have gotten to a point where they will have increased emissions to levels that are considerably higher than typical emission levels. As such, PEMS would not be able to identify the full range of broken, repairable, or replaceable components that are present in the fleet at any given moment in time, except as part of an OBD-like connection done in conjunction with the PEMS testing. Costs of mini-PEMS can vary greatly from $30,000 to $50,000 for a more complete sensor-based type of mini-PEMS with the ability to measure multiple components or designed to meet a traceable metric, such solid PN. On the lower end, hand held condensation particle counters (CPCs) or other technologies are available for $3,500 to $10,000 that can be used as a quick check of PN.

2.4.1.3 Remote Sensing Devices

RSD has been utilized for the measurement of emissions of large samples of in-use vehicles on the road for more than 20 years. RSD is currently used in Colorado, Connecticut, Rhode Island, Tennessee, Texas and Vermont for clean and/or high emitter screening for LDVs, but not as the sole determinant of pass or fail. RSD, and other roadside measurement techniques such as PEAQS and OHMS, have set ups that provide greater flexibility in program implementation, as these systems can be deployed in a wider range of locations. The advantages of RSD include the fact that the devices are non-invasive, and have the ability to capture emissions of vehicles as they are driven by the owner/operator under real-world conditions. To eliminate the need for trucks to report to a centralized facility, RSD/OHMS/PEAQS-like systems could be set up at truck weighing stations or other locations where there is a high incidence of HDV traffic throughout the state. Although such systems provide measurements under a limited range of operating conditions, they have shown the potential to identify high emitting vehicles for both light-duty and heavy-duty vehicles. Additional testing is probably necessary to better understand the effectiveness of such systems for different exhaust configurations (i.e., whether the stack is low or high), and different spacing between vehicles.

Having a system that can be operated at a low cost and largely unmanned for extended hours could be key for this implementation. The latest generation RSD by HEAT offers the potential for unmanned operation for extended hours at different sites. If such a system were to be deployed at weigh stations throughout the state, this could provide coverage at 51 operational inspection points at 37 locations. Capital costs for such systems could range from $100,000 or more depending on the complexity of the system design.

RSD/OHMS/PEAQS-like systems would provide the potential to measure HC, NOx, PM, CO, and CO_2. Coupled with the emissions information, the RSD would also be able to provide speed information as well as license plate to identify the vehicle. Through informational databases, the vehicle registration information could be used to identify the specific engine that the vehicle is equipped with. The speed information coupled with the weight information from the scale at the weigh station could be used to determine the load on a brake horsepower-hour (bhp-hr) basis. This could provide the potential to provide emissions measurements in g/bhp-hr that could be compared back to the engine certification standard.

Similar to PEMS and chassis dynamometer systems, a limitation of RSD-like systems is that they do not detect failures until the failures have gotten to a point where they will have increased emissions to levels that are considerably higher than typical emission levels. Similar to tailpipe emissions, but unlike OBD, RSD does not offer any cause for the elevated emissions, merely that they are elevated. As such, RSD would not likely be the primary technique used in a full scale HD I/M program, but would rather be used more in a validation role in conjunction with OBD.

2.4.2 On-Board Diagnostics

HD OBD II systems were designed in anticipation of statewide I/M. Phased in beginning with 2010 model year engines, OBD is required on all 2013 and newer model year heavy-duty vehicles. The advantages of the use of these systems in an enhanced I/M program are numerous. All emissions critical components are monitored continuously by OBD while the vehicles are in service, as such the vehicles and engines are by definition being tested under “real world” driving conditions. The algorithms used to illuminate the MIL are intrinsic to the vehicle and are based upon its certified level of emissions thus eliminating the need to establish either representative driving cycles or pass/fail cut-points. OBD also has the greatest potential for shortening the interval between emission control system malfunction, detection, and vehicle repair. In contrast to alternative strategies, OBD provides diagnostic and repair information, which should prove invaluable to the repair and maintenance community compared to reports of levels of pollutant that they may not be familiar with. It should also be noted that the use of OBD minimizes the potential liability borne by the state associated with dynamometer testing, requiring a vehicle to be driven over a uniform route, or the installation and removal of portable emissions measurement equipment on privately owned vehicles by agents of the state.

An OBD-based test could be relatively quick, convenient to the owner operator, and the pre-test costs are considerably lower than the dynamometer or PEMS-based alternatives. The OBD system itself is already integrated into the engine design for 2013 and newer vehicles. So, the only costs would be those associated with the visit to the repair or inspection station. Upgrading the OBD to remote OBD could be done for less than $100 per unit or vehicle. OBD scan information could be remotely transmitted via a Wi-Fi network to a kiosk at a designated location. Kiosks for this type of application range on the order of $50k with another ~$50k for installation. Alternatively, data could be monitored continuously through transmissions with a cellular network for approximately $17 per vehicle per month for data transmission, although subjecting vehicle owners to continuous monitoring could be more difficult to implement from a practical standpoint.

Particular concerns regarding enhanced statewide HD I/M include the monitoring of out-of-state vehicles, and vehicles that can perform their normal operations without reporting to a designated point of control such as a weigh station, terminal, or border crossing. It is also anticipated that a significant portion of the heavy-duty fleet will be OBD II equipped when enhancements to HD I/M are anticipated to be enacted, with 75% of HD vehicles in the in-use fleet expected to be 2013 or newer by 2025. In each of these instances, the use of remotely monitored OBD should be considered. A diminishing percentage of non-OBD equipped trucks will remain in use, however, particularly during the initial years of implementation of a HD I/M program. Another potential issue with OBD is that it has been shown in previous analyses that some HDVs can emit excessive levels of pollutants without illuminating the MIL.

3 Pilot Study Objective and Methodology

3.1 Objective

One of the main components of this study was a pilot I/M evaluation to assess various methods of emissions measurement that might be employed in a full I/M program, emissions reductions from OBD-related repairs, and the associated repair costs. The exploratory pilot program included evaluating tailpipe emissions from approximately 50 vehicles before and after repairs using a chassis dynamometer. The vehicles were procured from two local repair facilities based on the need for emissions related repairs. Emissions measurements using I/M grade emissions analyzers were used to evaluate the emissions benefits from various repairs based on a comparison of the before and after emissions measurements. For vehicles so equipped, the OBD system was monitored pre- and post-repair to evaluate the effectiveness of the OBD in identifying emissions related issues and what benefits are obtained from OBD based repairs. Several mini-PEMS systems were also evaluated in conjunction with the chassis dynamometer emissions measurements to evaluate their potential for use in an I/M program. Additionally, a remote sensing device (RSD) and a Portable Emissions AcQuisition System (PEAQS) probe system were used to provide additional information for a subset of the test vehicles before and after repair. The data from this exploratory pilot study were subsequently used to evaluate the potential benefits and effectiveness of different I/M methodologies.

3.2 Experimental

3.2.1 Test Matrix

Fifty heavy-duty over-the-road tractors were selected as candidate vehicles for evaluation in the pilot program. Candidate vehicles were selected from those arriving at two repair facilities (J&R Fleet Services and Cummins Pacific) based on whether they fell into specific model year ranges and on the nature of their emissions related malfunction. The objective of the selection process was to evaluate a distribution representative of the 2025 fleet and its probable emissions related maintenance issues, as this represents a timeframe when the program may be into full implementation.

The target and actual test matrices were focused on 2010 and new engines, as pre-2010 engines are expected to be largely retired from the in-use fleet by the time the heavy-duty I/M program is implemented in the mid-2020s. The 2010 and newer engines were then separated in pre-2013 engines (MY 2010-2012) and 2013 and newer engines (MY 2013+), as full implementation of OBD for heavy-duty engines began in 2013. The actual age distribution of the test fleet was as follows: ~80% of the test vehicles were MY2013+, 20% were MY2010-2012, and 0% were pre-2010. This distribution is compared to projections from EMFAC2014 model estimates of the fleet distribution for 2016, 2020, and 2025 in Table 3-1. As part of the initial planning, the anticipated test fleet distribution was compared with a 14 day sample of data from April of 2016 that was provided by J&R prior to initiating the program. The preliminary J&R records included 296 pre-2010 vehicles, 153 2010-2012 vehicles, and 116 2013 and newer vehicles. Note that the actual test matrix is reasonably representative of the fleet distribution for the 2025 year inputs used in EMFAC2014. The J&R and the 2016 and 2020 EMFAC2014 distributions are older than our test fleet, especially as the J&R fleet represents vehicles that are seeking some sort of repair.

Table 3-1 Comparison of Vehicle Distributions for EMFAC2014, J&R, and the Suggested Test Fleet

MY Group	EMFAC (2016)	EMFAC (2020)	EMFAC (2025)	J & R	Target and Actual Test Fleet
Pre-2010	50%	20%	2%	52%	0%
2010 to 2012	35%	49%	24%	27%	20%
2013+	15%	31%	75%	21%	80%

Trucks were procured with the assistance of J&R Fleet Services of Fontana and Cummins Pacific in Bloomington with the objective of collectively assembling a fleet equipped with emission control technologies and displaying malfunctions that are typical for in-use heavy-duty trucks. The vehicles procured through these repair facilities were all in need of repairs or corrective maintenance. As such, the expense related with repairs are borne by the fleet operator/vehicle owner and the accuracy of diagnosis and resulting change in emissions due to repairs are reflective of the actual abilities of heavy-duty engine mechanics. For this program, the majority of the vehicles were recruited through the J & R facility, as this facility has a higher volume throughput than the Cummins Pacific facility, and it was also the location that UCR personnel operated out of directly.

Table 3-2 shows the target repair test matrix that was used for this project, and actual number of identified vehicles needing each of the corresponding repairs. These repairs categories were selected based on the component or system malfunctions that are expected to cause excessive emissions of different pollutants. The target test matrix was developed based on information about the frequency at which the repairs were expected to occur, based on the J&R repair records, coupled with estimates of the expected emissions increases for different failures, based on EMFAC2014 estimates and durability demonstration vehicle (DDV) report analyses. It should be noted that the full testing sequence could not be completed on a subset of the procured test vehicles, so these vehicles were quantified as being a half vehicle. At the same time, some vehicles returned for additional testing after the initial repair testing was completed. These additional tests were also credited as half a vehicle test.

Table 3-2 Target Repair Test Matrix

No.	Part/Repair	Targeted # of Test Vehicles	# Identified Test Vehicles
1	DPF filter cleaning*	3	3
2	DPF filter	6	3
3	exhaust pressure sensor	2	2
4	oxidation catalyst	2	0
5	injector doser	4	5.5
6	EGR valve/cooler/system	4	4.5
7	DEF filter, fluid & parts	2	5
8	turbocharger	2	2
9	boost pressure sensor	2	0
10	inlet or outlet NOx sensor	2	7.5
11	charge air cooler	2	0
12	ammonia sensor	2	1
13	SCR	2	3
14	temperature sensor	6	2
15	fuel injector	2	1
16	fuel system components	2	3
17	Engine control module (ECM)	2	3
18	lambda(O2) sensor	2	0
19	crankcase filter		2
20	crankcase pressure sensor		1
21	crank position sensor		1
22	air filter	1	1
	aborted vehicles		3 (Count as half vehicle)
	total number of vehicles	50	50.5

* DPF filter cleaning is included in the matrix, although it is not considered as repair.

3.2.2 Vehicle Recruitment

This program was carried out over a period from November of 2016 to May of 2017. It is estimated that approximately 900 to 1800 2010+ vehicles passed through the facility during the period of the pilot study as potential test vehicles for the study. Candidate vehicles were identified based on vehicles with the check engine light on indicating a repair or maintenance, and being diagnosed as having an issue in one of the target categories in Table 3-2 at the repair facilities. Vehicles were typically diagnosed based on the OBD-codes, sometimes coupled with additional diagnoses by a repair technician. The depth of the diagnoses depended on the specific OBD code/problem identified. In some cases, the problem could be identified based solely on the OBD code and some preliminary diagnostics by the repair technician. In other cases, multiple codes were present or some disassembly of the engine or other parts was required to provide a more specific diagnosis of the problem. An example of the information that was to be collected is provided in Appendix A.

An iterative process between UCR personnel at the facility and CARB personnel was used to identify and accept test vehicles into the program. A CARB representative was either stationed on-site or was in communication with UCR personnel throughout the testing. Communication between CARB and UCR personnel during the initial testing in November 2016, where CARB personnel were not on site, was problematic as the repair facilities did not want to delay their customers while waiting for acceptance decisions. As such, a CARB representative was stationed on site for the testing program.

The vehicles recruited for the pilot program are listed in Table 3-3 along with the issue that was identified based on the engine control module (ECM) trouble codes and the actual repair. The status of the DM1 MIL is also included in the table, where the DM1 MIL on indicates that active DTCs for emissions related issues in one of the target categories were found from either the OBD scan performed with the Silver Scan Tool or from the ECM data collected during the actual testing by the HEM data loggers, as discussed below in section 3.2.4.2. It should be noted that the HEM data logger used was not designed for reading diagnostic messages, and the Silver Scan Tool was an older version that did not have the latest software updates, which could have caused some issues in determining the DM1 Mil status, although in most cases the Mil status identified by the HEM data loggers and Silver Scan Tool was the same. The repairs included DPF cleanings/repairs, issues with NOx, ammonia, and temperature sensors, and issues with the DEF system and turbocharger. Vehicles are numbered based on the order they were identified and accepted into the program at each repair facility. A comparison of the actual repairs compared to the target test matrix is provided above in Table 3-2. Of the vehicles identified, 11 vehicles were equipped with MY 2010-2012 engines and 36 vehicles were equipped with MY 2013+ engines. Four vehicles that were accepted into the test program ultimately did not complete the testing sequence due to reasons that included the vehicle being unfit for dynamometer testing, the customer refusing to repair the vehicle after the initial dynamometer test, and the vehicle having a late model Society of Automotive Engineers (SAE) J1939 connector that was not compatible with the dynamometer and the J&R facility. This included 3 vehicles for which the DM1 MIL was on for the post-repair test, indicating that the repair sequence to fully fix the vehicle had not been completed. At the same time, several vehicles that completed the initial pre- and post-repair testing cycles also returned for additional repairs for either a similar or a new problem and were retested.

Table 3-3 List of ECM Trouble Codes identified and the repairs for each vehicle

Vehicle NO.	Engine Year & Make	ECM Trouble Codes	Repairs/Maintenance	DM1 MIL =1 Pre-repair	DM1 MIL =1 Post-repair
J&R01	2011 Cummins	Catalyst filter, injector doser	DPF, injector doser, DPF cleaning	YES	NO
Cum01	2015 Cummins	No fault codes	DEF Module Calibration	NO	NO
Cum02	2010 Cummins	high DPF pressure	Injector doser, turbocharger	N/A	NO
J&R03	2013 Cummins	SCR intermediate NH3 sensor	SCR temperature sensor connectors	YES	YES
J&R04	2013 Volvo	EGR Temperature sensor	EGR Temperature sensor	N/A	NO
J&R05	2012 Cummins	Aftertreament Diesel exhuast fluid pressure	Burned DEF system relays, DEF filter	NO	NO
J&R06	2015 Cummins	DPF regen too frequent, SCR out temperature, DPF differential pressure	Clean DPF, DPF Temp. sensor, injector doser, SCR Temp. sensor	NO	NO
J&R07	2014 Volvo	Turbo speed sensor	Turbo speed sensor	N/A	NO
J&R09	2012 Cummins	SCR conversion efficiency, DPF regen too frequent, DPF incomplete regen, DPF intake pressure	Clean DPF	NO	NO
J&R10	2011 Cummins	Outlet SCR NOx sensor	Outlet NOx sensor	YES	NO
J&R11	2013 Cummins	SCR system missing, outlet NOx sensor, Fuel leakage	Injector Doser, outlet NOx sensor, DPF cleaning	YES	NO
J&R12	2011 Volvo	multiple SCR-related codes	DEF lines at dosing valve, manual regen	YES	NO
J&R13	2013 Cummins	SCR intermidiate NH3 sensor, exhuast gas pressure, Intake NOx Sensor	Intake NOx Sensor, Engine Harness	NO	NO
J&R14	2010 DDC	Engine crankcase breather oil separator speed	Crankcase breather/separator & wiring	NO	NO
J&R15	2010 Navistar*	DPF soot load	Injector doser/DPF clean/fuel line (DPF found to be damaged)	NO	NO
J&R16	2010 Mack	DPF system, variable geometry turbocharger (VGT), engine injector cylinder, fuel delivery pressure	Turbocharger & injector doser	NO	NO
J&R17	2011 Cummins	DPF intake pressure	Injector doser, Intake NOx sensor, clean DPF	YES	NO
J&R18	2014 Cummins		air filter	NO	NO
J&R19	2015 Cummins	DEF fluid dosing valve and water in fuel indicator	DEF harness	YES	NO
Second visit		Intake NOx sensor	DEF Harness	YES	NO
J&R20	2011 Cummins	Intake NOx sensor circuit	Intake NOx sensor	YES	NO
J&R21	2013 Cummins	DPF ash load percent	Clean DPF	NO	NO
J&R22	2013 Cummins	EGR Valve position Circuit, exhaust gas pressure	Exhaust Pressure Sensor	YES	NO
Second visit		Intake NOx sensor	Intake NOx sensor/DEF Filter	YES	NO
J&R23	2013 Cummins	SCR catalyst system missing, coolant temperature	Clean DPF/Engine Oil Cooler	YES	NO
J&R25	2013 Cummins	engine coolant temp, engine cooling system monitor	Short w/ coolant temperature sensor, thermostat	NO	NO

Table 3-3 List of ECM Trouble Codes identified and the repairs for each vehicle (continued)

Vehicle NO.	Engine Year & Make	ECM Trouble Codes	Repairs/Maintenance	DM1 MIL =1 Pre-repair	DM1 MIL =1 Post-repair
J&R26	2013 Paccar	Common rail fuel pressure, fuel dosing module, crankcase air pressure	Aftertreatmnet fuel shut-off valve	NO	NO
J&R27	2014 Volvo	exhaust aftertreatment fuel air purge valve stuck closed	Injector Doser, aftertreatment fuel shut off valve, clean DPF	YES	NO
J&R28	2013 Cummins	DEF dosing valve, SCR intermediate NH3 sensor, power supply lost with ignition on	DEF harness	NO	NO
J&R29	2014 Cummins	Crankcase pressure-data valid but above normal operational range	Crankcase filter	NO	NO
J&R30	2013 Cummins	DEF dosing valve, injector metering rail, SCR NH3 sensor	Corrected/Cleaned DEF pump/harness connections	YES	NO
J&R31	2013 Cummins	SCR catalyst is missing	Replace SCR, Temperture Sensor, Inlet NOx Sensor, Dosing Valve, Clean DPF	YES	NO
J&R32	2013 Volvo	aftertreatment DPF diff pressure too low	differential pressure sensor	YES	NO
J&R33	2015 Cummins	Aftertreatment DPF diff pressure sensor circuit	differential pressure sensor + DPF harness	NO	NO
J&R34	2015 Volvo	aftertreatment fuel air purge valve stuck closed, cloased loop DPF regen control temp too low	aftertreatment fuel valve	YES	NO
J&R35	2014 Volvo	Engine high resolution crankcase pressure circuit range	Crankcase pressure sensor & oil pressure sensor	YES	NO
J&R36	2013 Volvo	camshaft position sensor 'A' bank 1 or single sensor no signal	Camshaft position sensor	YES	NO
J&R37	2016 DDC	EGR flow target error diadnostic ---low flow, EGR slow response	EGR cooler, valve assembly, & actuator	YES	NO
J&R38	2013 Cummins	SCR catalyst conversion efficiency, SCR operator inducement, NOx limit exceed due to insufficient reagent quality	update ECM	NO	NO
J&R39	2013 Cummins	SCR catalyst system missing, outlet NOx sensor circuit, DEF dosing valve, SCR intermediate NH3 sensor	SCR repair	YES	NO
J&R40	2013 Cummins	SCR intermediate NH3 sensor, DEF dosing valve	Wiring for DEF dosing valve & SCR NH3 sensor	YES	NO
Second visit		DEF dosing valve, SCR operator inducement	DEF dosing valve	NO	NO
Third visit		after treatment fuel injector	Aftertreatment fuel injector	YES	NO
J&R41	2014 Paccar	No active fault code	EGR valve assembly	YES	YES
J&R42	2013 Cummins	aftertreatment intake NOx sensor	update ECM, Intake NOx Sensor, SCR Temp Sensor	YES	NO
J&R43	2014 Cummins	Engine fuel leak, water in fuel indicitor sensor, SAE J1939 multiplex PGN timeout error	update ECM & timing sensor	YES	NO
J&R44	2014 Volvo	DPF pressure sensor 'A' circuit range/ lower	DPF Delta Pressure Sensor, clean DPF	YES	NO
J&R45	2013 Cummins	Injector solenoid driver cylinder 3	Fuel injector	NO	NO
J&R46	2013 Cummins	intake NOx sensor Heater/ circuit, DEF tank level	Intake NOx Sensor	YES	NO
J&R47	2013 Volvo	EGR valve position flow excessive detected, NOx sensor performance	Intake NOx Sensor	YES	NO
J&R48	2013 Navistar*	Inactive fault codes: EGRP signal out of rang low. EGRP dose not agree with commanded position. Boost slow response fault	Engine throttle valve	YES	YES
J&R02	2012 Paccar	EGR coolant issue	aborted	N/A	N/A
J&R08	2011 DDC	SCR conversion efficiency	aborted	N/A	N/A
J&R24	2016 DDC	Fuel water separator	Water fuel separator_aborted	N/A	N/A

"*" vehicles with Navistar engines not equipped with SCR.

3.2.3 Overall Flow Chart for the Pilot Program

A generalized flow chart of the proposed sequence for the pilot program is provided below in Figure 3-1. This provides an overview of the methodology that was utilized for the pilot program, with the specific elements of the testing being discussed in greater detail below.

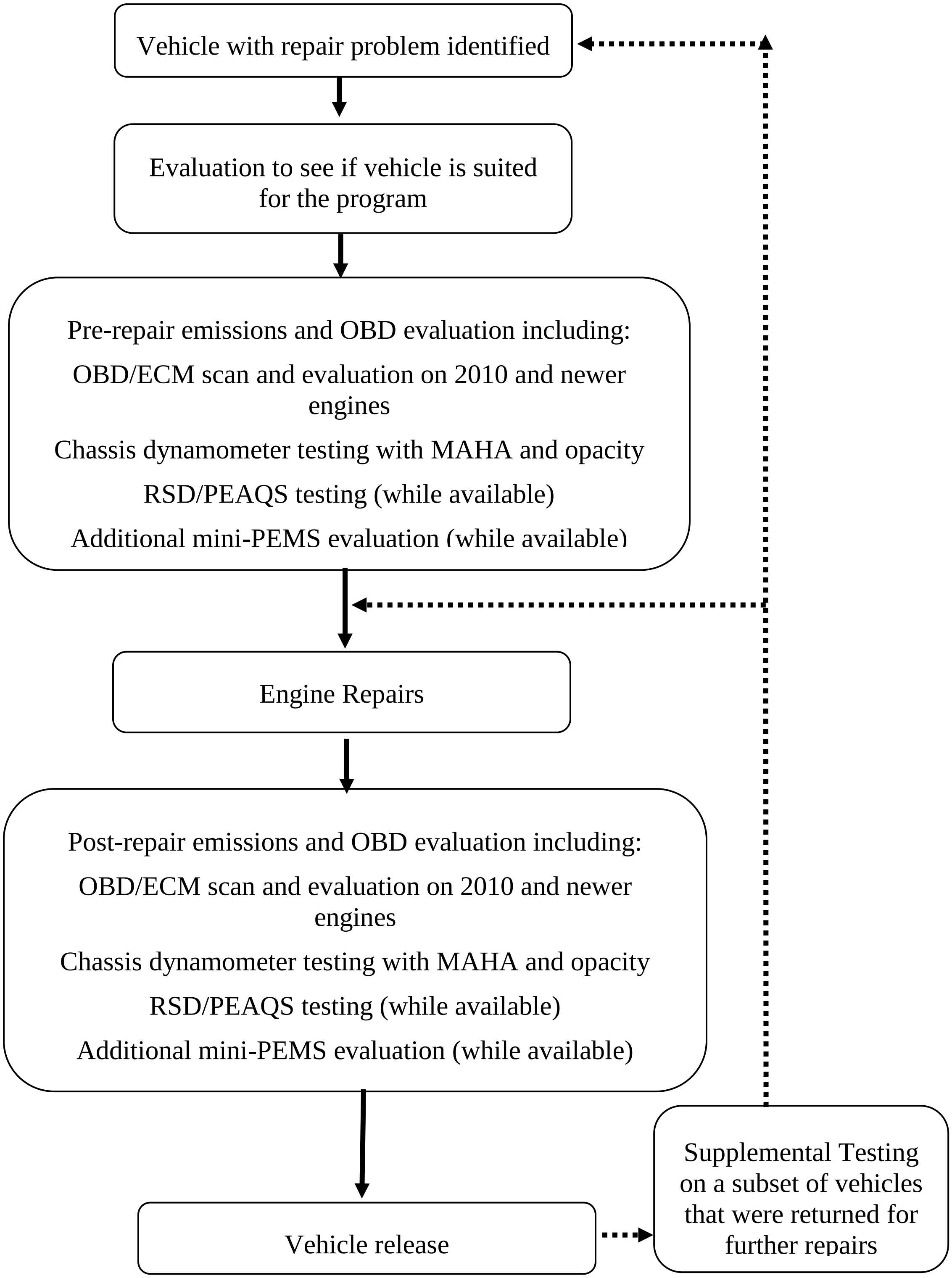


Figure 3-1 Overall flow chart for pilot demonstration program

3.2.4 Test methods

3.2.4.1 Chassis Dynamometer Testing

For this study, dynamometer testing with a repair grade dynamometer was used as the reference method or gold standard around which the effectiveness of the prototype I/M program was evaluated. J&R Fleet Services and Cummins Pacific both maintained repair-grade eddy current chassis dynamometers on site. A description of these facilities is provided in Appendix B.

An array of instruments capable of collecting emissions of HC, CO, NOx, CO_2, and PM were used in conjunction with the chassis dynamometer measurements. The primary emissions analyzer was a Maschinenbau Haldenwang GmbH & Co. KG (MAHA) MGT 5 Emissions Tester for HC, CO, NOx, and CO_2. A description of this test equipment is provided in Appendix C. Two MAHA MGT 5 Emissions Tester were utilized, which allowed the instruments to be installed at both the J&R Fleet Services and the Cummins Pacific facilities. MAHA MPM4 Particle Analyzers were also utilized, but the PM measurements with this instrument did not show measureable PM above the baseline level, which was around 0.001 g/bhp-hr, for the majority of the vehicles. As such, this instrument was not deemed sufficiently reliable for characterize the pre- and post-repair PM emissions, and the results were not included in this report. These emissions analyzers are being operated by the UCR personnel stationed at the repair facilities. The analyzers were set up by members of the technical staff from UCR, and data analysis and data QA/QC is being done by UCR in conjunction with WVU. Additional mini-PEMS were also utilized in conjunction with the chassis dynamometer measurements, as discussed in section 3.2.3.5.

The chassis dynamometer tests were conducted over multiple steps with emissions measurements being collected for each of the primary steps. The vehicle was initially warmed by driving the vehicle until the engine coolant temperature reached ~140°F. The vehicle was then driven to its maximum speed with no load and a lug down test was conducted, where a load was applied until the vehicle reached its maximum horsepower and then started to drop. The vehicle speed reached approximately 60-65 miles per hour (mph) during this segment. This is the standard test done at the repair facilities to evaluate the performance of the engine, and appeared to sufficiently warm up the engine and aftertreatment systems.

Following this warm up sequence, the vehicle's speed was then dropped back down to 50 mph and the dynamometer load was adjusted until it reached approximately 200 hp. This required matching of the torque demand by the driver to suit the applied load. Once the vehicle operation was reasonably stable at this hp level, the emissions testing was conducted for a period of approximate 2 minutes. This portion of the test was done with the vehicle typically in 9^{th} gear, which is the standard gear that the repair facilities use with a 10-speed transmission for their normal testing. The vehicle speed was then dropped to 30 mph, and the dynamometer load was adjusted until it reached approximately 100 hp. Once the vehicle operation was reasonably stable at this hp level, the emissions testing was conducted for a period of approximate 2 minutes. It should be also be noted that because the dynamometers were based on water brake controls, which cannot instantaneously stabilize at a given load, there was typically some differences in load between the pre- and post-repair tests. As such, the results were normalized by either bhp-hr or CO_2 emissions to provide an appropriate comparison point. It should also be noted that the amount of stabilization time needed at each hp differed between the two speeds, and typically between the pre- and post-tests. For each speed, the hp levels were selected to represent hps that would be representative of typical driving on the road with a loaded trailer at the respective speeds. For the 50 mph point in particular, the hp was typically near the peak torque point on the power curve. It should be noted that a full range of possible cycles was examined for use in this study, as described in Appendix D. The selected test was developed on site after considering the dynamometer capabilities, the typical procedures performed at the facility, the work flow at the facility, and the study objectives. It is also worth noting that although the cycle is set based on a particular speed on the dynamometer, the main set point for the testing is the horsepower, as the dynamometer does not utilized road load coefficients to accurately represent loads on the truck at a given speed. As such, emissions results can be normalized to g/bhp-hr units based on the J1939/J1979 output or by CO_2 emissions, but results can not be reliably reported in g/mi units because the truck operation being simulated is likely to represent driving on a road with a sustained gradient.

Following the loaded tests, the vehicle was returned to idle and measurements were made for a period of approximately 1 minute. The vehicle was then brought up to a high idle and emissions were sampled for approximately 1 minute. The collection of data for the high idle began with vehicle J&R09. A SAE J1667 snap and idle opacity test was then performed on each truck either immediately after the main chassis dynamometer test for both the pre- and post-repair measurements. Three clean out snap accelerations were performed, followed by the 3 snaps accelerations for the opacity measurements. A Red Mountain opacity meter was used for these opacity measurements. A schematic of the test sequence is provided in Table 3-4. A picture of a typical set up of a vehicle on the dynamometer is provided in Figure 3-2.

Table 3-4 Test sequence

Test Sequence	
Vehicle warmed up using a lug down test @ 60-65 mph	
Dyno 50 mph @ 200 hp	
2 minutes @ 50 mph / 200 hp	Collect Emissions
Dyno 30 mph @ 100 hp	
2 minutes @ 30 mph / 100 hp	Collect Emissions
1 minute Idle @ 600-700 rpm	Collect Emissions
1 minute High Idle @ 1800 rpm	Collect Emissions
Opacity	Triplicate tests

Figure 3-2 Vehicle on the dyno

3.2.4.2 OBD Measurements

OBD measurements were another important aspect of this study. As discussed above, 80% of the test vehicles were equipped with engines with model years (MYs) of 2013 or newer, so a majority of the vehicles recruited were equipped with OBD. For vehicles equipped with OBD, information was obtained on-site during testing by directly interfacing with the OBD system. For the November 2016 testing campaign, the OBD scans were performed by repair facilities. Pre-repair OBD scans were obtained for all of the identified test vehicles. Post-repair OBD scans were obtained for all vehicles after vehicle J&R07, due to logistical considerations with the earlier vehicles, and for both vehicles tested at the Cummins Pacific facility. For the remainder of testing from January to May 2017, UCR performed the pre- and post-repair OBD scans using a Silver Scan Tool software package. These OBD scans were while the vehicle was on the dynamometer prior to the pre- and post-repair emissions tests, or as time allowed to facilitate smooth operation within the on-going work flow of the test facility. The OBD scans were set up for both SAE J1939 and SAE J1979 protocols.

UCR also equipped each test vehicle with a HEM data logger during the course of the chassis dynamometer testing to obtain data on engine parameters as the tests were being conducted. It should be noted that the HEM logger data was utilized to identify the MIL status, as it was available for nearly all vehicles. In most cases, the DTCs identified by the HEM logger and the Silver Scan Tool were the same, although some differences were found in a few cases.

3.2.4.3 RSD Measurements

In addition to the chassis dynamometer and OBD measurements, RSD measurements were obtained on a subset of the test fleet with a HEAT EDAR system. A more complete description of the EDAR system is provided in Appendix E. HEAT provided its EDAR system for a two week period in November 2016.

For most of the test vehicles during the November 2016 test campaign, HEAT provided CO_2 normalized NO, NO_2, and PM, emissions data. The data record included a means of identifying the vehicle (such as a license plate), and the date and time of the measurement. Other metrics of the data quality also were included in the data records, such as a valid/invalid flag, signal to noise ratio, total plume CO_2 mass, or cross section CO_2 mass, or similar information that allowed judging the quality of the signal. In addition to the test vehicles identified for pre- and post-repairs, a number of randomly selected vehicles that were at the test facility undergoing repairs were also driven through the RSD system to provide an overview of RSD results over a broader range of vehicles.

The EDAR system was positioned on the east side of the J & R Fleet Services facility. A photograph of the test set up is provided in Figure 3-3. An overview showing the positioning of the EDAR system is provided below in Figure 3-4. This side of the facility is opposite to the entrance where more vehicle traffic exists, and hence made it easier to provide consistent operation driving through the RSD. For the EDAR testing, vehicles were driven through over a range of speeds from 6 to 40 mph with an average speed of 22 mph after an acceleration. Measurements were conducted in triplicate for both pre- and post-repair tests, and for the additional vehicles selected for RSD measurements. For the tests associated with the pre- and post-repair chassis dynamometer tests, the EDAR measurements were made after the chassis dynamometer tests to provide preconditioning in terms of warming up the SCR catalyst. It should be noted that due to logistical considerations, the measurements were made with the trucks without a trailer load. As such, the measurements for the RSD system are not directly comparable to the chassis dynamometer tests that were conducted with a load.

Figure 3-3 EDAR system setup

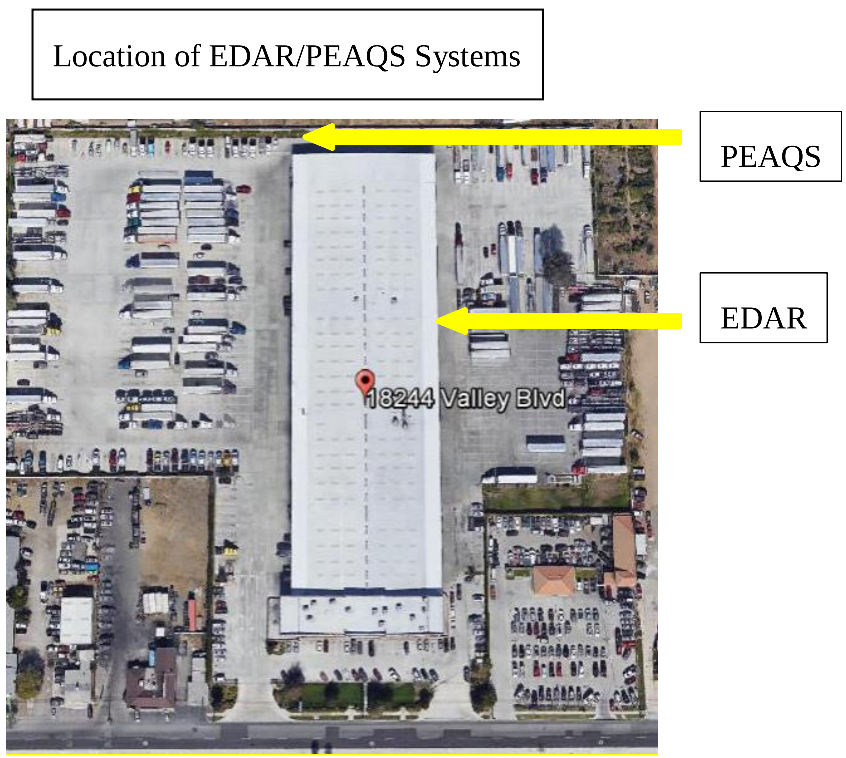


Figure 3-4 Overview of J&R Facility and positioning of EDAR and PEAQS systems

3.2.4.4 PEAQS Measurements

CARB also provided its PEAQS system for about a one week period during the November 2016 testing campaign. The PEAQS system consists of two sampling lines (one 'updraft' pipes and one for 'downdraft' pipes), connected to some emissions analyzers, and a license plate reader (LPR). For this program, the PEAQS measured black carbon (BC) emission factors (EF_{BC}) with a Magee Scientific AE-33 7 channel aethalometer, total NO_X emission factors (EF_{NOX}) with a CAI 600 Series chemiluminesence analyzer, and vehicle speed and acceleration. A picture of the PEAQS set up at J&R is provided in Figure 3-5. A key component of the system is a 'cable protector' for the downdraft sampling line that is laid across the roadway being sampled. The cable protector is an 18-inch wide, 1 or 2 inch tall ramp with an internal channel, that is laid across the roadway to protect the sampling line connected to the emissions analyzers, and can be up to 40 feet long. The 'downdraft' sampling line fits inside the channel which protects the sampling line as HDVs pass over the ramp and sampling line. The updraft sampling line can be attached to the support trailer, or some other location that provides a place to attach sampling line, such as a fence or fence post. Additional pictures of the PEAQS system are provided in Appendix F.

The PEAQS system was located in the northwest corner of the J&R facility, and it was operated by CARB staff. The PEAQS system was used to measure in triplicate the same subset of vehicles being measured by the EDAR system, including the pre- and post-repair test vehicles, as well as the additional vehicles selected for RSD measurements. All measurements reported here are for vehicles passing through the PEAQS, not snap accelerations.

Figure 3-5 Picture of PEAQS setup at the J&R facility

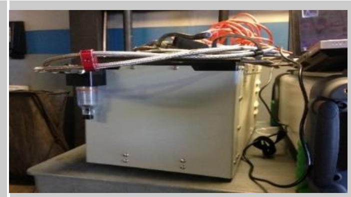
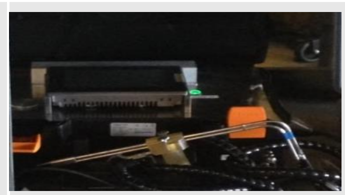
3.2.4.5 Mini-PEMS Measurements

Mini-PEMS are a potential candidate for inclusion in a broader HD I/M program. For a widespread HD I/M program, mini-PEMS could be deployed at locations such as weigh stations that trucks must routinely visit during the course of normal operations. Mini-PEMS would have to be utilized under snap acceleration or idle conditions that would not require the instruments to be mounted on the vehicle, their use would be limited to locations such as weigh stations where trained personnel could be stationed.

UCR utilized a number of mini-PEMS type of systems, including a Pegasor PPS-M, the NTK Compact Emissions Meter (NCEM), the TSI Nanoparticle Emissions Tester (NPET), the Testo Portable Emission Particle Analyzers (PEPA), and a 3DATX Corporation parSYNC® PLUS, which is a smaller size integrated portable emissions measurement systems (iPEMS). These instruments are shown in Table 3-5. A description of each of these systems and their operating principles and technical specifications is provided in Appendix G.

These instruments were all available for the November 2016 testing campaign, with some of the instruments also being available for subsequent testing campaigns. The instruments that were available for more extensive testing past November of 2016 included the Testo for the full duration of testing, NTK system for testing from March to May 2017, and TSI NPET for part of May 2017. The sampling systems for the mini-PEMS include some tailpipe probes and some sensors that were set up in a manifold. After some initial testing, it was determined that it was not practical to utilize a manifold for the dynamometer testing due to the time constraints of working with the facility, and the need to disassemble the exhaust pipe for installation. Subsequent measurements were conducted by putting the sampling probes/sensors down the vehicle’s exhaust pipe. Note that the NTK system was not set up for the sensor to be directly placed into the vehicles tailpipe, so a special connector was fabricated that attached directly to the tailpipe that held the probe in the exhaust. It should also be noted that and issue with the zero current offset was identified for the NTK system PM and PN measurements following the testing (Tange, 2017; Yang et al., 2018), so these measurements are not included in the report.

Table 3-5 MAHA, Opacity, and mini-PEMS used

Instrument	Pollutants Measured	When System was used	Picture
MAHA	NOx, CO_2, HC, CO	November 2016 to May 2017	
MAHA MPM4	PM	November 2016 to May 2017	
Opacity	PM	November 2016 to May 2017	
Pegasor Mi3	PM	November 2016	
TSI NPET	Solid PN	November 2016, May 2017	
Testo	Solid PN	November 2016 to May 2017	
parSYNC® PLUS	NOx, CO_2	November 2016	
NTK	NOx, PM	November 2016, March to May 2017	

4 Pilot Study Results

This chapter presents the emissions and repair results from the pilot study. This includes the results for the chassis dynamometer testing, RSD, and PEAQS. Emission reductions are also calculated from the emissions testing performed during the pilot study. The repair costs and repair frequencies obtained by evaluating historical repair data and cost data from the two private repair facilities are also presented.

4.1 Emissions Testing Results

Pre- and post-repair chassis dynamometer tests were conducted on a total of 47 vehicles, with three of these vehicles requiring a second or third visit to resolve their repair issue. The results for PM and PN, NOx, THC, and CO emissions are presented in this subsection. The results are typically presented normalized to CO_2 emissions or normalized on a g/bhp-hr basis. This allows the pre- and post-test results to be more readily compared by normalizing out any variations in load that might be seen within the tests itself. Results for tests with the HEAT EDAR and the PEAQS system are also included in this subsection.

4.1.1 Chassis Dynamometer Emissions Results

4.1.1.1 Chassis Dynamometer NOx Results

4.1.1.1.1 NOx Results - Overview

Pre- and Post-repair NOx emissions were measured with a variety of instruments. This included a MAHA NOx analyzer, as discussed in section 3.2.3.1, and several mini-PEMS systems, as discussed in 3.2.3.5, and 3DTAX parSYNC® PLUS and NTK NCEM systems. This subsection provides an overview of the NOx results from the pilot study, which are discussed in greater detail below.

The pre-repair MAHA NOx emissions results showed that a number of vehicles had emissions higher than 0.20 g/bhp-hr for both the initial 30 and 50 mph tests. However, it is acknowledged that the results should not be directly compared to certification standards, which are set for engine dynamometer testing that was not performed in the pilot study. This included 4 vehicles with particularly high NOx emissions, which had problems that included injector dosers, DPF replacement, and exhaust pressure sensors. All these vehicles showed significant reductions in NOx emission after repair, with reductions of greater than 83% after repair for all test conditions. Vehicles with other problems, including DEF system issues and SCR inlet and outlet NOx sensors, showed mixed trends in comparing the pre- and post-repair NOx emissions. The results showed that NOx reductions of greater than 80% were found for 43% of the 30 mph tests and 28% of the 50 mph tests after repair, with the highest emitters showed greater than 80% NOx reductions under all conditions. The fleet average NOx emissions reductions were 75% at 30 mph and 46% at 50 mph for the vehicles with a check engine light on before repairs and the DM1 MIL off post-repair, excluding the Navistar non-SCR trucks. The fleet average NOx emissions reductions were 81% at 30 mph and 53% at 50 mph for the vehicles with DM1 MIL on pre-repair and DM1 MIL off post-repair and excluding the Navistar trucks (J&R15 and J&R48).

For the mini-PEMS systems, the NTK system showed relatively high NOx emissions for vehicles that showed high NOx emissions for the MAHA, although the highest NOx emitting trucks were not me showed very high NOx emissions before the repair and significant reductions after the repair for this vehicle asured by the NTK system. Data were more limited for 3DATX parSYNC® PLUS, but it did include testing of vehicle J&R01, which was one of the highest emitting vehicles in the MAHA test data. The parSYNC® PLUS, which were consistent with the MAHA measurements. Overall, the results suggest that the mini-PEMS show the potential for identifying high NOx emitters.

Some additional analyses were also conducted to look NOx emissions trends between different engine manufacturers, as discussed in section 4.1.1.1.4. There were some different trends between vehicles from different engine manufacturers, with one engine manufacturer showing relatively lower NOx emissions for the idle and high idle mode but much higher emissions at 50 mph than the other. SCR efficiency calculations were also made based on readings from the inlet and outlet NOx sensors for a subset of 9 vehicles, as discussed in section 4.1.1.1.5. For one engine manufacturer, SCR efficiencies were higher than 84% for 5 engines between the pre- and post-repair tests. Three other engines from this manufacturer had SCR efficiencies that were below 70% pre-repair, including two vehicles with SCR efficiencies below 15% pre-repair. The SCR efficiencies for two vehicles with very low values improved to greater than 90% for most test conditions after repair.

4.1.1.1.2 MAHA NOx Results

Pre- and post-repair NOx emissions on a g/bhp-hr basis are shown in Table 4-1 for the MAHA for the 30 and 50 mph tests. The characterization of the emissions on a g/bhp-hr basis is useful, since this is a metric commonly used to evaluate emissions from heavy-duty vehicles and engines. The g/bhp-hr results are primarily based on ECM data to get the bhp-hr values during the testing. The g/bhp-hr results for some vehicles were not available from the ECM.[2] For the tests where engine ECM data were not available, i.e., such that bhp-hr information was not available from the ECM, a linear regression was used to determine the g/bhp-hr values based on the emission concentrations. In particular, since the 30 and 50 mph tests were each conducted at the same horsepower for each vehicle, as discussed in section 3.2.4, there is a strong correlation between grams and g/bhp-hr values over the different vehicles in the test fleet. It is worth noting that while g/bhp-hr units are used for certification, the steady state conditions at 30 and 50 mph are not representative of the transient operating conditions found in the FTP certification engine dynamometer test. As such, comparisons with engine dynamometer certification levels are only meant to provide a rough estimate of the emission levels of a vehicle relative to a commonly available metric, and are not meant to be indicative of a vehicles compliance with emissions standards.

These results show that only J&R03, 10, 13, 18, 20, 21, 29, and 40 were below the 0.2 g/bhp-hr NOx standard that is in place for 2010+ truck engines for both the initial 30 and 50 mph tests. Other vehicles had relatively high emissions relative to the certification levels, with the highest being J&R01, 09, 11, 17, 48, and the initial repair of J&R22. A plot of the pre- and post-repair emission test for the ten highest emitters is provided in Figure 4-1 and Figure 4-2 for 30 and 50 mph, respectively, along with the repairs for each of these vehicles. It should be noted that J&R48 is not included in these Figures, even though it was one of the 10 highest NOx emitters, because this truck was equipped with a Navistar engine that was not equipped with an SCR, and would not be representative of repair results for SCR equipped trucks. This vehicle also left with the DM1

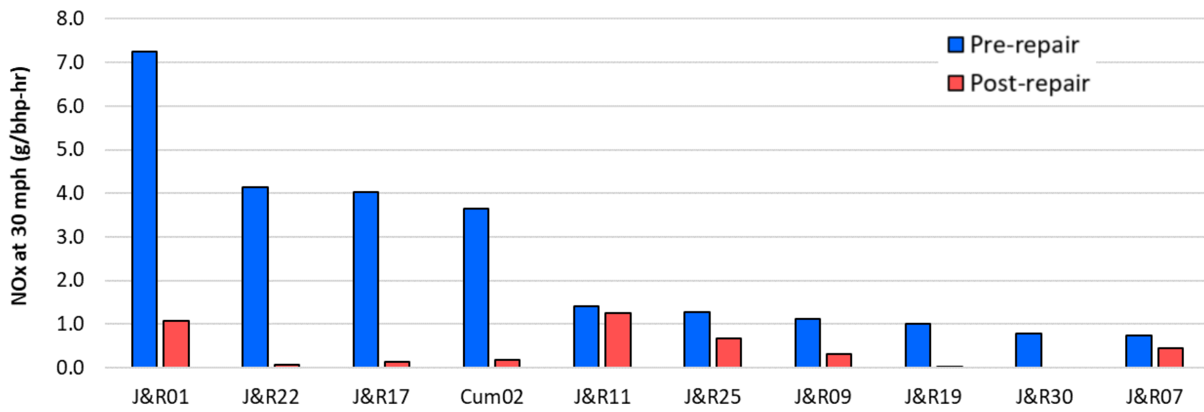
[2] Vehicle J&R04, 07, and 12 were all Volvo trucks using a SAE J1979 protocol, which we could not connect with at the time. For subsequent vehicles equipped with SAE J1979 protocols, we used data loggers to download engine parameters. Other vehicles had rectangular connections, which we did not initially have, or upgraded green connectors that could not be read until later in the study.

MIL on for the post-repair test, indicating that the vehicle did not complete the full repair process that would be required under a HD I/M program, as discussed further below.

Table 4-1 Pre- and post-repair NOx emissions for the MGT5 for each vehicle on a g/bhp-hr basis

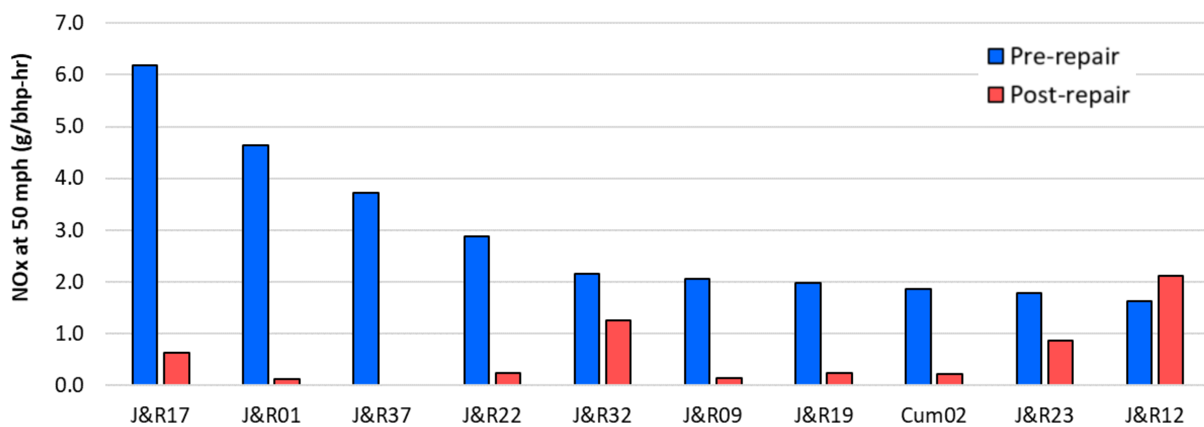
Vehicle NO.	Engine Year & Make	Pre-repair NOx Emissions (g/bhp-hr)		Post-repair NOx Emissions (g/bhp-hr)	
		30 mph	50 mph	30 mph	50 mph
J&R01	2011 Cummins	7.2414	4.6397	1.0852	0.1254
J&R03	2013 Cummins	0.0709	0.1958	0.0361	0.1582
J&R04	2013 Volvo	0.3719	1.4564	0.0641	0.9486
J&R05	2012 Cummins	0.0000	0.0000	0.3676	0.3800
J&R06	2015 Cummins	0.5908	0.3542	0.0644	0.6863
J&R07	2014 Volvo	0.7453	1.2653	0.4506	1.1816
J&R09	2012 Cummins	1.1271	2.0508	0.3089	0.1459
J&R10	2011 Cummins	0.0000	0.0299	0.0000	0.0000
J&R11	2013 Cummins	1.4148	0.6416	1.2461	0.3404
J&R12	2011 Volvo	0.3260	1.6298	0.1538	2.1200
J&R13	2013 Cummins	0.0041	0.0006	0.1877	0.1908
J&R14	2010 DDC	0.7011	0.8681	0.8523	1.2550
J&R15	2010 Navistar	0.5396	0.4925	2.9103	1.1526
J&R16	2010 Mack	0.6601	0.5184	0.0730	1.1320
J&R17	2011 Cummins	4.0220	6.1849	0.1457	0.6375
J&R18	2014 Cummins	0.0000	0.2498	0.0542	0.0749
J&R19	2015 Cummins	1.0161	1.9865	0.0267	0.2324
J&R19 Second visit		0.0309	0.2335	0.0226	0.1927
J&R20	2011 Cummins	0.0000	0.0110	0.0000	0.0000
J&R21	2013 Cummins	0.0871	0.4910	0.0103	0.4045
J&R22	2013 Cummins	4.1298	2.8683	0.0660	0.2424
J&R22 Second visit		0.0516	0.1872	0.0004	0.3194
J&R23	2013 Cummins	0.5158	1.7869	0.0000	0.8630
J&R25	2013 Cummins	1.2703	0.0389	0.6818	0.1915
J&R26	2013 Paccar	0.0173	0.0409	0.0000	0.0000
J&R27	2014 Volvo	0.1476	1.0005	0.0000	2.3426
J&R28	2013 Cummins	0.0250	0.6710	0.0000	0.0000
J&R29	2014 Cummins	0.1104	0.0176	0.0916	0.0363
J&R30	2013 Cummins	0.7864	0.5962	0.0000	0.4472
J&R31	2013 Cummins	0.2239	0.0000	0.0005	0.0855
J&R32	2013 Volvo	-0.0001	2.1591	0.0485	1.2540
J&R33	2015 Cummins	0.0000	0.0000	0.0000	0.0023
J&R34	2015 Volvo	0.0000	0.0000	0.0000	0.2021
J&R35	2014 Volvo	0.0629	0.7729	0.0000	0.3955
J&R36	2013 Volvo	0.5965	0.9612	0.1008	0.8486
J&R37	2016 DDC	0.0184	3.7177	0.0000	0.0000
J&R38	2013 Cummins	0.0226	0.0000	0.1296	0.0566
J&R39	2013 Cummins	0.0000	0.0121	0.0000	0.2593
J&R40	2013 Cummins	0.0161	0.0000	0.0000	0.0000
J&R40 Second visit		0.0000	0.0000	0.0048	0.2032
J&R40 Third visit		0.0000	0.0000	0.0048	0.2032
J&R41	2014 Paccar	0.0000	0.3651	0.0210	0.0656
J&R42	2013 Cummins	0.0000	0.3783	0.0193	0.0505
J&R43	2014 Cummins	0.0000	0.0000	0.0000	0.0000
J&R44	2014 Volvo	0.1254	1.0606	0.0536	0.9052
J&R45	2013 Cummins	0.0145	0.0975	0.0000	0.0000
J&R46	2013 Cummins	0.0000	0.0000	0.0000	0.4404
J&R47	2013 Volvo	0.1312	0.3027	0.8927	2.2740
J&R48	2013 Maxxforce	2.0742	2.2385	5.9258	5.0924
Cum01	2015 Cummins	0.4130	0.2745	0.4036	0.2647
Cum02	2010 Cummins	3.6492	1.8663	0.1708	0.2092

Note: n/a - not available; values with 0.0000 represent MAHA measurements essentially at the zero level.



Vehicle NO	Repair	Vehicle NO	Repair
J&R01	Replaced DPF and injector doser, clean DPF	J&R25	Short w/ coolant temperature sensor, thermostat
J&R22	Exhaust pressure sensor	J&R09	Clean DPF
J&R17	Injector doser, Intake NOx sensor, clean DPF	J&R19	DEF harness
Cum02	Injector doser, turbocharger	J&R30	Corrected/Cleaned DEF pump/harness connections
J&R11	Outlet NOx sensor, Injector Doser	J&R07	Turbo speed sensor

Figure 4-1 Ten Highest Pre-Repair NOx Emissions at 30 mph and Their Associated Repairs



Vehicle NO	Repair	Vehicle NO	Repair
J&R17	Injector doser, Intake NOx sensor, clean DPF	J&R09	Clean DPF
J&R01	DPF, injector doser, DPF cleaning	J&R19	DEF harness
J&R37	EGR cooler, valve assembly, & actuator	Cum02	Injector doser, turbocharger
J&R22	Exhaust Pressure Sensor	J&R23	Clean DPF/Engine Oil Cooler
J&R32	differential pressure sensor	J&R12	DEF lines at dosing valve, manual regen

Figure 4-2 Ten Highest Pre-Repair NOx Emissions at 50 mph and Their Associated Repairs

The pre and post MAHA NOx emission measurements for all of the vehicles are shown in Table 4-2 in units of ppm/CO_2%. NOx emissions showed a fairly wide range, depending on the test condition and the vehicle, with values ranging from <0.01 to 129.90.

Of the vehicles tested, four showed particularly high NOx emissions, including J&R01, 17, 22 and Cum02. Both J&R01 and J&R17 had injector doser issues. The repairs for Cum02 and J&R22 were for other issues, with the DPF being replaced for Cum02 and exhaust pressure sensors being replaced for J&R22. All these vehicles showed significant reductions in NOx emission after repair, with reductions of greater than 83% after repair for all test conditions.

The highest NOx emissions were generally seen for either the 30 or 50 mph tests. The NOx emissions results for 30 and 50 mph were examined for any trends based on different types of repairs. Overall, of the 51 repairs done, 22 resulted in reductions of greater than 80% for the 30 mph test. Repair issues such as those associated with the EGR, DEF, or SCR systems, or NOx sensors are ones that could have an impact on NOx emissions. A total of 15 vehicles (Cum01, J&R01, 05, 06, 12, 15, 17, 19, 22 second visit, 27, 28, 30, 31, 37 and 40 second visit) had issues associated with the DEF system. Eight of these vehicles (Cum01, J&R01, 12, 17, 19 first visit, 28, 30, and 37) showed lower NOx emissions readings after fixing the DEF associated issues. Other vehicles showed opposite trends between the 30 mph and 50 mph, while J&R15 and the second visit for J&R 40 showed increases in NOx emissions. There were 10 vehicles (J&R10, 11, 13, 17, 20, 22 second visit, 31, 42, 46 and 47) where either the SCR inlet or outlet NOx sensors were replaced. Of these 10 vehicles, only J&R10, 11, 17 and 20 showed NOx emission reductions after the repair, while J&R13, 46 and 47 showed higher NOx emissions post-repair, and the remaining test vehicles showed mixed trends between the 30 and 50 mph driving conditions. J&R31 was the only vehicle where the SCR system was completely replaced, it is expected that this vehicle might show significant NOx reductions. J&R31 did show decreases in NOx emissions from 4.4 ppm to <0.01 ppm for the 30 mph driving condition, but slightly increased NOx emissions for the 50 mph driving condition. J&R37 showed the largest NOx emission reductions (from 68 ppm/%CO_2 to 0.3 ppm/%CO_2) after replacing the EGR cooler and valve. J&R41, on the other hand, showed similar NOx emissions before and after changing the EGR valve. Other vehicles that showed post-repair NOx emission reductions include, J&R03, 04 and 25 after replacing temperature sensors, except for J&R25 under for the 50 mph test. J&R38, 39 and 42 had higher NOx emissions after updating or calibrating the ECM. J&R45 showed NOx emission reductions after replacing the fuel injectors.

It should be noted that a number of vehicles showed either minimal or no emissions reductions for the post-repair test, and in some cases even showed higher emissions for the post-repair test compared to the pre-repair test for either the 30 or 50 mph test. In evaluating these data, it is important to note that the OBD system is designed to identify issues with components or systems, including failures that might not immediately lead to elevated emissions. Hence, the emissions benefits of OBD repairs can not entirely be characterized based on only benefits obtained immediately following a repair. For vehicles that showed higher emissions in the post-repair tests at either 30 or 50 mph, some of the vehicles had emissions levels that were below or near the 0.2 g NOx/bhp-hr for both the pre- and post-repair tests (e.g., JR13, JR31, JR38, and JR40_second visit). For others, the DM1 MIL was off during the pre-repair test (e.g., JR06, JR13, JR14, and JR15), suggesting that reductions in post-repair emissions would not necessarily be expected, and that the emissions differences could be attributed to variability in the testing associated with the challenges of testing with a water-brake dynamometer. For J&R48, in particular, it is important to point out that this vehicle was equipped with a 2013 Maxforce engine without an SCR system and was certificated to a 0.5 g/bph-hr NOx standard. The NOx emissions for this vehicle were much higher compared with other engine manufacturers in same model year range under the same test conditions. The repairs for this vehicle showed an increase in NOx emissions after the engine throttle valve assembly was replaced. The owner declined the full repair of the intake manifold, however, and hence the vehicle was not repaired completely for the post-repair test. This is reflected as having the DM1 MIL on during the post-repair test. JR15 also showed higher emissions for the post-repair tests than the pre-repair tests. This vehicle was also equipped with a Navistar engine without a SCR system. The DM1 MIL for this vehicle was also off for the pre-repair.

The changes in NOx emission before and after the repairs under the idle and high idle driving conditions can also be examined for different repair issues. A total of 15 vehicles (Cum01, J&R01, 05, 06, 11, 12, 15, 17, 19, 22 second visit, 27, 28, 30, 31, 37 and 40 second visit) had issues associated with the DEF system. Most of these vehicles showed lower NOx emissions after fixing the DEF system under idle conditions, except for J&R15, 31 and 12. There were 10 vehicles (J&R10, 11, 13, 17, 20, 22 second visit, 31, 42, 46 and 47) where either the SCR inlet or outlet NOx sensors were replaced. Only J&R10, 11, 17, 20 and 22 (second visit) showed NOx reductions after repairs, while J&R13, 31, 42, 47 and 48 showed increased NOx emissions. J&R31 had the full SCR system replaced, but did not show significant changes in NOx emissions under idle conditions as the pre-repair NOx emissions were negligible under idle conditions. J&R37 showed significant NOx emissions reduction (from 15.4 ppm/%CO_2 to 0.3 ppm/%CO_2) after replacing the EGR cooler and valve. Similar to J&R37, J&R41 also showed a decrease in NOx emission after changing the EGR valve. Temperature sensors were replaced on several vehicles, with J&R04 and J&R25 showing higher readings of NOx emissions after repair under both idle and high idle conditions, and J&R03 showing higher NOx emissions under idle. The higher idle NOx emissions for J&R03 was opposite of the trend seen under the 30 and 50 mph driving conditions. J&R38, 39 and 42 were found to have higher idle NOx emissions after updating or calibrating the ECM, which was consistent with the trends found for the 30 and 50 mph driving conditions. J&R45 showed lower idle NOx emissions after replacing the fuel injectors, while the idle NOx emissions for J&R48 increased after replacing the intake air manifold.

Table 4-2 Pre- and post-repair for NOx emissions from MAHA normalized by CO_2 for each vehicle

Vehicle NO.	Engine Year & Make	Pre-repair NOx Emissions (ppm/CO2%)				Post-repair NOx Emissions (ppm/CO2%)				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R01	2011 Cummins	129.90	61.62	9.04		22.23	2.01	0.00		-83%	-97%	-100%	
Cum01	2015 Cummins	7.42	4.67	0.01	20.71	6.11	4.53	0.11	18.02	-18%	-3%		-13%
Cum02	2010 Cummins	66.96	34.37	38.66	25.06	3.38	4.08	1.39	0.00	-95%	-88%	-96%	-100%
J&R03	2013 Cummins	1.34	3.53	2.99		0.72	3.06	1.70		-46%	-13%	-43%	
J&R04	2013 Volvo	7.05	26.88	0.01		1.43	17.59	0.32		-80%	-35%		
J&R05	2012 Cummins	0.00	7.89	0.00		4.37	6.14	0.00			-22%	-100%	
J&R06	2015 Cummins	10.93	6.62	0.23		1.45	12.38	1.13		-87%	87%	382%	
J&R07	2014 Volvo	13.88	23.38	1.37		8.49	21.85	0.71		-39%	-7%	-49%	
J&R09	2012 Cummins	13.71	29.09	6.32	9.39	5.25	2.39	2.35	19.58	-62%	-92%	-63%	108%
J&R10	2011 Cummins	0.00	0.43	0.00	5.09	0.02	0.00	0.02	0.00		-100%		-100%
J&R11	2013 Cummins	29.70	13.80	1.74	7.57	26.16	5.95	0.12	0.00	-12%	-57%	-93%	-100%
J&R12	2011 Volvo	6.21	30.05	1.31	1.58	3.06	39.01	1.40	0.34	-51%	30%	7%	-79%
J&R13	2013 Cummins	0.10	0.02	0.02	0.17	4.39	4.61	2.62	1.82				
J&R14	2010 DDC	10.35	10.89	0.03	0.18	11.10	15.34	2.17	6.38	7%	41%	6637%	3514%
J&R15	2010 Navistar	3.81	7.00	2.20	12.85	35.25	14.87	18.17	22.02	826%	112%	727%	71%
J&R16	2010 Mack	12.32	9.73	0.05	0.78	1.59	20.95	0.92	0.84	-87%	115%	1649%	7%
J&R17	2011 Cummins	79.46	101.40	49.12	52.40	2.69	10.04	3.09	6.19	-97%	-90%	-94%	-88%
J&R18	2014 Cummins	0.00	5.14	0.00	0.00	1.07	1.48	1.58	1.39		-71%		
J&R19	2015 Cummins	12.83	31.15	10.00	60.28	0.43	3.31	0.78	15.47	-97%	-89%	-92%	-74%
Second visit		0.43	3.31	0.78	15.47	0.40	4.06	0.44	0.00	-8%	23%	-43%	-100%
J&R20	2011 Cummins	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00		-100%		
J&R21	2013 Cummins	1.68	9.91	1.21	1.29	0.18	8.14	0.02	0.01	-89%	-18%	-99%	-99%
J&R22	2013 Cummins	75.88	56.56	106.34	49.96	1.14	4.91	0.06	2.33	-99%	-91%	-100%	-95%
Second visit		1.14	4.91	0.06	2.33	0.01	7.66	0.00	0.00	-99%	56%	-100%	-100%
J&R23	2013 Cummins	9.47	29.82	1.93	2.69	0.00	16.10	0.00	0.00	-100%	-46%	-100%	-100%
J&R25	2013 Cummins	22.92	0.70	0.00	4.24	13.10	3.80	3.91	19.30	-43%	439%		355%
J&R26	2013 Paccar	0.31	0.67	0.63	0.64	0.00	0.00	0.00	0.00	-100%	-100%	-100%	-100%
J&R27	2014 Volvo	2.95	18.54	0.01	0.00	0.01	43.08	0.00	0.00	-100%	132%	-100%	
J&R28	2013 Cummins	0.71	12.52	0.67	0.75	0.00	0.23	0.00	0.00	-100%	-98%	-100%	-100%
J&R29	2014 Cummins	2.41	0.33	0.45	1.02	1.66	0.85	0.00	0.01	-31%	156%	-99%	-99%
J&R30	2013 Cummins	14.63	11.15	0.25	5.45	0.00	8.43	0.00	0.00	-100%	-24%	-100%	-100%
J&R31	2013 Cummins	4.43	0.00	0.01	0.00	0.01	1.56	0.01	0.20	-100%		36%	
J&R32	2013 Volvo	0.25	39.72	0.00	0.00	1.14	23.18	0.08	0.01	355%	-42%		
J&R33	2015 Cummins	0.00	0.02	0.00	0.00	0.00	0.29	0.00	0.00		1171%		
J&R34	2015 Volvo	0.00	0.00	0.09	0.00	0.06	3.95	0.03	0.00			-70%	
J&R35	2014 Volvo	1.40	14.38	0.00	0.00	0.00	7.48	0.01	0.00	-100%	-48%		
J&R36	2013 Volvo	10.97	15.03	0.00	0.00	1.80	15.56	0.00	0.00	-84%	3%		
J&R37	2016 DDC	0.59	68.22	0.22	15.43	0.12	0.25	0.07	0.32	-80%	-100%	-70%	-98%
J&R38	2013 Cummins	0.67	0.00	0.08	0.07	2.62	1.29	2.46	4.15	293%			
J&R39	2013 Cummins	0.00	0.23	0.00	0.38	0.00	5.70	0.00	0.49		2416%		29%
J&R40	2013 Cummins	0.23	0.00	0.03	0.00	0.01	0.00	0.01	0.00	-95%		-57%	
Second visit		0.00	0.00	0.01	0.00	0.34	3.97	0.00	0.00			-94%	
Third visit		0.36	4.08	0.00	0.00	0.00	0.00	0.04	0.00	-100%	-100%		
J&R41	2014 Paccar	0.01	0.00	0.11	0.12	0.01	0.06	0.00	0.00	102%		-97%	-100%
J&R42	2013 Cummins	0.00	7.94	0.00	0.00	0.37	1.02	0.05	0.14		-87%		
J&R43	2014 Cummins	0.00	0.00	0.27	0.00	0.00	0.13	0.00	0.43		3636%	-100%	
J&R44	2014 Volvo	2.56	22.22	1.08	0.86	1.11	18.99	0.01	0.05	-57%	-15%	-99%	-94%
J&R45	2013 Cummins	0.52	2.03	0.73	0.95	0.00	0.05	0.01	0.00	-100%	-97%	-99%	-100%
J&R46	2013 Cummins	0.01	0.15	0.27	0.34	0.14	8.30	0.08	1.98			-70%	
J&R47	2013 Volvo	2.53	5.79	1.01	0.76	18.24	45.44	1.34	1.22			32%	61%
J&R48	2013 Maxxforce	62.76	52.39	50.93	33.74	123.40	105.02	103.53	38.66	97%	100%	103%	15%

4.1.1.1.3 Mini-PEMS NOx Results

The pre and post 3DATX parSYNC® PLUS and NTK NOx emission measurements are shown in Table 4-3 in units of ppm/CO_2%. There are 2 vehicles for the parSYNC® PLUS and 24 vehicles for the NTK. Note that the NOx emissions from NTK were normalized by the CO_2 from MAHA, as the NTK does not provide CO_2 emissions, while the NOx emissions from parSYNC® PLUS were normalized by the CO_2 emissions measured by the parSYNC® PLUS itself. NOx emissions showed a fairly wide range for the NTK, depending on the test condition and the vehicle, with values ranging from 0.03 to 53.82 ppm/CO_2%, which was a little higher compared with results from MAHA. Similar to the MAHA, J&R04, 25, 27, 32, 35, 36 and 44 showed relatively higher NOx emissions with the NTK system, with emissions values greater than 14 ppm/CO2% under certain driving conditions. J&R01, 17, 22 and Cum02 vehicles showed particularly high NOx emissions measured by MAHA, but corresponding NTK NCEM measurements were not available. Data was more limited for 3DATX parSYNC® PLUS, but it did include testing of vehicle J&R01, which was one of the highest emitting vehicles in the MAHA test data. The parSYNC® PLUS showed very high NOx emissions before the repair and significant reductions after the repair, which were consistent with the MAHA measurements. The parSYNC® Plus showed somewhat higher NOx emissions than the MAHA for the 30 and 50 mph pre-repair tests, and 30 mph post-repair test, significantly higher NOx emissions for the pre-repair idle and post-repair 50 mph test, and lower NOx for the post-repair 30 mph test. The higher parSYNC® Plus normalized NOx emissions can be attributed in part to the lower CO_2 emissions measured by the parSYNC® plus (as shown in Appendix H-1), as much as to differences in NOx ppm values.

Table 4-3 Pre- and post-repair for NOx emissions from 3DATX parSYNC® PLUS and NTK normalized by CO_2 for each vehicle

Vehicle NO.	Engine Year & Make	Pre-repair NOx Emissions (ppm/CO_2%)				Post-repair NOx Emissions (ppm/CO_2%)				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
		3DATX											
J&R01	2011 Cummins	146.737	90.240	n/a	n/a	44.352	37.461		n/a	-70%	-58%		
J&R03	2013 Cummins	1.226	1.399	1.779	n/a	n/a	n/a	n/a	n/a				
		NTK											
J&R04	2013 Volvo	12.210	30.540	1.795	n/a	2.759	20.184	0.557	n/a	-77%	-34%	-69%	
J&R05	2012 Cummins	2.091	10.237	0.599	n/a	9.936	9.868	0.509	n/a		-4%	-15%	
J&R25	2013 Cummins	4.30	16.84	8.99	11.13	21.53	4.50	15.18	31.85	69%	186%		-73%
J&R26	2013 Paccar	0.64	1.66	3.45	4.98	0.23	0.41	0.97	1.46	-72%	-71%	-65%	-75%
J&R27	2014 Volvo	7.91	23.71	3.67	3.64	9.53	44.61	8.06	12.29	119%	238%	20%	88%
J&R28	2013 Cummins	1.26	9.31	4.45	4.65	1.40	1.78	1.29	1.45	-71%	-69%	11%	-81%
J&R29	2014 Cummins	3.32	1.07	1.16	2.11	4.63	3.79	0.73	2.80	-37%	33%	39%	255%
J&R30	2013 Cummins	6.54	8.58	36.54	33.23	2.53	2.89	0.94	1.15	-97%	-97%	-61%	-66%
J&R31	2013 Cummins	7.87	2.75	0.74	0.95	0.73	2.60	1.62	1.22	118%	29%	-91%	-6%
J&R32	2013 Volvo	13.28	34.37	8.26	4.99	4.75	23.68	0.66	1.17	-92%	-76%	-64%	-31%
J&R33	2015 Cummins	0.82	1.32	1.88	2.01	0.21	0.18	1.08	1.46	-42%	-27%	-75%	-86%
J&R34	2015 Volvo	1.92	2.67	1.44	1.38	1.29	8.92	0.99	1.02	-31%	-26%	-33%	235%
J&R35	2014 Volvo	9.35	18.16	3.52	2.57	2.23	13.36	3.51	2.40	0%	-7%	-76%	-26%
J&R36	2013 Volvo	16.21	19.78	19.34	18.64	8.97	17.94	5.29	6.33	-73%	-66%	-45%	-9%
J&R37	2016 DDC	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a				
J&R38	2013 Cummins	13.77	3.36	6.02	12.33	8.99	2.68	5.42	8.54	-10%	-31%	-35%	-20%
J&R39	2013 Cummins	5.62	4.50	3.11	4.82	3.99	7.91	0.90	0.76	-71%	-84%	-29%	76%
J&R40	2013 Cummins	4.88	0.60	5.43	5.29	1.46	3.36	3.08	2.04	-43%	-61%	-70%	460%
Second visit		1.46	3.34	3.08	2.04	1.61	6.87	1.11	2.11	-64%	4%	10%	106%
Third visit		1.61	6.87	1.11	2.11	0.93	1.45	1.57	1.79	41%	-15%	-42%	-79%
J&R41	2014 Paccar	1.88	0.03	1.48	2.12	0.27	1.25	0.06	1.14	-96%	-46%	-86%	3625%
J&R42	2013 Cummins	2.12	10.66	1.27	1.12	0.06	3.72	0.82	0.89	-35%	-20%	-97%	-65%
J&R43	2014 Cummins	0.43	2.95	2.20	3.51	0.74	1.33	2.22	1.83	1%	-48%	69%	-55%
J&R44	2014 Volvo	53.82	46.21	14.02	5.66	21.09	41.85	5.54	1.30	-61%	-9%	-60%	-77%
J&R45	2013 Cummins	6.89	0.00	0.30	1.61	2.40	3.03	2.25	3.08		91%	-65%	
J&R46	2013 Cummins	3.18	3.46	2.59	8.42	5.30	13.13	1.00	3.76	-61%	-55%	67%	280%
J&R47	2013 Volvo	4.69	8.70	2.13	2.66	37.97	59.48	1.26	2.01	-41%	-24%		

Note: n/a - Not available

Figure 4-3 shows a comparison of real-time NOx emissions for the MAHA and 3DTAX parSYNC® PLUS, and the corresponding exhaust temperature, and Figure 4-4 shows a comparison of real-time NOx emissions for the MAHA and NTK NCEM system. For the NTK graphs, the initial peak typically represents the warm-up driving, while the second peak represents the testing conducted at 50 and then 30 mph. The parSYNC® PLUS graph begins with the tests at 30 and 50 mph, noting that immediately after the this vehicle the testing order for the 30 and 50 mph tests were reversed for the main sequence of vehicles. For the 3DTAX parSYNC® PLUS, it showed similar trends compared with MAHA, with lower readings than the MAHA for the 50 and 30 mph tests, and a slight upward slope towards the end of the high idle segment, which led to much higher high idle emissions for the parSYNC® PLUS on a ppm/CO_2%. For the NTK, overall, the peaks for the two systems agreed with each other, with the NTK generally showing higher NOx emissions than the MAHA. During the latter stages of the test, where the vehicle was either in an idle, high idle, or during the opacity snap idles, there were typically peaks during the high idle and opacity snaps. Under these conditions, MAHA measured near zero NOx emissions for some parts of the cycle, while the NTK showed readings around 10-30 ppm as a baseline. NOx correlation plots between the MAHA and the NTK and the 3DATX systems are shown in Figure 4-5 and Figure 4-6, respectively. The NTK system showed a good correlation with the MAHA NOx measurements over the vehicles tested with both instruments, with a slope of 1.04 and an R^2 = 0.86. The data set for the 3DATX NOx measurements is considerably smaller. The regression between the 3DATX and MAHA system showed a slope of 1.04 and an R^2 = 0.93, but with a 17.3 ppm/CO_2% y-intercept.

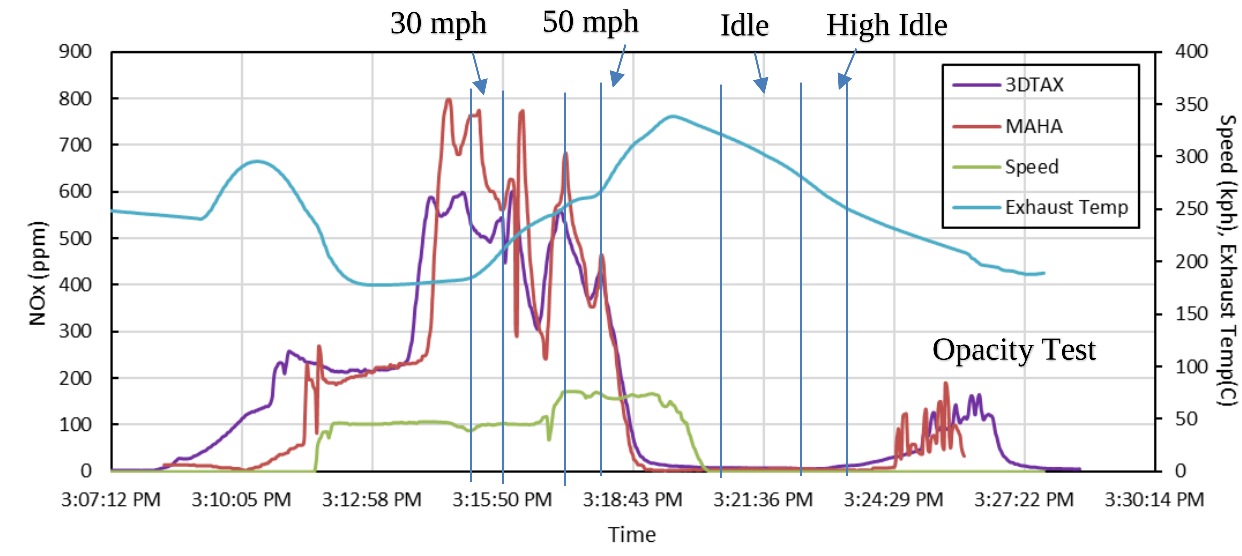


Figure 4-3 Real-time NOx emissions with the 3DTAX ParSync® PLUS vs. MAHA system for a pre-test for J&R01

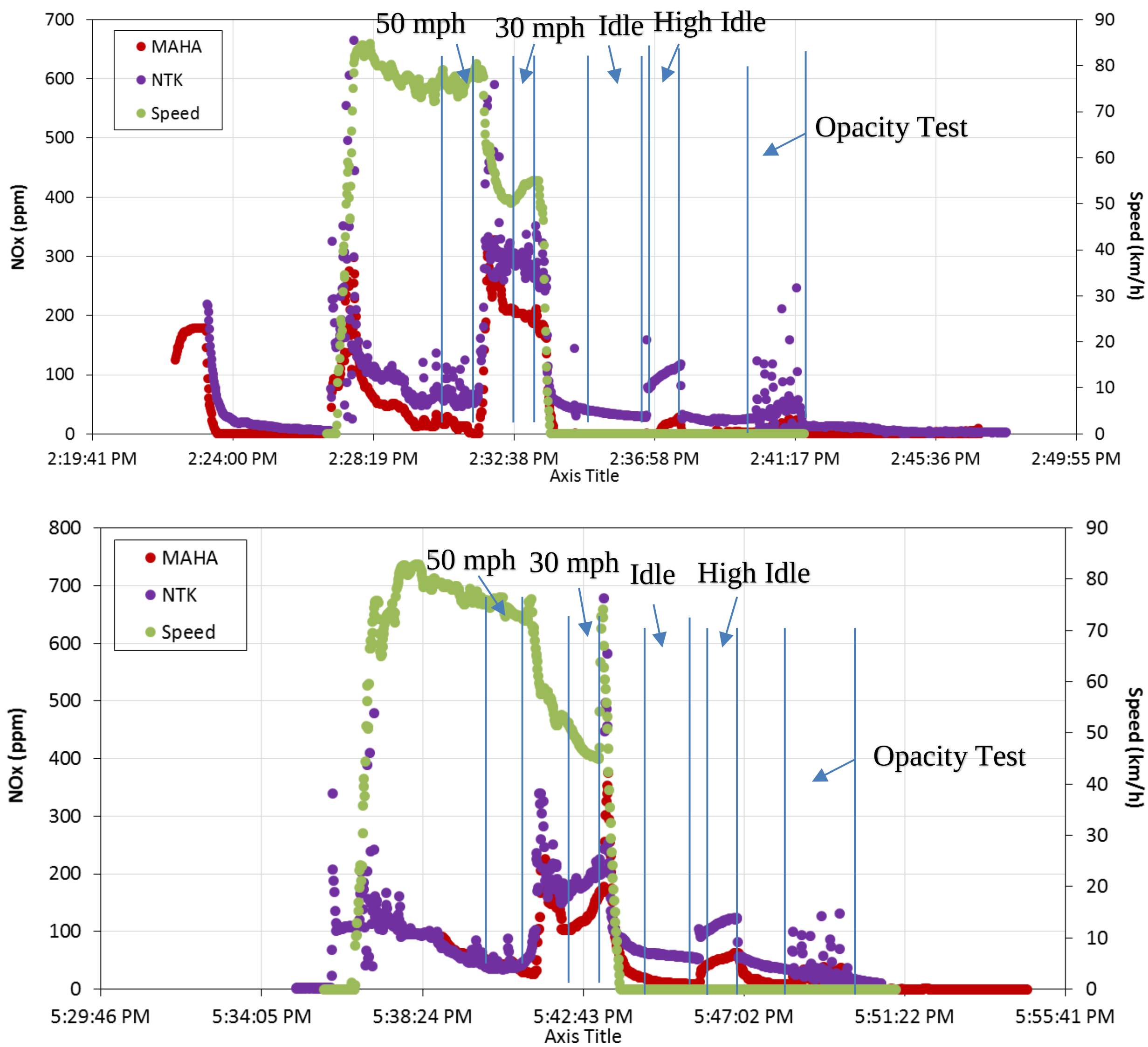


Figure 4-4 Real-time NOx emissions with the MAHA vs. NTK system for a pre-test (top) and post-test (bottom) for J&R25

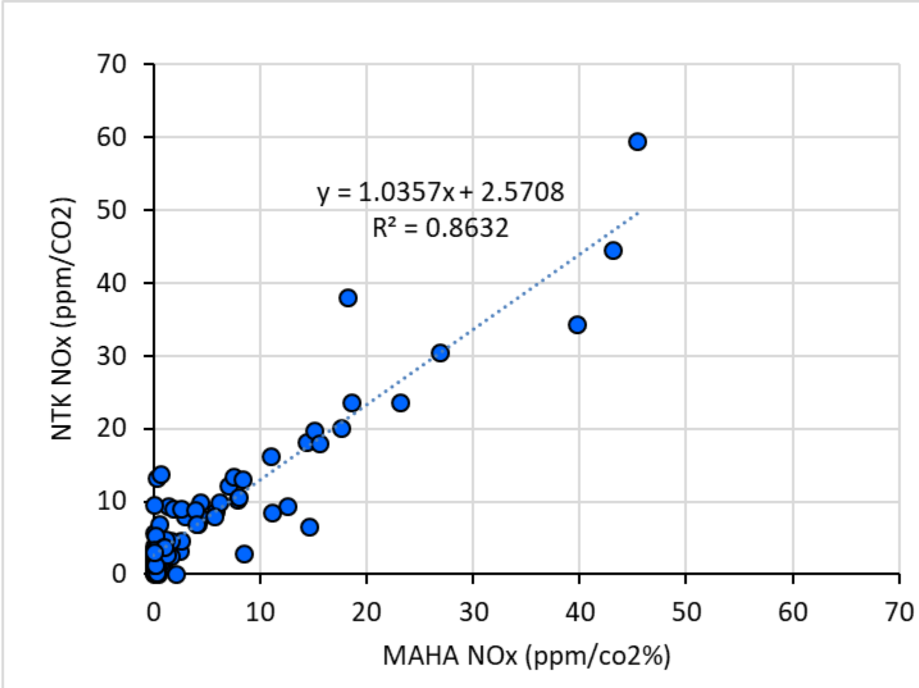


Figure 4-5 Correlation between MAHA and NTK NOx

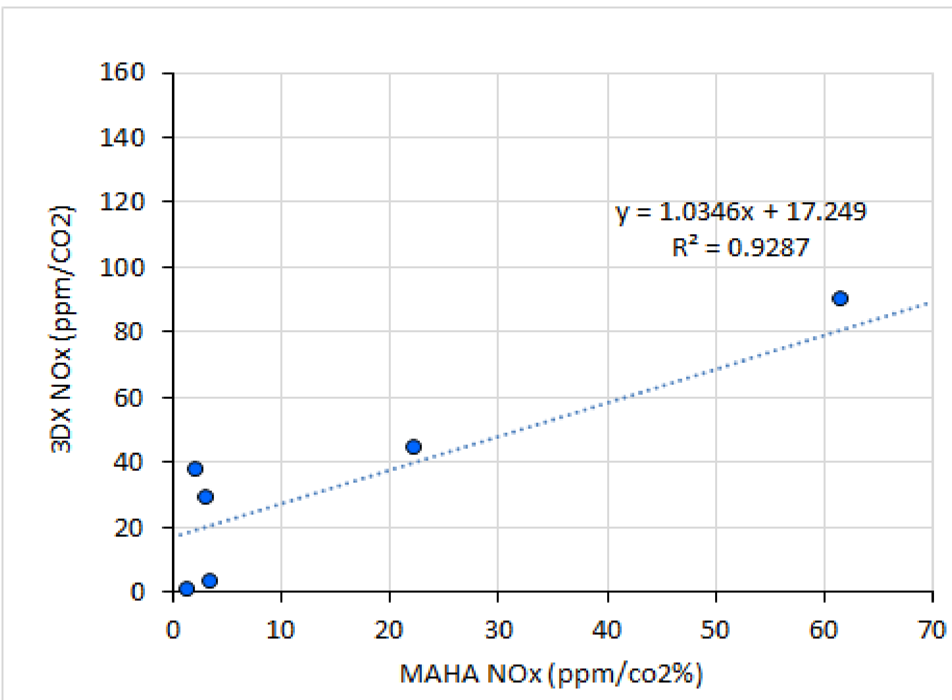


Figure 4-6 Correlation between MAHA and 3DATX NOx

4.1.1.1.4 Comparison of Emissions for Different Manufacturers

Figure 4-7 shows a comparison of pre and post normalized NOx emissions for two of the primary manufacturers (i.e., trucks equipped with Volvo and Cummins engines) represented in the pilot study, which accounted over 80% of total vehicles. The vehicles were divided into two groups depending on their engine model year for each engine manufacturers. There were three outliers for the three Cummins engine-equipped vehicles showed considerably higher NOx emissions than the other vehicles that were over 10 times the 0.2 g/bhp-hr NOx standard. Figure 4-7 shows results both with and without these outliners. The Volvo engines generally showed relatively lower NOx emissions for the idle and high idle mode than the Cummins engines. The NOx emissions rates for the 30 mph driving condition were comparable between the two engine manufacturers, on the other hand, with the exception of the outliers, the Volvo engines showed much higher NOx emissions than the Cummins engines under the 50 mph driving condition, in general, with the exception of the 2010-2012 Cummins engine data that included the outlier vehicles. When comparing the NOx emission rates between the different driving speeds and loads for the Volvo engines, the ones at 50 mph and 200 hp load were much higher than those at the 30 mph and 100 hp condition. This trend can be found for both pre- and post-repair for Volvo engines, which suggests Volvo engines tend to emit high NOx emissions under the high speed (50 mph) and high load (200 hp) conditions.

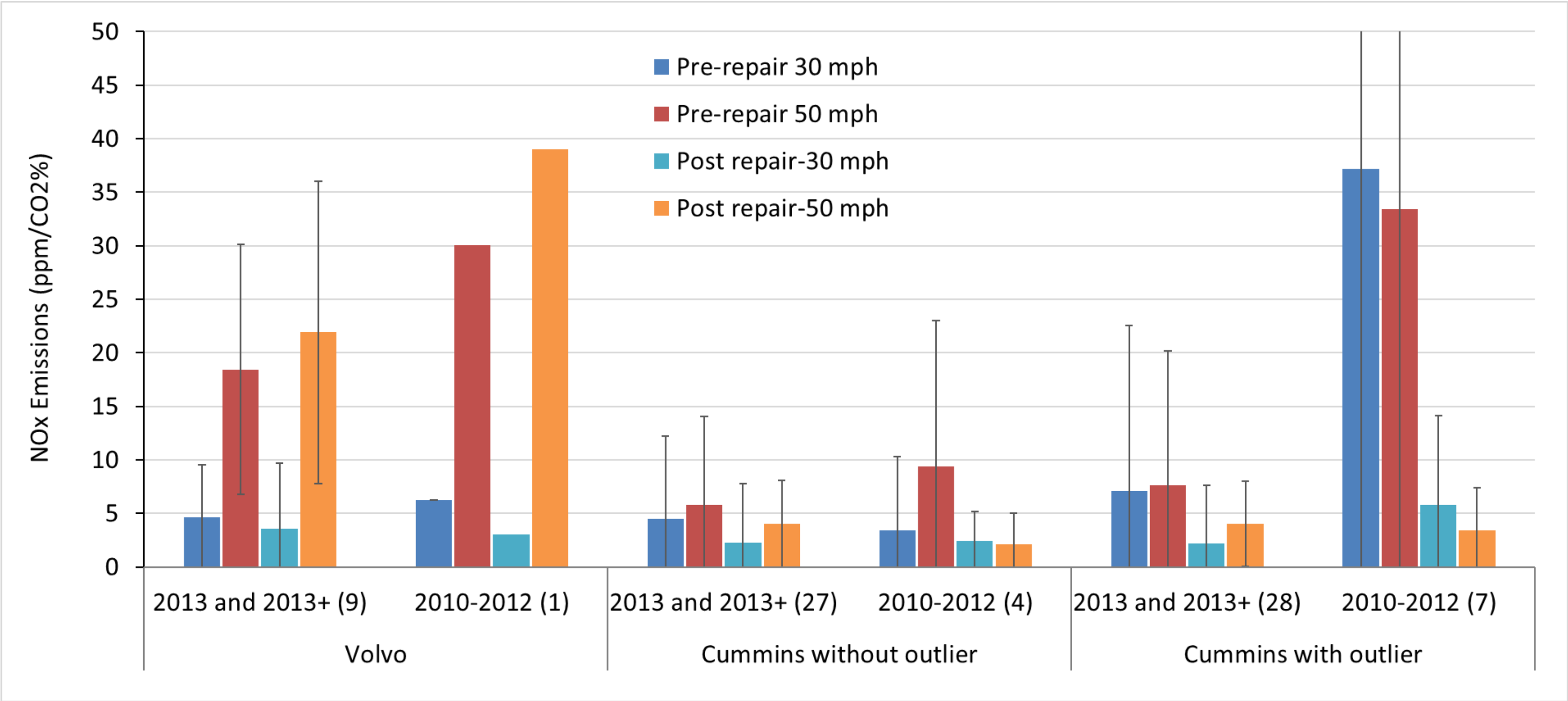


Figure 4-7 Comparisons of normalized NOx emissions between Volvo and Cummins Engines
Note: Only one Manufacturer A vehicle with MY2010-2012

4.1.1.1.5 SCR Efficiency Data

Table 4-4 shows the calculated SCR efficiency based on readings from the inlet and outlet NOx sensors. Figure 4-8 shows the SCR efficiencies at high idle for these vehicles. NOx sensor data were available for only 9 vehicles, because the NOx sensors need to be warmed up several minutes before they start to work, and the warm-up time was sometimes insufficient to get the NOx sensors operating. The calculated SCR efficiencies for the Cummins engines were higher than 84% for vehicles J&R18, 19 second visit, 21, 22 second visit, and 23, between the pre-repair and post-repair tests, which indicated good SCR performance. Three Cummins vehicles had pre-repair SCR efficiencies below 70%, including J&R19 first time with a DEF fluid dosing valve issue, 22 first visit with an exhaust pressure sensor malfunction, and 25 with an engine coolant temperature sensor issue. Having an SCR efficiency below 70% is a condition that can trigger a fault code, but the algorithm to turn the MIL on could also require additional conditions that may not have been met in the pilot study, as none of these vehicles had a fault code for SCR efficiency. The results showed that the repairs of the DEF harness for J&R19_first visit considerably improved the efficiency of the SCR. The exhaust pressure sensor repair for J&R22_first visit improved the SCR efficiency at idle and high idle, but did not provide a significant improvement in the SCR efficiency at 30 mph. There were only three Volvo vehicles that had available NOx sensor data, i.e., J&R36, 44, and 47. NOx emissions for the 50 and 30 mph driving conditions were generally not available for the Volvo vehicles, except for the pre-repair intake NOx sensor data for J&R 44 at 50 mph. The calculated SCR efficiencies for the three Volvos were above 75% for the idle and high idle conditions, suggesting good SCR performance under these conditions. It should be noted that since the SCR efficiencies only include operation when the temperature was high enough to activate the sensor, the overall efficiencies including the periods when the sensors were inactive could be lower.

Table 4-4 Calculated SCR efficiency based on the readings of Inlet and Outlet NOx sensors

Vehicle NO.	Engine Year & Make	Repair performed	Intake NOx sensor								Outtake NOx sensor								Calculated SCR Efficiency							
			Pre-repair NOx Emissions (ppm)				Post-repair NOx Emissions (ppm)				Pre-repair NOx Emissions (ppm)				Post-repair NOx Emissions (ppm				Pre-repair %				Post-repair %			
			30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R18	2014 Cummins	Air filter	672.8	561.2	249.8	207.6	740.0		377.4	206.9	39.7		18.5	1.2	5.1		40.6	10.2	94.1%		92.6%	99.4%	99.3%		89.2%	95.1%
J&R19	2015 Cummins	DEF harness	155.6	368.6	81.8	273.7	348.6	331.8	102.3	299.9	150.3	361.4	81.4	242.1	12.9		4.2	46.3	3.4%	2.0%	0.5%	11.6%	96.3%		95.9%	84.6%
Second visit		DEF harness	348.6	331.8	102.3	299.9	951.1	461.4	131.1	285.2	12.9		4.2	46.3			0.8		96.3%		95.9%	84.6%			99.4%	
J&R21	2013 Cummins	Clean DPF	692.2	567.0	131.8	255.0	912.7	538.3	130.6	262.5	15.0		1.4	0.4					97.8%		98.9%	99.8%				
J&R22	2013 Cummins	Exhaust pressure sensor	961.4	771.8	480.5	236.2	924.1	254.8	137.0	314.5	876.3	663.5	473.2	222.4	702.4		3.5	22.8	8.9%	14.0%	1.5%	5.8%	24.0%		97.4%	92.8%
Second visit		Intake NOx sensor & DEF filter	924.1	254.8	137.0	314.5	915.6	721.2	138.6	361.2			3.5	22.8			1.0	6.6			97.4%	92.8%			99.2%	98.2%
J&R23	2013 Cummins	Clean DPF/Engine Oil Coole	860.4	725.0	124.0	290.0	835.5	685.7	138.9	315.4	73.7		9.3	15.5			1.6	43.4	91.4%		92.5%	94.6%			98.9%	86.2%
J&R25	2013 Cummins	Short w/ coolant temperature sensor, thermostat	602.8	100.7	97.2	257.4	476.3	80.7	91.1	241.2	107.2		31.4	90.0			36.3	80.1	82.2%		67.7%	65.0%			60.2%	66.8%
J&R36	2013 Volvo	Camshaft position sensor			43.9	267.4			234.9	233.0							58.2	13.2							75.2%	94.3%
J&R44	2014 Volvo	DPF Delta Pressure Sensor, clean DPF	214.1		295.9	202.4			269.2	217.1			37.5	9.9			45.6	2.5			87.3%	95.1%			83.0%	98.9%
J&R47	2013 Volvo	Intake NOx sensor			427.3	312.2			56.9	272.2			37.3	5.2							91.3%	98.3%				

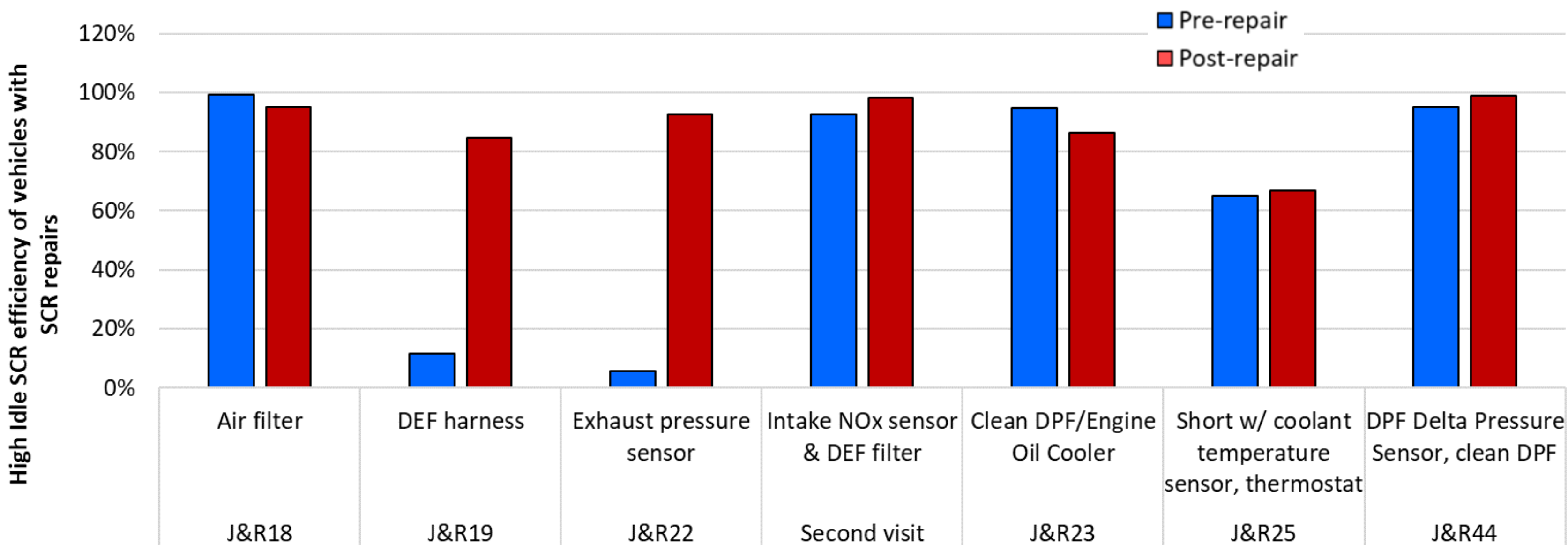


Figure 4-8 High Idle SCR efficiency of vehicles with SCR repairs

4.1.1.1.6 Analysis of Pilot Study NOx Emission Reductions

Determining the emissions reductions of the repairs in a broader sense was an important part of the data analysis of the pilot study. The running exhaust emissions benefit for each vehicle repair was determined in g/bhp-hr units for 30 and 50 mph. Two scenarios were then developed to represent different potential implementation plans for an I/M program. The first scenario included all vehicles that were tested as part of the pilot study that were recruited with the check engine light on indicating a repair or maintenance need in one of the target categories, where the check engine light was subsequently turned off by the repair performed. This essentially included most of the vehicles in the test program. In examining the results for the test vehicles, it was noted that two vehicles were equipped with Navistar engines that did not utilize SCR aftertreatment and that showed significant emissions increases in the post-repair results compared to the pre-repair results. Since the HD I/M emissions inventory estimates are based on time periods of 2025 and beyond, it is estimated that the fraction of Navistar non-SCR engines in the fleet will represent a very small fraction of the fleet. Additionally, the likelihood of having a category of vehicles that will consistently show increases in emissions upon repair is unlikely. As such, it was decided that these two Navistar vehicles should be removed from the sample for the subsequent analyses.

Since the OBD systems for heavy-duty vehicles provide different levels of information on the failure condition of the vehicle, an additional scenario was evaluated that included only those vehicles where the DM1 MIL was on prior to the repair. This indicates that the vehicle was found to have active DTCs indicating an emissions related malfunction in one of the target categories. This provides a stronger indication that a problem that is beyond typical maintenance is occurring with the vehicle that could be impacting emissions. Of the 51 repair sequences tested, a total of 30 had the DM1 MIL on in either the pre-repair OBD scan, or in the data logger information. Of the remaining repair sequences, 18 had the DM1 MIL off, while the DM1 status was not available for an additional 3 vehicles.

The results for the NOx running exhaust emissions repair benefits for the vehicles in the broader categories having their check engine light on provided in Table 4-5. The results for the vehicles that all had the DM1 MIL on in the pre-repair OBD scan are provided in Table 4-6. The results show fleet average NOx emissions reductions of 74% at 30 mph and 47% at 50 mph for the vehicles with a check engine light on before repairs, excluding the Navistar trucks. Additional averages were calculated excluding 3 vehicles where the DM1 MIL was on post-repair, as it is expected that under an I/M program that these vehicles could require further repairs in order to be considered passing. When only the vehicles with the DM1 MIL off post-repair were included, the fleet average NOx emissions reductions are 75% at 30 mph and 46% at 50 mph for the vehicles with a check engine light on before repairs, excluding the Navistar trucks. For the vehicles with DM1 MIL on pre-repair and excluding the Navistar trucks, the fleet average NOx emissions reductions were 81% at 30 mph and 53% at 50 mph. For the vehicles with the DM1 MIL on pre-repair and the DM1 MIL off post-repair and excluding the Navistar trucks, the fleet average NOx emissions reductions were 81% at 30 mph and 53% at 50 mph.

Table 4-5 Running Exhaust NOx Emissions Reductions for Vehicles with Check Engine Light On Pre-Repair

Vehicle No.	Engine Year & Make	50 km/h Pre-repair NOx Emissions (g/bhp-hr)	80 km/h Pre-repair NOx Emissions (g/bhp-hr)	50 km/h Post-repair NOx Emissions (g/bhp-hr)	80 km/h Post-repair NOx Emissions (g/bhp-hr)	DM1 MIL = 1 Pre-repair
J&R01	2011 Cummins	7.24	4.64	1.09	0.13	YES
J&R03*	2013 Cummins	0.07	0.20	0.04	0.16	YES
J&R04	2013 Volvo	0.37	1.46	0.06	0.95	N/A
J&R05	2012 Cummins	0.00	0.00	0.37	0.38	NO
J&R06	2015 Cummins	0.59	0.35	0.06	0.69	NO
J&R07	2014 Volvo	0.75	1.27	0.45	1.18	N/A
J&R09	2012 Cummins	1.13	2.05	0.31	0.15	NO
J&R10	2011 Cummins	0.00	0.03	0.00	0.00	YES
J&R11	2013 Cummins	1.41	0.64	1.25	0.34	YES
J&R12	2011 Volvo	0.33	1.63	0.15	2.12	YES
J&R13	2013 Cummins	0.00	0.00	0.19	0.19	NO
J&R14	2010 DDC	0.70	0.87	0.85	1.25	NO
J&R15	2010 Navistar**	0.54	0.49	2.91	1.15	NO
J&R16	2010 Mack	0.66	0.52	0.07	1.13	NO
J&R17	2011 Cummins	4.02	6.18	0.15	0.64	YES
J&R18	2014 Cummins	0.00	0.25	0.05	0.07	NO
J&R19	2015 Cummins	1.02	1.99	0.03	0.23	YES
J&R19 Second visit		0.03	0.23	0.02	0.19	YES
J&R20	2011 Cummins	0.00	0.01	0.00	0.00	YES
J&R21	2013 Cummins	0.09	0.49	0.01	0.40	NO
J&R22	2013 Cummins	4.13	2.87	0.07	0.24	YES
J&R22 Second visit		0.05	0.19	0.00	0.32	YES
J&R23	2013 Cummins	0.52	1.79	0.00	0.86	YES
J&R25	2013 Cummins	1.27	0.04	0.68	0.19	NO
J&R26	2013 Paccar	0.02	0.04	0.00	0.00	NO
J&R27	2014 Volvo	0.15	1.00	0.00	2.34	YES
J&R28	2013 Cummins	0.02	0.67	0.00	0.00	NO
J&R29	2014 Cummins	0.11	0.02	0.09	0.04	NO
J&R30	2013 Cummins	0.79	0.60	0.00	0.45	YES

Table 4-5 Running Exhaust NOx Emissions Reductions for Vehicles with Check Engine Light On Pre-Repair (continued)

Vehicle No.	Engine Year & Make	50 km/h Pre-repair NOx Emissions (g/bhp-hr)	80 km/h Pre-repair NOx Emissions (g/bhp-hr)	50 km/h Post-repair NOx Emissions (g/bhp-hr)	80 km/h Post-repair NOx Emissions (g/bhp-hr)	DM1 MIL = 1 Pre-repair
J&R31	2013 Cummins	0.22	0.00	0.00	0.09	YES
J&R32	2013 Volvo	0.00	2.16	0.05	1.25	YES
J&R33	2015 Cummins	0.00	0.00	0.00	0.00	NO
J&R34	2015 Volvo	0.00	0.00	0.00	0.20	YES
J&R35	2014 Volvo	0.06	0.77	0.00	0.40	YES
J&R36	2013 Volvo	0.60	0.96	0.10	0.85	YES
J&R37	2016 DDC	0.02	3.72	0.00	0.00	YES
J&R38	2013 Cummins	0.02	0.00	0.13	0.06	NO
J&R39	2013 Cummins	0.00	0.01	0.00	0.26	YES
J&R40	2013 Cummins	0.02	0.00	0.00	0.00	YES
J&R40 Second visit		0.00	0.00	0.00	0.20	NO
J&R40 Third visit		0.00	0.20	0.00	0.00	YES
J&R41*	2014 Paccar	0.00	0.37	0.02	0.07	YES
J&R42	2013 Cummins	0.00	0.38	0.02	0.05	YES
J&R43	2014 Cummins	0.00	0.00	0.00	0.00	YES
J&R44	2014 Volvo	0.13	1.06	0.05	0.91	YES
J&R45	2013 Cummins	0.01	0.10	0.00	0.00	NO
J&R46	2013 Cummins	0.00	0.00	0.00	0.44	YES
J&R47	2013 Volvo	0.13	0.30	0.89	2.27	YES
J&R48*	2013 Navistar**	2.07	2.24	5.93	5.09	YES
Cum01	2015 Cummins	0.41	0.27	0.40	0.26	NO
Cum02	2010 Cummins	3.65	1.87	0.17	0.21	N/A
Simple Average		*0.65*	*0.88*	*0.33*	*0.56*	
Benefit				*50%*	*37%*	
Simple Average (Exclude Navistar)		*0.63*	*0.86*	*0.16*	*0.45*	
Benefit				*74%*	*47%*	
Simple Average (exclude Navistar and DM1=1 post-		*0.65*	*0.87*	*0.17*	*0.46*	
Benefit				*75%*	*47%*	

"**" denoted Navistar engines not equipped with SCR. "*" denoted vehicles where DM1 was on post-repair.

Table 4-6 Running Exhaust NOx Emissions Reductions for Vehicles with DM1 MIL On Pre-Repair

Vehicle No.	Engine Year & Make	50 km/h Pre-repair NOx Emissions (g/bhp-hr)	80 km/h Pre-repair NOx Emissions (g/bhp-hr)	50 km/h Post-repair NOx Emissions (g/bhp-hr)	80 km/h Post-repair NOx Emissions (g/bhp-hr)	DM1=1
J&R01	2011 Cummins	7.24	4.64	1.09	0.13	YES
J&R03*	2013 Cummins	0.07	0.20	0.04	0.16	YES
J&R10	2011 Cummins	0.00	0.03	0.00	0.00	YES
J&R11	2013 Cummins	1.41	0.64	1.25	0.34	YES
J&R12	2011 Volvo	0.33	1.63	0.15	2.12	YES
J&R17	2011 Cummins	4.02	6.18	0.15	0.64	YES
J&R19	2015 Cummins	1.02	1.99	0.03	0.23	YES
J&R19 Second visit		0.03	0.23	0.02	0.19	YES
J&R20	2011 Cummins	0.00	0.01	0.00	0.00	YES
J&R22	2013 Cummins	4.13	2.87	0.07	0.24	YES
J&R22 Second visit		0.05	0.19	0.00	0.32	YES
J&R23	2013 Cummins	0.52	1.79	0.00	0.86	YES
J&R27	2014 Volvo	0.15	1.00	0.00	2.34	YES
J&R30	2013 Cummins	0.79	0.60	0.00	0.45	YES
J&R31	2013 Cummins	0.22	0.00	0.00	0.09	YES
J&R32	2013 Volvo	0.00	2.16	0.05	1.25	YES
J&R34	2015 Volvo	0.00	0.00	0.00	0.20	YES
J&R35	2014 Volvo	0.06	0.77	0.00	0.40	YES
J&R36	2013 Volvo	0.60	0.96	0.10	0.85	YES
J&R37	2016 DDC	0.02	3.72	0.00	0.00	YES
J&R39	2013 Cummins	0.00	0.01	0.00	0.26	YES
J&R40	2013 Cummins	0.02	0.00	0.00	0.00	YES
J&R40 Third visit		0.00	0.20	0.00	0.00	YES
J&R41*	2014 Paccar	0.00	0.37	0.02	0.07	YES
J&R42	2013 Cummins	0.00	0.38	0.02	0.05	YES
J&R43	2014 Cummins	0.00	0.00	0.00	0.00	YES
J&R44	2014 Volvo	0.13	1.06	0.05	0.91	YES
J&R46	2013 Cummins	0.00	0.00	0.00	0.44	YES
J&R47	2013 Volvo	0.13	0.30	0.89	2.27	YES
J&R48*	2013 Navistar**	2.07	2.24	5.93	5.09	YES
Simple Average		*0.77*	*1.14*	*0.33*	*0.66*	
Benefit				*57%*	*42%*	
Simple Average (Exclude Navistar)		*0.72*	*1.10*	*0.14*	*0.51*	
Benefit				*81%*	*54%*	
Simple Average (exclude DM1 MIL =1 post-repair)		*0.77*	*1.16*	*0.14*	*0.54*	
Benefit				*81%*	*54%*	

"**" denoted Navistar engines not equipped with SCR. "*" denoted vehicles where DM1 was on post-repair.

Similar calculations were also performed for the idle emissions, as this is another category in the emissions inventory modeling. Note that idle emissions were used, as opposed to high idle, because only standard idle emissions are represented in the EMFAC model. The two scenarios were the same as for the running exhaust emissions, including a scenario for all vehicles that were recruited with the check engine light on, and a scenario for only those vehicles where the DM1 MIL was on pre-repair. Separate averages were also calculated excluding the non-SCR Navistar trucks and for vehicles that had the DM1 MIL off post-repair.

The results for the idle emissions repair benefits for the vehicles in the broader categories having their check engine light on provided in Table 4-7 and for the vehicles that all had the DM1 MIL on in the pre-repair OBD scan are provided in Table 4-8. The results show fleet average idle emissions reductions of 50% for NOx for the vehicles with a check engine light on before repairs and where the DM1 MIL was off post-repair, excluding the Navistar trucks. The results show fleet average idle emissions reductions of 50% for NOx. For the vehicles with a check engine light on before repairs and where the DM1 MIL was off post-repair, excluding the Navistar trucks, the fleet average idle emissions reductions were 74% for NOx. For the vehicles with DM1 MIL on pre-repair and DM1 MIL off post-repair and excluding the Navistar trucks, the fleet average idle emissions reductions were 75% for NOx.

Table 4-7 Idle NOx Emissions Reductions for Vehicles with Check Engine Light On Pre-Repair

Vehicle No.	Engine Year & Make	Idle Pre-repair NOx Emissions (g/h)	Idle Post-repair NOx Emissions (g/h)	DM1 MIL = 1 Pre-repair
J&R01	2011 Cummins	7.93	0.00	YES
J&R03*	2013 Cummins	0.01	0.14	YES
J&R04	2013 Volvo	29.27	2.44	N/A
J&R05	2012 Cummins	2.65	1.42	NO
J&R06	2015 Cummins	1.44	1.67	NO
J&R07	2014 Volvo	0.32	0.00	N/A
J&R09	2012 Cummins	6.29	0.90	NO
J&R10	2011 Cummins	2.43	1.95	YES
J&R11	2013 Cummins	19.96	1.94	YES
J&R12	2011 Volvo	0.00	0.32	YES
J&R13	2013 Cummins	42.22	15.53	NO
J&R14	2010 DDC	0.00	1.39	NO
J&R15	2010 Navistar**	0.00	1.39	NO
J&R16	2010 Mack	0.03	2.82	NO
J&R17	2011 Cummins	2.69	19.13	YES
J&R18	2014 Cummins	1.48	2.10	NO
J&R19	2015 Cummins	36.86	2.60	YES
J&R19 Second visit		0.00	1.76	YES
J&R20	2011 Cummins	16.18	1.18	YES
J&R21	2013 Cummins	1.18	0.35	NO
J&R22	2013 Cummins	0.00	0.00	YES
J&R22 Second visit		0.88	0.01	YES
J&R23	2013 Cummins	108.86	0.09	YES
J&R25	2013 Cummins	0.10	0.00	NO
J&R26	2013 Paccar	1.93	0.00	NO
J&R27	2014 Volvo	0.00	4.41	YES
J&R28	2013 Cummins	0.49	0.00	NO
J&R29	2014 Cummins	1.44	1.44	NO
J&R30	2013 Cummins	1.92	1.44	YES

Table 4-7 Idle NOx Emissions Reductions for Vehicles with Check Engine Light On Pre-Repair (continued)

Vehicle No.	Engine Year & Make	Idle Pre-repair NOx Emissions (g/h)	Idle Post-repair NOx Emissions (g/h)	DM1 MIL = 1 Pre-repair
J&R31	2013 Cummins	0.76	0.00	YES
J&R32	2013 Volvo	1.62	1.44	YES
J&R33	2015 Cummins	0.01	0.00	NO
J&R34	2015 Volvo	1.44	1.50	YES
J&R35	2014 Volvo	1.44	1.44	YES
J&R36	2013 Volvo	1.50	1.46	YES
J&R37	2016 DDC	1.44	1.45	YES
J&R38	2013 Cummins	1.44	1.44	NO
J&R39	2013 Cummins	1.60	1.49	YES
J&R40	2013 Cummins	1.50	3.21	YES
J&R40 Second visit		0.00	0.00	NO
J&R40 Third visit		1.46	1.45	YES
J&R41*	2014 Paccar	1.45	1.44	YES
J&R42	2013 Cummins	1.44	1.47	YES
J&R43	2014 Cummins	1.52	1.44	YES
J&R44	2014 Volvo	0.00	0.07	YES
J&R45	2013 Cummins	1.64	0.00	NO
J&R46	2013 Cummins	2.22	1.45	YES
J&R47	2013 Volvo	0.56	1.44	YES
J&R48*	2013 Navistar**	1.63	0.09	YES
Cum01	2015 Cummins	2.17	2.40	NO
Cum02	2010 Cummins	16.31	75.98	N/A
Simple Average		*6.46*	*3.28*	
Benefit			*49%*	
Simple Average (Exclude Navistar)		*6.70*	*3.38*	
Benefit			*50%*	
Simple Average (exclude Navistar and DM1=1 post-repair)		*6.95*	*3.49*	
Benefit			*50%*	
Repair Effectiveness factor (post-repair /pre-repair)				

"**" denoted Navistar engines not equipped with SCR. "*" denoted vehicles where DM1 was on post-repair.

Table 4-8 Idle NOx Emissions Reductions for Vehicles with DM1 MIL On Pre-Repair

Vehicle No.	Engine Year & Make	Idle Pre-repair NOx Emissions (g/h)	Idle Post-repair NOx Emissions (g/h)	DM1=1
J&R01	2011 Cummins	7.93	0.00	YES
J&R03*	2013 Cummins	0.01	0.14	
J&R10	2011 Cummins	2.43	1.95	YES
J&R11	2013 Cummins	19.96	1.94	YES
J&R12	2011 Volvo	0.00	0.32	YES
J&R17	2011 Cummins	2.69	19.13	YES
J&R19	2015 Cummins	36.86	2.60	YES
J&R19 Second visit		0.00	1.76	YES
J&R20	2011 Cummins	16.18	1.18	YES
J&R22	2013 Cummins	0.00	0.00	YES
J&R22 Second visit		0.88	0.01	YES
J&R23	2013 Cummins	108.86	0.09	YES
J&R27	2014 Volvo	0.00	4.41	YES
J&R30	2013 Cummins	1.92	1.44	YES
J&R31	2013 Cummins	0.76	0.00	YES
J&R32	2013 Volvo	1.62	1.44	YES
J&R34	2015 Volvo	1.44	1.50	YES
J&R35	2014 Volvo	1.44	1.44	YES
J&R36	2013 Volvo	1.50	1.46	YES
J&R37	2016 DDC	1.44	1.45	YES
J&R39	2013 Cummins	1.60	1.49	YES
J&R40	2013 Cummins	1.50	3.21	YES
J&R40 Third visit		1.46	1.45	YES
J&R41*	2014 Paccar	1.45	1.44	YES
J&R42	2013 Cummins	1.44	1.47	YES
J&R43	2014 Cummins	1.52	1.44	YES
J&R44	2014 Volvo	0.00	0.07	YES
J&R46	2013 Cummins	2.22	1.45	YES
J&R47	2013 Volvo	0.56	1.44	YES
J&R48*	2013 Navistar**	16.31	75.98	YES
Simple Average		*7.80*	*4.39*	
Benefit			*44%*	
Simple Average (Exclude Navistar)		*7.51*	*1.92*	
Benefit			*74%*	
Simple Average (exclude Navistar and DM1=1 post-repair)		*8.01*	*2.01*	
Benefit			*75%*	

"**" denoted Navistar engines not equipped with SCR. "*" denoted vehicles where DM1 was on post-repair.

4.1.1.2 Chassis Dynamometer PM Results

4.1.1.2.1 PM Results Overview

Pre- and Post-repair PM emissions were measured with a variety of instruments. This included an opacity meter, as discussed in section 3.2.4.1 and several mini-PEMS systems, as discussed in 3.2.4.5, including the Pegasor for measuring solid PM mass, and TSI NPET and Testo for PN emissions. It should be noted that, as discussed in section 3.2.3.1, the MAHA MPM4 did not show measureable PM emissions above the baseline level for the majority of vehicles, so the results are not included in this discussion. This subsection provides an overview of the PM results from the pilot study, which are discussed in greater detail below.

The pre-repair opacity values were 5% or less for all but 8 vehicles. Of the 8 vehicles with pre-repair opacity readings that were above 5%, 6 vehicles showed reductions in opacity to below the 5% level for the post-repair tests. Overall, the solid PN and other PM instruments showed greater sensitivity in measuring at such low PM levels than the MAHA MPM4.

Although a DPF was replaced on one vehicle, the other vehicles did not appear to have catastrophic DPF failures. It was also difficult to quantify PM repair benefits because the DPF is often still capable of physically capturing excess PM even if a PM-related repair failure is present. The impact of repairs on soot loading and regeneration frequency and improved maintenance in preventing more catastrophic failures was also not evaluated. It is suggested that further studies be conducted to better understand potential PM repair benefits for 2010+ vehicle technologies.

In comparing between the different instruments that were used for the measurement of PM and PN, the results were more complicated than for the NOx instrument comparisons. In particular, the opacity, PM mass, and PN measurements generally did not show a strong correlation for measurements on different test vehicles. This is likely due in part to the low PM levels that were found for the test vehicles and the small sample size. The opacity measurements were also done under snap accelerations, whereas the other instruments measured under steady state or idle conditions. Also, the fact that the PM instruments measure different characteristics of PM (mass vs. number), different properties (total vs. solid PM), and different particle size ranges, can influence comparisons between instruments. Most of the PM instruments were generally light weight, easy to use, and had short warmup times. It is suggested that a more systematic study may be needed to better understand the types of instruments that would be most appropriate for identifying PM failures for DPF-equipped vehicles, although other studies have suggested that PN may be the best metric for this application.

4.1.1.2.2 Opacity Results

In evaluating PM emission results, it is useful to first examine opacity emissions to provide a context for evaluating the other measurement methods/instruments. The pre- and post-opacity measurements for all of the vehicles are shown in Table 4-9 for all vehicles with the check engine light pre-repair and in Table 4-10 for the vehicles that also had the DM1 MIL on pre-repair. The pre- and post-repair emissions for the ten highest emitters are shown in Figure 4-9, along with the associated repairs. Note that JR48 is excluded from Figure 4-9, because the DM1 MIL was on for the post-repair test, indicating the repair was not completed.

The pre-repair opacity readings were 5% or less for all vehicles, except for the J&R01, 10, 13, 15, 17, 19, 25, and 48. For most vehicles, the post-repair repair opacity readings were either comparable to or lower than pre-repair values. Of the vehicles with pre-repair opacity readings that were above 5%, 7 of the 9 cases showed reductions in opacity to below the 5% level for the post-repair tests. This included J&R17, 19 second visit, 01, 15, 25, 13, and 10, which had repairs for injector doser, DEF harness, DPF replacement, injector doser assembly, thermostat, intake NOx sensor, and outlet NOx sensor, respectively. Interestingly, the opacity readings for J&R19 increased after the first repair of the DEF harness, but this vehicle returned to the repair facility five days later suggesting the repair was not fully completed. The opacity reading dropped to 2% after the initial DEF harness repair was corrected during a second visit. Utilizing the same classifications as used in section 4.1.1.1.6, it was found that opacity was reduced by 43% comparing the pre-repair and post-repair tests for the pilot study fleet for both all vehicles with the check engine light on pre-repair and for vehicles that also had the DM1 MIL on pre-repair, excluding the Navistar trucks and the vehicles where the DM1 MIL was on for the post-repair test.

It is also worth evaluating the pilot study fleet compared to opacity measurements collected in roadside studies by CARB. Roadside opacity measurements have indicated that the fraction of 2010 and newer engines with opacity readings above the 5% and 10% opacity limits is approximately 2-3% and 0-1%, respectively, as shown in Table 4-11. Roadside opacity measurements have also indicated that approximately 4 to 6% of 2010+ vehicles with 500,000 or less miles have opacity readings ≥3%. While the fraction of vehicles with opacity measurements higher than 5% is greater in the pilot study (8 of 47 vehicles = 18%) than in the in-use fleet, this does not necessarily indicate that the pilot study fleet is representative of the full range of high opacity level vehicles in the in-use fleet. In particular, high PM emitters were not necessarily a target in the recruitment, and also the main focus of the recruitment was on relatively newer vehicles that were 2013 and newer.

Table 4-9 Pre- and post-repair for opacity for Vehicles with Check Engine Light On Pre-Repair

Vehicle No.	Engine Year & Make	Pre_repair Opacity	Post-repair Opacity	DM1 MIL = 1 Pre-repair
J&R01	2011 Cummins	11.30	4.54	YES
J&R03*	2013 Cummins	0.85	2.10	YES
J&R04	2013 Volvo	0.00	0.76	N/A
J&R05	2012 Cummins	4.40	0.00	NO
J&R06	2015 Cummins	0.00	2.33	NO
J&R07	2014 Volvo	2.69	0.00	N/A
J&R09	2012 Cummins	4.81	2.46	NO
J&R10	2011 Cummins	5.30	1.29	YES
J&R11	2013 Cummins	0.00	0.00	YES
J&R12	2011 Volvo	0.70	0.24	YES
J&R13	2013 Cummins	5.74	0.00	NO
J&R14	2010 DDC	4.18	4.45	NO
J&R15	2010 Navistar**	9.69	0.00	NO
J&R16	2010 Mack	0.00	0.00	NO
J&R17	2011 Cummins	12.30	0.00	YES
J&R18	2014 Cummins	0.00	1.03	NO
J&R19	2015 Cummins	7.53	12.10	YES
J&R19 Second visit		12.10	1.81	YES
J&R20	2011 Cummins	0.00	0.00	YES
J&R21	2013 Cummins	3.15	2.29	NO
J&R22	2013 Cummins	0.76	3.69	YES
J&R22 Second visit		3.69	4.52	YES
J&R23	2013 Cummins	3.33	6.38	YES
J&R25	2013 Cummins	6.40	0.00	NO
J&R26	2013 Paccar	3.84	6.05	NO
J&R27	2014 Volvo	0.00	0.74	YES
J&R28	2013 Cummins	0.00	3.96	NO
J&R29	2014 Cummins	0.00	0.00	NO
J&R30	2013 Cummins	0.00	0.00	YES

Table 4-9 Pre- and post-repair for opacity for Vehicles with Check Engine Light On Pre-Repair (continued)

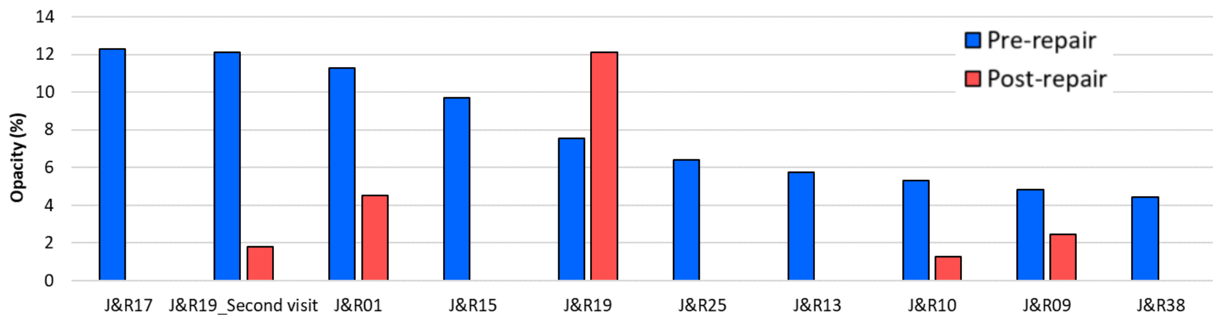
Vehicle No.	Engine Year & Make	Pre_repair Opacity	Post-repair Opacity	DM1 MIL = 1 Pre-repair
J&R31	2013 Cummins	0.00	0.00	YES
J&R32	2013 Volvo	0.00	0.00	YES
J&R33	2015 Cummins	2.15	0.00	NO
J&R34	2015 Volvo	1.59	2.53	YES
J&R35	2014 Volvo	0.55	0.00	YES
J&R36	2013 Volvo	4.16	0.00	YES
J&R37	2016 DDC	2.18	0.00	YES
J&R38	2013 Cummins	4.45	2.02	NO
J&R39	2013 Cummins	0.00	0.00	YES
J&R40	2013 Cummins	3.03	1.46	YES
J&R40 Second visit		1.46	0.00	NO
J&R40 Third visit		0.00	0.00	YES
J&R41*	2014 Paccar	0.00	3.73	YES
J&R43	2014 Cummins	0.00	0.00	YES
J&R44	2014 Volvo	0.00	0.00	YES
J&R45	2013 Cummins	1.54	1.49	NO
J&R46	2013 Cummins	0.00	0.00	YES
J&R47	2013 Volvo	0.00	0.00	YES
J&R48*	2013 Navistar**	6.96	9.21	YES
Cum01	2015 Cummins	1.00	0.90	NO
Cum02	2010 Cummins	1.20	1.60	N/A
Simple Average		*2.66*	*1.67*	
Benefit			*37%*	
Simple Average (Exclude Navistar)		*2.42*	*1.55*	
Benefit			*36%*	
Simple Average (exclude Navistar and DM1=1 post-repair)		*2.60*	*1.49*	
Benefit			*43%*	

"**" denoted Navistar engines not equipped with SCR. "*" denoted vehicles where DM1 was on post-repair.

Table 4-10 Pre- and post-repair for opacity for Vehicles with DM1 On Pre-Repair

Vehicle No.	Engine Year & Make	Pre_repair Opacity	Post-repair Opacity	DM1 MIL = 1 Pre-repair
J&R01	2011 Cummins	11.30	4.54	YES
J&R03*	2013 Cummins	0.85	2.10	YES
J&R10	2011 Cummins	5.30	1.29	YES
J&R11	2013 Cummins	0.00	0.00	YES
J&R12	2011 Volvo	0.70	0.24	YES
J&R17	2011 Cummins	12.30	0.00	YES
J&R19	2015 Cummins	7.53	12.10	YES
J&R19 Second visit		12.10	1.81	YES
J&R20	2011 Cummins	0.00	0.00	YES
J&R22	2013 Cummins	0.76	3.69	YES
J&R22 Second visit		3.69	4.52	YES
J&R23	2013 Cummins	3.33	6.38	YES
J&R27	2014 Volvo	0.00	0.74	YES
J&R30	2013 Cummins	0.00	0.00	YES
J&R31	2013 Cummins	0.00	0.00	YES
J&R32	2013 Volvo	0.00	0.00	YES
J&R34	2015 Volvo	1.59	2.53	YES
J&R35	2014 Volvo	0.55	0.00	YES
J&R36	2013 Volvo	4.16	0.00	YES
J&R37	2016 DDC	2.18	0.00	YES
J&R39	2013 Cummins	0.00	0.00	YES
J&R40	2013 Cummins	3.03	1.46	YES
J&R40 Third visit		0.00	0.00	YES
J&R41*	2014 Paccar	0.00	3.73	YES
J&R43	2014 Cummins	0.00	0.00	YES
J&R44	2014 Volvo	0.00	0.00	YES
J&R46	2013 Cummins	0.00	0.00	YES
J&R47	2013 Volvo	0.00	0.00	YES
J&R48*	2013 Navistar**	6.96	9.21	YES
Simple Average		*2.63*	*1.87*	
Benefit			*29%*	
Simple Average (Exclude Navistar)		*2.48*	*1.61*	
Benefit			*35%*	
Simple Average (exclude Navistar and DM1=1 post-		*2.64*	*1.51*	
Benefit			*43%*	

"**" denoted Navistar engines not equipped with SCR. "*" denoted vehicles where DM1 was on post-repair.



Vehicle NO	Repair	Vehicle NO	Repair
J&R17	Injector doser, Intake NOx sensor, clean DPF	J&R25	Short w/ coolant temperature sensor, thermostat
J&R19_Second visit	DEF harness	J&R13	Intake NOx sensor & engine harness
J&R01	Replaced DPF and injector doser, clean DPF	J&R10	Outlet NOx sensor
J&R15	Injector doser assembly, clean DPF	J&R09	Clean DPF
J&R19	DEF harness	J&R38	update ECM

Figure 4-9 Ten Highest Pre-Repair Opacity Emissions and Their Associated Repairs

Table 4-11 Fraction of 2010+ MY Engines with Opacity Values above different levels

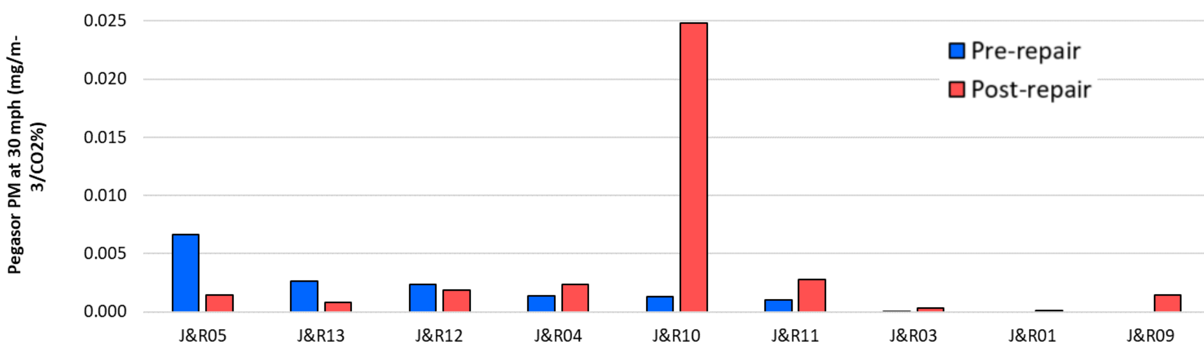
OEM DPF/SCR (2010+ MY Engines)			
Opacity Level	2011 Campaign	2014 Campaign	2016 Campaign
10% Opacity	0% Above	1% Above	1% Above
8% Opacity	1% Above	1% Above	2% Above
5% Opacity	2% Above	2% Above	3% Above
Sample Count	179	346	374

4.1.1.2.3 Mini-PEMS PM and PN Results

The PM mass emission results for the Pegasor are presented in Table 4-12 in units of $mg/m^{-3}/CO_2\%$. The Pegasor was only available for J&R01 to J&R12 and Cum01. The pre- and post-repair Pegasor PM mass emissions for the five highest emitting vehicles at 30 and 50 mph are shown in Figure 4-10 and Figure 4-11, respectively, along with their associated repairs. The highest values were generally seen for either the idle or high idle conditions, as the results were normalized by CO_2. The Pegasor showed the highest pre-repair emissions for J&R03, 05 and 09 over the 50 mph test. Post-repair PM reductions were seen for each of these vehicles/conditions, ranging from 71 to 94%, except for J&R05 at 30 mph. J&R12 and 13 also showed reductions in post-repair PM emissions for some test points.

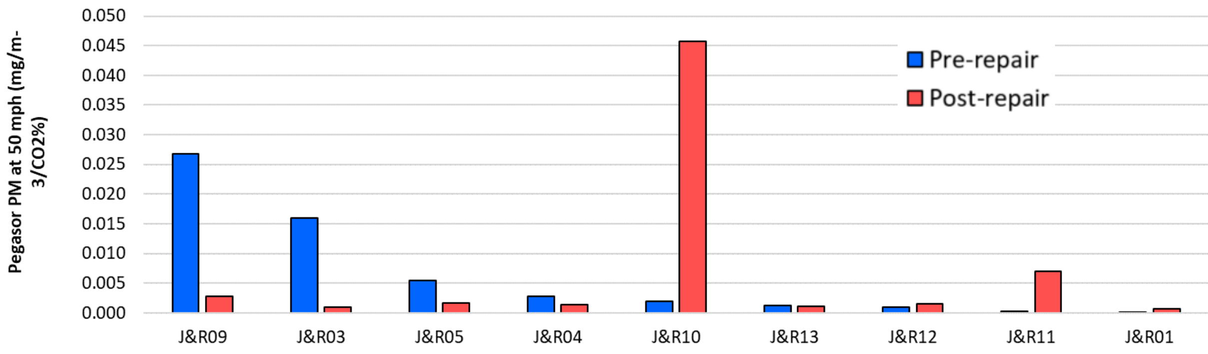
Table 4-12 Pre- and post-repair for solid PM from Pegasor normalized by CO_2 for each vehicle

Vehicle NO.	Pre-repair PM Emissions (mg/m-3/CO2%)				Post-repair PM Emissions (mg/m-3/CO2%)				% difference			
	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R01	0.0000	0.0002	0.0022		0.0001	0.0007	0.0002		n/a	318%	-93%	
Cum01	n/a	n/a	n/a		n/a	n/a	n/a					
J&R03	0.0000	0.0160	0.0000		0.0004	0.0009	0.0000		1567%	-94%	n/a	
J&R04	0.0014	0.0027	0.0010		0.0024	0.0014	0.0014		71%	-47%	43%	
J&R05	0.0066	0.0055	0.0019		0.0015	0.0016	0.0001		-78%	-71%	-95%	
J&R06	n/a	n/a	n/a		n/a	n/a	n/a					
J&R07	n/a	n/a	n/a		n/a	n/a	n/a					
J&R09	0.0000	0.0268	0.0000	0.0000	0.0015	0.0028	0.0006	0.0014	n/a	-90%	n/a	n/a
J&R10	0.0013	0.0020	0.0016	0.0018	0.0248	0.0457	0.0046	0.0347	1841%	2243%	177%	1873%
J&R11	0.0010	0.0003	0.0000	0.0000	0.0028	0.0069	0.0035	0.0029	172%	2140%	n/a	n/a
J&R12	0.0024	0.0010	0.0013	0.0029	0.0018	0.0014	0.0010	0.0008	-23%	45%	-25%	-73%
J&R13	0.0026	0.0012	0.0007	0.0041	0.0008	0.0011	0.0010	0.0009	-68%	-13%	46%	-78%



Vehicle NO	Repair	Vehicle NO	Repair
J&R05	Burned DEF system relays, DEF filter	J&R11	Injector Doser, outlet NOx sensor, DPF cleaning
J&R13	Intake NOx Sensor, Engine Harness	J&R03	SCR temperature sensor connectors
J&R12	DEF lines at dosing valve, manual regen	J&R01	DPF, injector doser, DPF cleaning
J&R04	EGR Temperature sensor	J&R09	Clean DPF
J&R10	Outlet NOx sensor		

Figure 4-10 Top 10 solid PM emitters on a mg/m^{-3}/CO_2% basis at 30 mph based on Pegasor measurements and their Associated Repairs.



Vehicle NO	Repair	Vehicle NO	Repair
J&R09	Clean DPF	J&R13	Intake NOx Sensor, Engine Harness
J&R03	SCR temperature sensor connectors	J&R12	DEF lines at dosing valve, manual regen
J&R05	Burned DEF system relays, DEF filter	J&R11	Injector Doser, outlet NOx sensor, DPF cleaning
J&R04	EGR Temperature sensor		
J&R10	Outlet NOx sensor		

Figure 4-11 Top 10 solid PM emitters based on a mg/m^{-3}/CO_2% basis at 50 mph on Pegasor measurements and their Associated Repairs.

Note: n/a - Not available - in % difference column n/a was utilized for cases were the pre-repair PM emissions were essentially not measureable (i.e., 0 mg/m^3 or negative value)

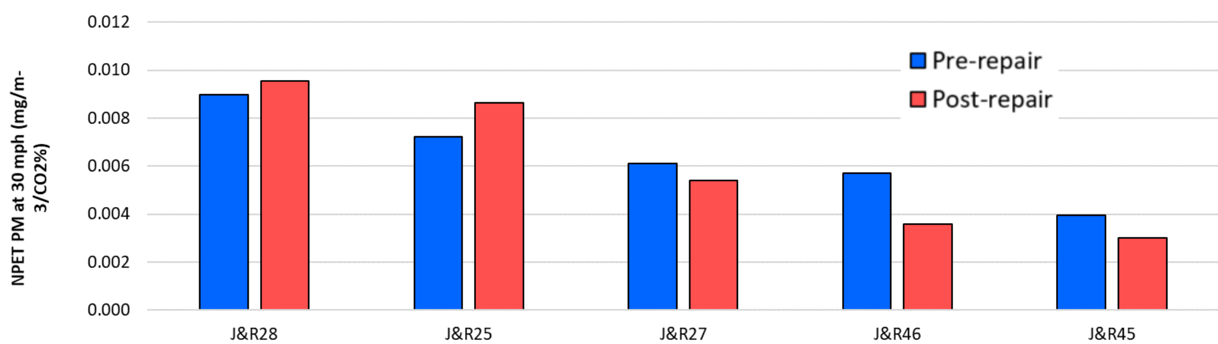
The PN mass emission results for the TSI NPET and Testo are presented in Table 4-13 and Table 4-14, respectively, in units of #/cm^{-3}/CO_2%. For the TSI NPET values ranged from 9.2×10^0 to 5.1×10^6 over the different vehicles and test conditions, while for the Testo values ranged from approximately 1.2×10^2 to 2.3×10^5. The highest values were generally seen for either the idle or high idle conditions.

The results for the 5 highest pre-repair PN emitters for the NPET are presented in Figure 4-12 and Figure 4-13, respectively, for 30 mph and 50 mph. The results for the 10 highest pre-repair PN emitters for the Testo are presented in Figure 4-14 and Figure 4-15, respectively, for 30 mph and 50 mph. Fewer vehicles are plotted for the NPET, since this instrument was available for a shorter period of time and for fewer vehicles. The highest PN emissions at either 30 or 50 mph were seen for J&R05, 10, and 48 for the NPET, and for J&R05, 42, 41, and 36 for the Testo. J&R05, which showed high PN emissions with both the NPET and Testo, had issues with DEF relays and filters, and showed good post-repair PN emissions. For the NPET, J&R48 also showed good post-repair PN emissions for an intake manifold repair. For the Testo, J&R37 and 41 also showed some good post-repair PN reductions for EGR valve assembly and EGR cooler, valve assembly, and actuator repairs, respectively.

Table 4-13 Pre- and post-repair for PN emissions from TSI NPET normalized by CO_2 for each vehicle

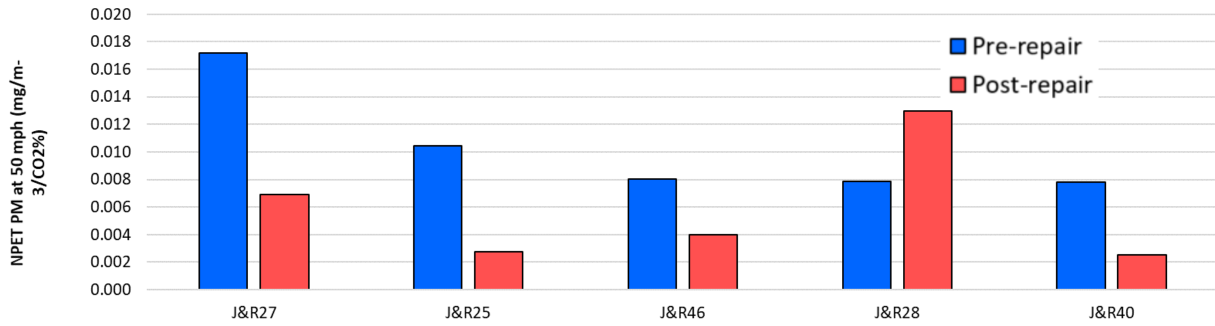
Vehicle NO.	Engine Year & Make	Pre-repair PN Emissions (#/cm-3/CO2%)				Post-repair PN Emissions (#/cm-3/CO2%)				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R01	2011 Cummins	8.5E+02	6.7E+02	1.2E+04		2.3E+02	1.0E+03	8.5E+02		-73%	48%	-93%	
Cum01	2015 Cummins	n/a	n/a	n/a		n/a	n/a	n/a					
J&R03	2010 Cummins	2.4E+02	2.7E+02	3.1E+02		6.3E+00	1.5E+01	9.2E+00		-97%	-94%	-97%	
J&R04	2013 Cummins	3.2E+02	2.8E+02	6.1E+02		5.3E+03	5.0E+03	2.5E+03					
J&R05	2013 Volvo	1.3E+04	1.4E+04	3.9E+03		1.0E+03	1.5E+03	1.1E+03		-92%	-89%	-72%	
J&R06	2012 Cummins	1.5E+03	2.3E+03	1.4E+03		1.4E+05	1.3E+05	1.9E+04					
J&R07	2015 Cummins	2.2E+03	1.5E+03	3.4E+03		1.9E+03	7.9E+02	2.7E+03		-12%	-48%	-22%	
J&R09	2014 Volvo	3.0E+02	3.2E+02	6.2E+02	4.7E+02	7.7E+03	1.7E+04	1.4E+03	5.0E+03			124%	
J&R10	2012 Cummins	3.1E+03	6.1E+03	2.8E+03	3.1E+03	9.2E+04	1.8E+05	1.1E+04	1.6E+05				
J&R11	2011 Cummins	7.3E+02	3.0E+02	1.1E+01	2.8E+00	3.1E+03	7.2E+03	3.6E+03	2.4E+03				
J&R12	2013 Cummins	1.3E+03	4.5E+02	4.9E+02	2.2E+03	1.9E+03	2.2E+03	1.1E+03	3.3E+03	41%		118%	48%
J&R13	2011 Volvo	1.8E+03	1.5E+03	4.1E+03	3.3E+03	2.1E+03	2.0E+03	2.5E+03	2.2E+03	16%	38%	-39%	-33%
J&R47	2013 Volvo	2.2E+03		3.4E+03	6.8E+03	6.3E+03	6.3E+03	5.8E+03	1.4E+04	186%		71%	111%
J&R48	2013 Maxxforce	3.8E+05	4.7E+05	3.9E+05	5.1E+05	7.9E+02	4.1E+03	1.2E+05	3.5E+03	-100%	-99%	-68%	-99%

Note: n/a - Not available



Vehicle NO	Repair
J&R28	DEF harness
J&R25	Short w/ coolant temperature sensor, thermostat
J&R27	Injector Doser, aftertreatment fuel shut off valve, clean DPF
J&R46	Intake NOx Sensor
J&R45	Fuel injector

Figure 4-12 Top 5 PN emitters on a $\#/cm^{-3}/CO_2\%$ basis at 30 mph based on NPET PN measurements and their Associated Repairs.



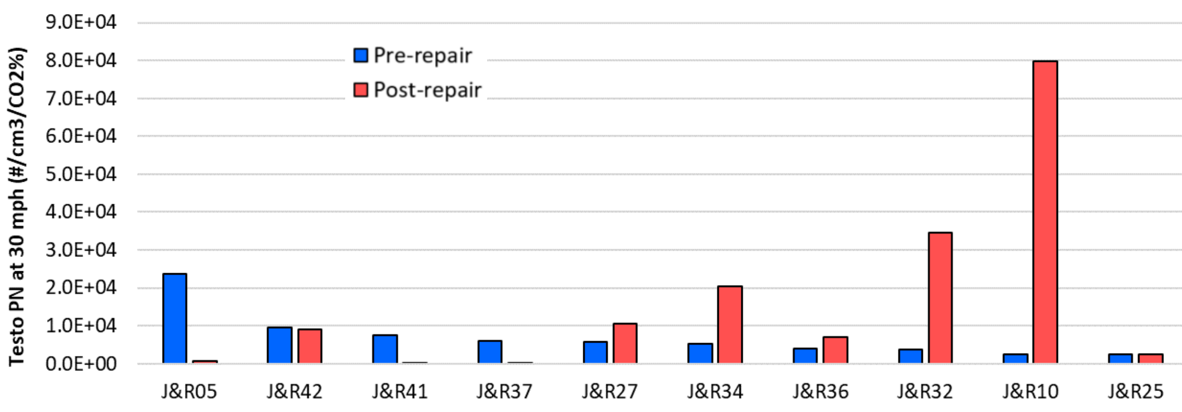
Vehicle NO	Repair
J&R28	DEF harness
J&R25	Short w/ coolant temperature sensor, thermostat
J&R27	Injector Doser, aftertreatment fuel shut off valve, clean DPF
J&R46	Intake NOx Sensor
J&R45	Fuel injector

Figure 4-13 Top 5 PN emitters on a #/cm^{-3}/CO_2% basis at 50 mph based on NPET PN measurements and their Associated Repairs.

Table 4-14 Pre- and post-repair for PN emissions from Testo normalized by CO_2 for each vehicle

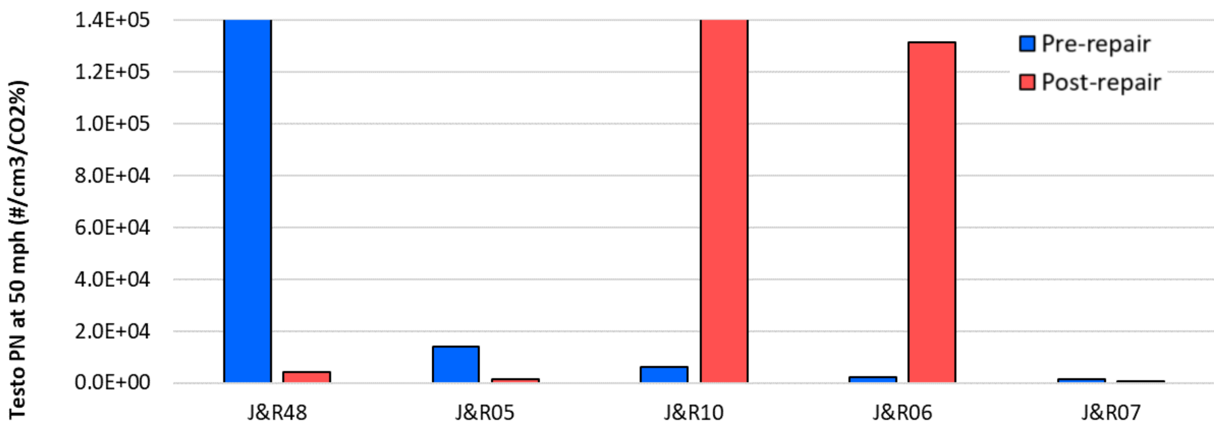
Vehicle NO.	Engine Year & Make	Pre-repair PN Emissions (#/cm-3/CO2%)				Post-repair PN Emissions (#/cm-3/CO2%)				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R04	2013 Volvo	1.2E+03	1.7E+03	1.3E+03	n/a	7.0E+03	6.1E+03	1.8E+03	n/a		250%	38%	
J&R05	2012 Cummins	2.4E+04	2.9E+03	2.6E+04	n/a	6.6E+02	1.5E+03	1.2E+02	n/a	-97%	-49%	-100%	
J&R06	2015 Cummins	8.3E+02	1.4E+03	1.3E+03	n/a	1.5E+05	1.3E+05	2.4E+04	n/a				
J&R07	2014 Volvo	7.5E+02	5.0E+02	2.2E+03	n/a	5.1E+03	2.3E+03	1.0E+04	n/a		360%	351%	
J&R09	2012 Cummins	2.0E+03	3.0E+03	3.4E+03	2.1E+03	6.9E+03	1.9E+04	5.1E+03	7.0E+03	255%	516%	48%	243%
J&R10	2011 Cummins	2.5E+03	6.2E+03	8.0E+03	2.6E+03	8.0E+04	1.4E+05	1.7E+04	1.4E+05			110%	
J&R11	2013 Cummins	1.8E+03	9.4E+02	1.9E+03	1.4E+03	3.1E+03	5.2E+03	4.5E+03	6.0E+03	74%	457%	137%	330%
J&R12	2011 Volvo	1.3E+03	1.2E+02	3.1E+03	2.3E+03	2.6E+03	1.2E+03	5.4E+03	2.1E+03	100%		73%	-10%
J&R13	2013 Cummins	6.5E+02	2.6E+02	6.6E+03	2.3E+03	6.0E+02	7.6E+02	3.7E+03	9.9E+02	-7%	197%	-44%	-57%
J&R17	2011 Cummins	2.8E+01	5.0E+01	2.8E+03	5.8E+02	4.0E+04	2.8E+05	1.1E+04	3.0E+03			297%	409%
J&R19	2015 Cummins	7.7E+02	3.2E+02	3.9E+02	1.4E+02	4.6E+02	4.2E+02	4.8E+02	4.6E+02	-41%	32%	24%	238%
Second visit		4.6E+02	4.2E+02	4.8E+02	4.6E+02	2.3E+05	1.4E+04	2.3E+05	6.3E+03				
J&R20	2011 Cummins	3.5E+02	9.6E+01	3.6E+03	5.1E+03	1.1E+05	1.9E+03	1.2E+05	2.3E+04				362%
J&R25	2013 Cummins	2.5E+03	4.5E+02	8.1E+02	4.3E+02	2.4E+03	2.2E+02	1.3E+03	2.3E+02	61%	-47%	-2%	-51%
J&R26	2013 Paccar	1.7E+02	6.8E+02	n/a	n/a	2.0E+02	7.9E+02	6.8E+03	1.1E+04			21%	16%
J&R27	2014 Volvo	5.9E+03	4.2E+03	5.6E+03	7.7E+03	1.1E+04	1.0E+03	8.3E+03	8.9E+03	47%	16%	82%	-75%
J&R31	2013 Cummins	1.2E+03	3.2E+02	4.1E+02	2.0E+02	3.6E+03	6.0E+02	6.8E+02	9.2E+01	64%	-55%	205%	88%
J&R32	2013 Volvo	3.7E+03	3.0E+03	3.4E+03	4.2E+03	3.5E+04	2.1E+04	1.6E+04	3.8E+04	361%			
J&R33	2015 Cummins	8.5E+02	3.9E+02	8.7E+02	3.8E+03	2.2E+02	5.6E+02	1.7E+02	3.3E+03	-81%	-14%	-74%	46%
J&R34	2015 Volvo	5.2E+03	4.3E+03	4.9E+03	7.5E+03	2.0E+04	3.2E+04	1.1E+04	2.7E+04	116%	255%	291%	642%
J&R35	2014 Volvo	9.9E+02	4.6E+03	8.6E+03	9.2E+03	4.9E+03	4.8E+03	1.2E+03	6.3E+03	-85%	-31%	401%	3%
J&R36	2013 Volvo	3.9E+03	9.4E+03	5.8E+03	2.1E+04	7.0E+03	7.9E+03	7.8E+03	2.1E+04	34%	-4%	77%	-16%
J&R37	2016 DDC	5.9E+03	4.8E+03	2.1E+04	4.0E+04	6.5E+01	1.6E+03	2.1E+03	5.0E+02	-90%	-99%	-99%	-67%
J&R38	2013 Cummins	4.4E+02	1.7E+04	1.2E+03	7.8E+03	7.8E+03	1.5E+05	1.2E+04	6.6E+04				
J&R41	2014 Paccar	7.6E+03	2.1E+02	1.2E+03	1.4E+02	2.0E+02	9.9E+02	6.4E+02	5.1E+03	-47%		-97%	372%
J&R42	2013 Cummins	9.6E+03	1.6E+02	5.9E+02	7.3E+03	9.0E+03	4.4E+03	2.4E+03	1.4E+04	316%	92%	-6%	
J&R43	2014 Cummins	2.6E+01	2.3E+02	1.4E+01	6.3E+02	2.7E+03	1.3E+03	3.1E+03	4.7E+03				451%
J&R44	2014 Volvo	5.4E+01	4.6E+01	1.4E+01	5.7E+00	2.1E+01	4.2E+01	5.5E+00	1.3E+00	-60%	-77%	-61%	-9%

Note: n/a - Not available



Vehicle NO	Repair	Vehicle NO	Repair
J&R05	DEF relays and filters	J&R34	Aftertreatment fuel valve
J&R42	update ECM, Intake NOx Sensor, SCR Temp Sensor	J&R36	Camshaft position sensor
J&R41	EGR valve assembly	J&R32	differential pressure sensor
J&R37	EGR cooler, valve assembly, & actuator	J&R10	Outlet NOx sensor
J&R27	Injector Doser, aftertreatment fuel shut off valve, clean DPF	J&R25	Short w/ coolant temperature sensor, thermostat

Figure 4-14 Top 10 PN emitters based on a $\#/cm^3/CO_2\%$ basis at 30 mph and their repairs (Testo)



Vehicle NC	Repair
J&R48	Engine throttle valve
J&R05	Burned DEF system relays, DEF filter
J&R10	Outlet NOx sensor
J&R06	DPF Temp. sensor, injector doser,
J&R07	Turbo speed sensor

Figure 4-15 Top 10 PN emitters based on a #/cm^3/CO_2% basis at 50 mph and their repairs (Testo)]

4.1.1.2.4 Analysis of PM Emission Results and mini-PEMS comparisons

Overall, the opacity data showed reductions of approximately 43% for both the full set of vehicles with the check engine light on and for the vehicles with the DM1 MIL on pre-repair. While this suggests that PM benefits can be obtained through a HD I/M program, it is recommended that additional studies be conducted to better characterize the magnitude of the PM emissions benefits. In particular, the pilot study fleet is relatively small, and there was not a concerted effort to recruit high PM emitters into the test program. Also, for the pilot study fleet, only a single vehicle had a full DPF replacement., whereas in the full J&R repair database, 3-6% of the 2010+ vehicles in the J&R database had full DPF replacements. Additional information about the potential for high PM emitters in the in-use fleet is provided in the next subsection.

Characterizing the PM emissions benefits for the chassis dynamometer testing proved to be more challenging. One of the challenges of characterizing PM emissions benefits is that PM emission levels for DPF-equipped engines are very low, near the 0.001 g/bhp-hr for the PM mass measurements, and can be difficult to quantify under steady state conditions at 30 and 50 mph, whereas most PM emissions are emitted under more transient operating conditions or during accelerations. The ability to characterize PM emissions at such low levels is also very challenging. Under such conditions, the MAHA MPM4 was not deemed sufficiently reliable for characterize the pre- and post-repair PM emissions. It is also worth noting that the effectiveness of a repair on PM emissions may not be adequately characterized based on simple comparing pre- and post-repair emissions, because DPFs can still filter PM even if it is in a state of disrepair. Thus, the impact of the repairs on soot loading and regeneration frequency would also need to be considered to fully understand the repair benefits. The improved maintenance would also help prevent more catastrophic failures of the DPF or associated components as the vehicle continues to age. Finally, it should be noted that by testing the parts immediately after the repair, some of the filter elements would not have been "broken in", which may require more extensive mileage accumulation. Overall, it is suggested that additional studies be conducted to better understand the potential PM benefits of PM-related repairs as part of a HD I/M program.

The comparisons between different opacity, PM mass and PN measurements with the different instruments also did not show as consistent results as for the different NOx measurement. This could be due in part to the small dataset and to the low overall PM emission levels. The opacity measurements were done under snap accelerations, whereas the other instruments measured under steady state or idle conditions. The characteristics of the PM measurement methodologies also differ between the different instruments, such as whether the measurement is for PM mass or PN, what type of PM is measured (total PM vs. elemental carbon vs. solid PM or PN), and the size ranges of PM measured. A poor correlation between different PM instruments for DPF-equipped engines has been seen in previous studies (Johnson et al., 2010, 2011, 2012; Khan et al., 2012).

The solid PN and PM measurements generally showed better sensitivity in measuring particle emissions at these low levels. The NPET and Testo solid PN instruments were sensitivity enough to measure PN from at all vehicles at levels above the background. The Pegasor was the most sensitive instrument for measuring PM mass emissions, which was cable of measuring PM emissions above the background levels for most of the vehicles. The NPET, Testo, and Pegasor are all designed to measure solid PM or PN, which provides for very low background levels.

More extensive studies in Europe have suggested that PN measurements can provide more repeatable and consistent measurements at PM emissions levels for DPF-equipped engines. This includes studies conducted by TNO in the Netherlands [Kadijk et al., 2016; Spreen et al., 2016; and as discussed in section 2.2.3], as well as studies conducted as part of the development of the Particulate Measurement Program regulations (Andersson et al., 2007). This includes the adoption of solid PN measurements for in-use monitoring of DPF-equipped non-road equipment under Swiss regulation 941.242.

The instruments were also evaluated in terms of ease of use. A summary of the operational characteristics of the mini-PEMS instruments is provided in Table 4-15. This summary includes both the PM/PN instruments as well as the gaseous phase instruments. The instruments were generally light weight, easy to use, and had short warmup times. There were some differences in the ease of use of the sample lines for the different instruments. The sample line issues may be specific to this particular repair station application, however, as a different sampling methodology would be used for some of these instruments in the field. There were also issues with some of the iPad control connections for some of the instruments.

Table 4-15 Summary of Operational Characteristics of mini-PEMS and MAHA

	Measurements	Operational Summary
Pegasor Mi3	Solid PM	Heated sample line requires 30 mins to warm up, too heavy to move around. Stable during testing.
TSI NPET	Solid PN	Warm-up time is short. Easy to use. Good design for sample line (steel). iPad control connection needs improvement, sometimes hard to connect. Stable during testing.
Testo	Solid PN	Warm-up time is short. Easy to use and install. Light weight and easy to carry. Plastic sample line could be improved and was too short. Stable during testing.
parSYNC® PLUS	NOx, CO_2	Light weight and easy to carry. Plastic sample line could be improved. iPad control connection could be improved. Showed some instability issues during testing.
NTK NCEM	NOx, PM	Easy to use and install. No calibration of NOx sensor needed. There were issues with the sample line “burning”, which could be improved. Sample line is a little hard to install. Stable during testing.

Overall, it is suggested that a more systematic study with a broader range of well-defined PM levels be conducted to better investigate the full range of mini-PEMS that might be available for use in a HD I/M program. It is suggested, however, that the better sensitivity available through PN measurements may be necessary to provide an improvement over the current opacity measurements being used in California for in-use PM monitoring.

4.1.1.2.5 Analysis of high PM emitter data from the in-use fleet

To better understand the potential contribution of high PM emitters in the fleet that could potentially be targeted by a HD I/M program, it is useful to review other studies that are available in the literature. This is particularly important as it can be difficult to get an adequate sample of high PM emitters in a sample of 47 vehicles and 51 repair sequences that was included in the pilot study. Roadside studies of opacity and PM emissions measured with OHMS and other methods can give provide some indication of the fraction of high PM emitters in the fleet. Studies by Bishop and coworkers using the OHMS system have indicated the presence of and importance of high PM emitters in the in-use fleet. Figure 4-16 and Figure 4-17 shown distributions of PM emissions from OHMS studies conducted at the Port of Los Angeles and the weight scales in Cottonwood, CA in g of PM/kg of fuel units. For comparison purposes, the certification standard of 0.01 g/bhp-hr represents approximately 0.067 g of PM/kg of fuel, based on the assumption that 0.15 kg of fuel is used per bhp-hr. These distributions both show the presence of vehicles with emissions considerably higher than what might be expected based on the PM emissions standard levels. It is important to note that these results were obtained from a fairly large sample size, where over 7,000 vehicles were measured between the two sites and the three years for which measurement campaigns were conducted (2013, 2015, and 2017).

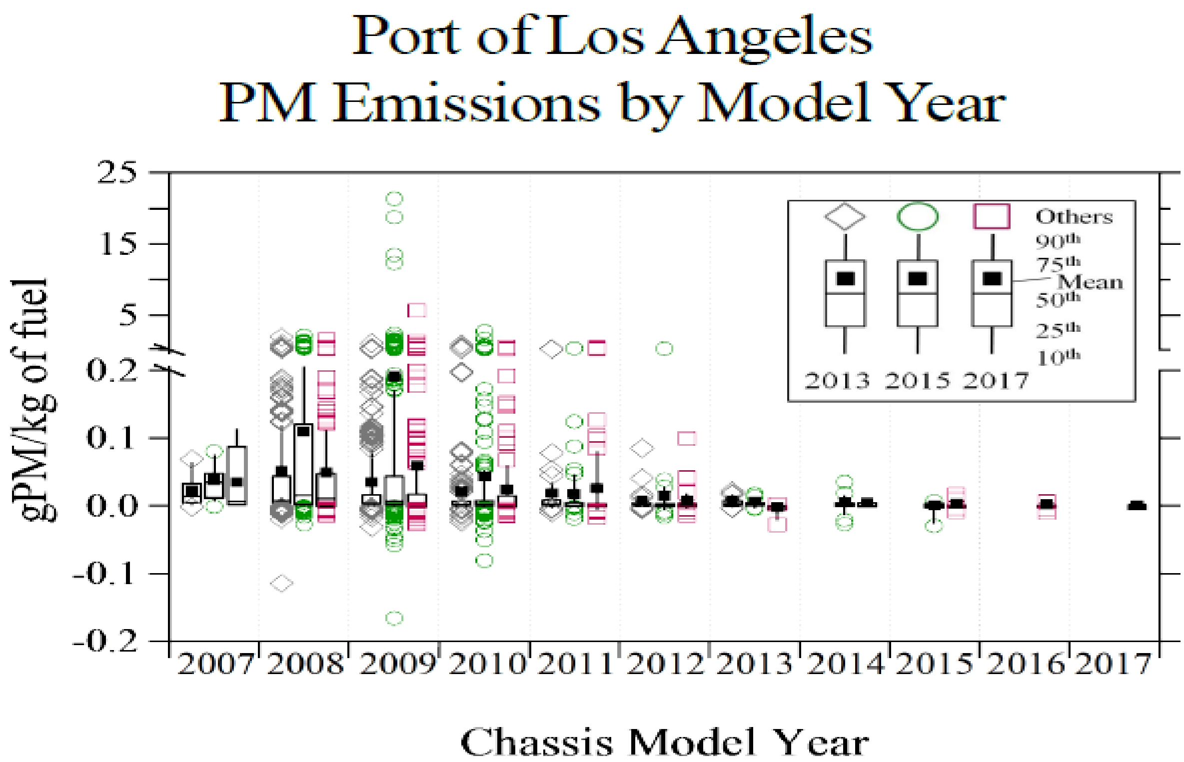


Figure 4-16 PM Emissions as a Function of Chassis Model Year for Measurements at the Port of Los Angeles

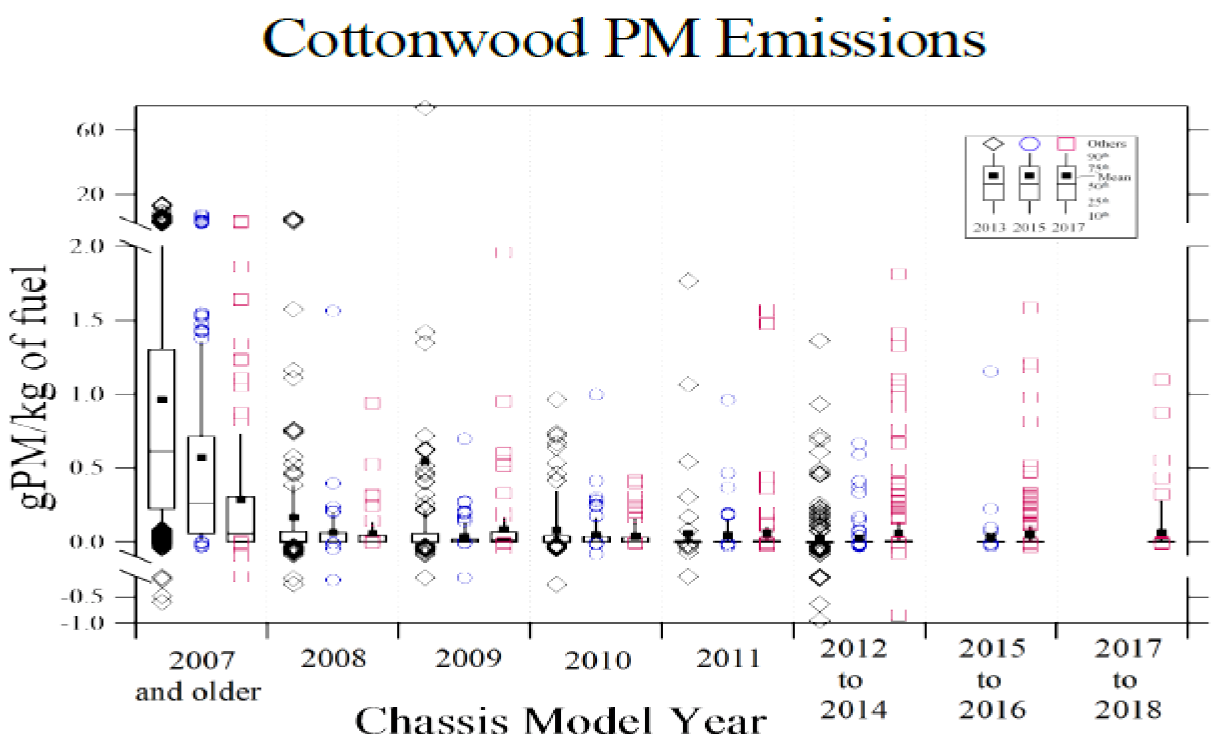


Figure 4-17 PM Emissions as a Function of Chassis Model Year for Measurements at the Cottonwood, CA Weight Station

EMFAC characterizes Tampering, mal-maintenance, and control component malfunction (TM&M) frequencies for DPFs that are leaking or disabled. As recent roadside studies have not been able to make a distinction between leaking and disabled DPFs, DPF failures are categorized under the leaking category for the current EMFAC2017 model. The associated TM&M frequencies in EMFAC2017 for DPF leaking at 1,000,000 miles range between 6.7 and 10% for 2010-2012 and 2013+ vehicles, as shown in Table 4-16. The emissions increase utilizes for DPF leaks is 5200% in EMFAC2017. Given that most engines certify to PM levels that are near 0.001 g/bhp-hr, this would translate to an emission rate of approximately 0.052 g/bhp-hr.

Table 4-16 TM&M Frequencies for Disabled and Leaking DPFs in EMFAC2014 and EMFAC2017

DPF Related TM&M	EMFAC2014			EMFAC2017		
	2007-09 MY	2010-12 MY	2013+ MY	2007-09 MY	2010-12 MY	2013+ MY
DPF Leaking	37.6%	37.6%	26.3%	38%	10%	6.7%
DPF Disabled	2%	2%	1.3%	0%	0%	0%

4.1.1.3 Chassis Dynamometer THC Results

The pre and post MAHA THC emission measurements for all of the vehicles are shown in Table 4-17 in units of ppm/CO_2%. THC emissions ranged from ambient level to 3.07, depending on the vehicle and test condition. The highest THC emissions were generally seen for either the idle or high idle tests. Overall, the THC emissions were relatively low on an absolute basis, as shown by the g/bhp-hr results shown in Appendix H.

The changes in THC emissions were mixed between the different vehicles, with some vehicles showing some increases and others showing decreases. THC emissions were generally in a narrow range for the testing, which is not surprising since engine-out THC emissions from diesel engines are typically low and are likely to be reduced further by the oxidation action of the DPF. Some vehicles showed consistent reductions in THC emissions for all test conditions, including J&R03, 07, 10, 19, 20, 21, 22, 23, 26, 27, 28 and 40. Other vehicles showed increases between the pre- and post-repair tests, including Cum01, J&R11, 13, 15, 18, 29, 31, 35, 39, 41, 43 and 46. These decreases/increases were generally within the range of the test measurements, however, so it cannot be certain that they were a direct results of the effectiveness of the repair itself, or simply testing variability between the pre- and post-tests that were conducted. Increases in THC were found for all test conditions for J&R14 after the replacement of the crankcase breather.

Table 4-17 Pre- and post-repair for THC emissions normalized by CO_2 for each vehicle

Vehicle NO.	Engine Year & Make	Pre-repair THC Emissions (ppm/CO2%)				Post-repair THC Emissions (ppm/CO2%)				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R01	2011 Cummins	1.30	1.00	2.35		1.34	0.33	2.40		3%	-67%	2%	
Cum01	2015 Cummins	0.76	0.69	1.75	2.42	0.92	0.66	2.20	2.34	22%	-5%	26%	-3%
Cum02	2010 Cummins	3.19	5.61	4.26	3.33	0.00	0.01	0.06	0.34	-100%	-100%	-99%	-90%
J&R03	2013 Cummins	0.92	0.93	2.28		0.69	0.59	1.57		-25%	-37%	-31%	
J&R04	2013 Volvo	0.30	0.52	1.49		0.74	0.66	1.20		143%	27%	-20%	
J&R05	2012 Cummins	0.89	0.68	1.14		0.62	0.36	1.36		-30%	-47%	19%	
J&R06	2015 Cummins	1.16	0.88	1.84		0.57	0.16	1.95		-51%	-82%	6%	
J&R07	2014 Volvo	1.05	0.72	2.38		0.08	0.13	0.15		-92%	-82%	-94%	
J&R09	2012 Cummins	1.28	2.86	1.39	1.07	0.81	0.10	0.74	1.27	-36%	-97%	-47%	18%
J&R10	2011 Cummins	1.04	0.81	2.65	2.32	0.49	0.61	2.10	1.82	-53%	-25%	-21%	-22%
J&R11	2013 Cummins	0.72	0.55	1.30	0.65	1.13	0.69	1.91	3.47	58%	26%	47%	430%
J&R12	2011 Volvo	1.10	0.98	2.43	2.12	1.09	1.09	2.34	2.87	-1%	11%	-3%	35%
J&R13	2013 Cummins	1.05	0.30	2.56	1.95	1.34	0.57	3.07	2.86	28%	89%	20%	47%
J&R14	2010 DDC	0.00	0.00	0.00	0.01	0.12	0.33	2.59	2.53	5607%	128278%	359250%	19455%
J&R15	2010 Navistar	0.54	0.36	2.17	2.30	1.03	2.67	1.78	2.02	90%	636%	-18%	-12%
J&R16	2010 Mack	0.07	1.30	0.62	1.10	0.43	0.68	1.79	1.80	472%	-48%	187%	64%
J&R17	2011 Cummins	1.01	1.20	1.14	1.29	0.41	0.67	1.29	1.98	-59%	-44%	13%	53%
J&R18	2014 Cummins	0.42	0.70	1.46	0.42	0.96	0.74	2.17	2.36	131%	5%	48%	456%
J&R19	2015 Cummins	0.73	1.03	1.15	1.93	0.47	0.75	0.75	0.32	-35%	-27%	-35%	-84%
Second visit		0.47	0.75	0.75	0.32	0.22	0.51	0.91	0.62	-54%	-32%	22%	97%
J&R20	2011 Cummins	0.54	0.60	0.87	1.28	0.08	0.14	0.29	0.23	-85%	-77%	-67%	-82%
J&R21	2013 Cummins	0.24	0.35	0.74	0.58	0.00	0.00	0.00	0.11	-99%	-100%	-100%	-80%
J&R22	2013 Cummins	1.74	1.27	4.58	1.79	0.17	0.38	0.35	0.31	-90%	-70%	-92%	-83%
Second visit		0.17	0.38	0.35	0.31	0.00	0.00	0.00	0.00	-99%	-100%	-100%	-100%
J&R23	2013 Cummins	0.72	0.69	1.39	1.55	0.00	0.00	0.00	0.00	-100%	-100%	-100%	-100%
J&R25	2013 Cummins	0.16	0.08	0.25	0.05	0.78	0.77	1.10	1.71	377%		345%	
J&R26	2013 Paccar	0.60	0.73	1.37	1.78	0.12	0.20	1.00	0.54	-79%	-73%	-27%	-70%
J&R27	2014 Volvo	0.78	0.82	2.14	2.16	0.23	0.19	0.74	0.82	-70%	-77%	-66%	-62%
J&R28	2013 Cummins	2.94	5.20	3.14	3.19	0.15	0.17	0.19	0.27	-95%	-97%	-94%	-92%
J&R29	2014 Cummins	0.48	0.39	0.75	0.44	0.84	0.92	1.38	2.23	75%	134%	85%	404%
J&R30	2013 Cummins	0.89	0.53	0.76	1.12	0.23	0.30	1.55	1.55	-74%	-44%	103%	39%
J&R31	2013 Cummins	0.50	0.32	0.76	0.91	1.05	0.88	2.30	2.90	111%	178%	203%	217%
J&R32	2013 Volvo	0.18	0.49	0.65	0.49	0.15	0.35	1.88	1.84	-17%	-29%	187%	278%
J&R33	2015 Cummins	0.58	0.67	1.33	1.94	0.64	0.42	1.06	1.35	12%	-37%	-21%	-31%
J&R34	2015 Volvo	0.72	0.75	1.78	1.66	0.71	0.79	1.95	2.45	-1%	6%	10%	47%
J&R35	2014 Volvo	0.83	0.92	2.13	1.90	1.16	1.11	3.38	3.24	40%	20%	59%	71%
J&R36	2013 Volvo	0.34	2.93	0.84	0.98	0.53	0.66	0.73	1.09	59%	-78%	-13%	12%
J&R37	2016 DDC	1.34	1.34	3.63	2.37	1.01	1.05	3.43	3.28	-24%	-22%	-5%	39%
J&R38	2013 Cummins	1.02	0.28	0.29	0.12	0.83	0.32	0.35	0.46	-19%	12%	20%	286%
J&R39	2013 Cummins	0.55	0.56	1.36	0.55	0.89	0.82	1.45	1.46	60%	47%	6%	166%
J&R40	2013 Cummins	0.94	1.04	1.86	2.50	0.74	0.72	1.26	1.02	-21%	-31%	-32%	-59%
Second visit		0.75	0.73	1.27	1.03	0.41	0.43	1.26	0.94	-45%	-42%	-1%	-8%
Third visit		0.42	0.43	1.26	0.93	0.37	0.47	0.59	0.32	-13%	11%	-53%	-66%
J&R41	2014 Paccar	0.31	0.48	0.83	0.21	0.58	0.54	1.31	1.23	84%	12%	58%	
J&R42	2013 Cummins	0.34	0.35	0.65	0.68	0.42	0.28	1.07	0.62	24%	-22%	64%	-9%
J&R43	2014 Cummins	0.48	0.57	0.94	0.86	1.03	0.86	1.75	1.76	114%	52%	88%	104%
J&R44	2014 Volvo	0.92	0.90	1.85	2.05	0.78	0.72	2.58	2.40	-15%	-20%	39%	17%
J&R45	2013 Cummins	0.81	0.75	1.62	1.47	0.83	0.69	0.83	0.80	2%	-8%	-48%	-45%
J&R46	2013 Cummins	0.10	0.23	0.50	0.40	0.88	0.98	1.90	1.95		322%	281%	391%
J&R47	2013 Volvo	0.31	0.55	0.55	0.25	0.70	0.60	0.47	0.05	124%	10%	-14%	-80%
J&R48	2013 Maxxforce	2.16	1.19	5.47	1.54	1.60	1.06	2.97	1.01	-26%	-11%	-46%	-34%

4.1.1.4 Chassis Dynamometer CO Results

Pre- and post-repair MAHA CO emission measurements for all of the vehicles are shown in Table 4-18 in units of ppm/CO_2%. CO emissions ranged from <0.001 to 0.99, depending on the vehicle and test condition. The highest CO emissions were generally seen for either the idle or high idle tests, with very low emissions for the 30 and 50 mph tests. This is to be expected, because combustion is less complete at low loads, and the aftertreatment influence will be reduced in a cooler exhaust environment. Overall, the CO emissions were relatively low on an absolute basis, as shown by the g/bhp-hr results in Appendix H. While some vehicles showed reductions, i.e., J&R03, 04, 05, 13, 15, 16, 17, 18, 19 (after the initial repair), 22 (after the initial repair), 23, 24, 30 and 37, these reductions generally represent very small changes on an absolute level.

Table 4-18 Pre- and post-repair for CO emissions normalized by CO_2 for each vehicle

Vehicle NO.	Engine Year & Make	Pre-repair CO Emissions (%/CO2%)				Post-repair CO Emissions (%/CO2%)				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R01	2011 Cummins	0.002	0.001	0.000		0.006	0.005	0.026		307%	260%		
Cum01	2015 Cummins	0.002	0.002	0.011	0.004	0.003	0.002	0.009	0.003	68%	19%	-20%	-26%
Cum02	2010 Cummins	0.003	0.005	0.009	0.007	0.002	0.002	0.003	0.004	-33%	-57%	-72%	-40%
J&R03	2013 Cummins	0.002	0.002	0.005		0.001	0.001	0.003		-53%	-51%	-47%	
J&R04	2013 Volvo	0.004	0.004	0.007		0.001	0.001	0.004		-70%	-76%	-52%	
J&R05	2012 Cummins	0.002	0.003	0.003		0.001	0.001	0.002		-47%	-65%	-33%	
J&R06	2015 Cummins	0.002	0.001	0.004		0.001	0.001	0.008		-19%	3%	98%	
J&R07	2014 Volvo	0.001	0.001	0.007		0.001	0.001	0.007		-7%	10%	1%	
J&R09	2012 Cummins	0.001	0.003	0.001	0.002	0.001	0.001	0.003	0.003	47%	-70%	73%	93%
J&R10	2011 Cummins	0.001	0.001	0.004	0.003	0.001	0.001	0.008	0.003	-21%	19%	102%	-16%
J&R11	2013 Cummins	0.001	0.001	0.002	0.003	0.002	0.001	0.003	0.005	28%	8%	19%	50%
J&R12	2011 Volvo	0.002	0.001	0.004	0.004	0.000	0.001	0.004	0.003	-81%	3%	-3%	-9%
J&R13	2013 Cummins	0.008	0.006	0.022	0.017	0.002	0.001	0.005	0.005	-78%	-76%	-77%	-73%
J&R14	2010 DDC	0.002	0.002	0.010	0.008	0.003	0.001	0.007	0.004	123%	-47%	-27%	-46%
J&R15	2010 Navistar	0.001	0.001	0.002	0.002	0.001	0.000	0.001	0.002	-24%	-73%	-61%	-25%
J&R16	2010 Mack	0.010	0.004	0.007	0.005	0.001	0.000	0.002	0.002	-95%	-94%	-71%	-55%
J&R17	2011 Cummins	0.002	0.002	0.010	0.005	0.001	0.000	0.006	0.004	-30%	-88%	-43%	-17%
J&R18	2014 Cummins	0.003	0.001	0.006	0.006	0.001	0.000	0.003	0.005	-50%	-83%	-51%	-21%
J&R19	2015 Cummins	0.001	0.001	0.002	0.003	0.000	0.000	0.001	0.003	-79%	-100%	-57%	0%
Second visit		0.000	0.000	0.001	0.003	0.002	0.000	0.003	0.002	656%		244%	-23%
J&R20	2011 Cummins	0.007	0.007	0.010	0.015	0.006	0.006	0.009	0.016	-9%	-12%	-3%	11%
J&R21	2013 Cummins	0.001	0.001	0.003	0.004	0.004	0.003	0.009	0.011	175%	194%	182%	192%
J&R22	2013 Cummins	0.005	0.005	0.022	0.016	0.001	0.000	0.000	0.003	-72%	-99%	-98%	-79%
Second visit		0.001	0.000	0.000	0.003	0.004	0.003	0.008	0.007	222%	7189%	1800%	114%
J&R23	2013 Cummins	0.001	0.001	0.003	0.003	0.003	0.002	0.006	0.006	138%	140%	115%	133%
J&R25	2013 Cummins	0.001	0.000	0.002	0.004	0.004	0.001	0.008	0.008	230%	298%	235%	99%
J&R26	2013 Paccar	0.001	0.001	0.003	0.004	0.002	0.002	0.005	0.011	91%	112%	84%	179%
J&R27	2014 Volvo	0.001	0.001	0.003	0.004	0.001	0.001	0.008	0.004	7%	-3%	134%	7%
J&R28	2013 Cummins	0.001	0.001	0.002	0.003	0.000	0.000	0.000	0.000	-98%	-100%	-100%	-100%
J&R29	2014 Cummins	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000		-1%		
J&R30	2013 Cummins	0.001	0.001	0.002	0.003	0.001	0.000	0.000	0.001	1%	-94%	-96%	-50%
J&R31	2013 Cummins	0.001	0.000	0.002	0.003	0.002	0.000	0.003	0.004	65%	-40%	25%	54%
J&R32	2013 Volvo	0.002	0.001	0.005	0.005	0.001	0.001	0.003	0.006	-51%	-28%	-47%	36%
J&R33	2015 Cummins	0.001	0.001	0.002	0.004	0.001	0.001	0.002	0.002	4%	-16%	0%	-59%
J&R34	2015 Volvo	0.001	0.001	0.004	0.004	0.001	0.001	0.008	0.007	14%	-6%	95%	62%
J&R35	2014 Volvo	0.000	0.000	0.004	0.004	0.001	0.001	0.004	0.004	125%		4%	2%
J&R36	2013 Volvo	0.007	0.001	0.008	0.007	0.003	0.001	0.006	0.007	-62%	102%	-30%	5%
J&R37	2016 DDC	0.003	0.003	0.012	0.007	0.003	0.004	0.011	0.012	4%	13%	-3%	63%
J&R38	2013 Cummins	0.003	0.002	0.007	0.008	0.003	0.001	0.004	0.004	-2%	-45%	-41%	-49%
J&R39	2013 Cummins	0.002	0.000	0.002	0.005	0.002	0.001	0.003	0.003	13%		6%	-39%
J&R40	2013 Cummins	0.001	0.001	0.003	0.004	0.001	0.001	0.003	0.004	24%	-1%	14%	-16%
Second visit		0.001	0.001	0.003	0.004	0.001	0.001	0.003	0.004	-2%	-38%	1%	7%
Third visit		0.001	0.001	0.003	0.004	0.004	0.002	0.007	0.006	233%	227%	117%	58%
J&R41	2014 Paccar	0.001	0.001	0.002	0.004	0.001	0.001	0.002	0.004	-20%	-3%	-8%	2%
J&R42	2013 Cummins	0.001	0.001	0.002	0.004	0.003	0.002	0.004	0.007	129%	84%	103%	105%
J&R43	2014 Cummins	0.002	0.001	0.003	0.003	0.001	0.001	0.002	0.002	-8%	-42%	-31%	-34%
J&R44	2014 Volvo	0.001	0.001	0.007	0.006	0.001	0.001	0.004	0.004	-12%	-9%	-40%	-41%
J&R45	2013 Cummins	0.003	0.002	0.006	0.008	0.001	0.001	0.002	0.003	-52%	-57%	-59%	-63%
J&R46	2013 Cummins	0.003	0.002	0.005	0.007	0.002	0.002	0.005	0.005	-8%	-34%	-2%	-22%
J&R47	2013 Volvo	0.000	0.000	0.003	0.004	0.002	0.002	0.007	0.012	352%		157%	242%
J&R48	2013 Maxxforce	0.001	0.000	0.007	0.002	0.000	0.000	0.003	0.002	-62%	-18%	-62%	12%

4.1.1.5 Chassis Dynamometer CO_2 Results

Pre- and post-repair MAHA CO_2 emission measurements for all of the vehicles for the 30 and 50 mph test conditions are shown in Table 4-19 in units of g/bhp-hr. CO_2 emissions on a percent basis are provided in Appendix H for the MAHA and parSYNC® PLUS. CO_2 emissions ranged from 340 to 720 g/bhp-hr for all the tested vehicles and test conditions. In comparing the 30 and 50 mph test conditions, some vehicles showed similar CO_2 work based emissions at these two driving conditions, while others showed larger differences between these two driving conditions. Overall, the CO_2 emissions were found to be relatively consistent from vehicle-to-vehicle, with values ranging from 450 to 650 g/bhp-hr, indicating these vehicle exhibit similar fuel efficiencies. Some vehicles showed a wider range of CO_2 emissions, including Cum01, J&R09, 22 second visit and 47 with Cum01, J&R09, and 47, which showed CO_2 emissions higher than 650 g/bhp-hr, and J&R22 the second visit, which showed CO_2 emissions lower than 450 g/bhp-hr.

There were some trends in lower CO_2 emissions for the post-repair tests compared to the pre-repair tests, suggesting that some improvements in fuel economy could be gained through the repair process. There was some inconsistency in the changes in CO_2 from vehicle to vehicle, with some vehicles showed small changes, while others showed changes that were greater than 10%. Also, there were some vehicles that showed reductions in CO_2 for either the 30 or 50 mph tests, but increases for the other speed. It should be noted that for the dynamometer tests performed, it is somewhat difficult to exactly replicate the dynamometer load between pre- and post-test, as discussed in section 3.2.3. As such, the changes in CO_2 emissions could be due to changes in the dynamometer loading, which could preclude the characterization of more precise changes in fuel economy. The CO_2 emissions on a g/bhp-hr basis for the MY2013+ vehicles had an average of 500 g/bhp-hr, while the MY2010-2012 vehicles had average CO_2 emissions of 560 g/bhp-hr. Again, this could suggests that the MY2013+ vehicles might have better fuel efficiencies than those MY2010-2012 for this subset of vehicles, but this could also simply reflect differences in dynamometer loadings across the full range of test vehicles.

Table 4-19 Pre- and post-repair for CO_2 emissions for the MGT5 for each vehicle on a g/bhp-hr basis

Vehicle NO.	Engine Year & Make	Pre-repair CO2 Emissions (g/bhp-hr)		Post-repair CO2 Emissions (g/bhp-hr)		% difference	
		30 mph	50 mph	30 mph	50 mph	30 mph	50 mph
J&R01	2011 Cummins	630	520	510	450	-19%	-13%
Cum01	2015 Cummins	560	570	570	660	2%	16%
Cum02	2010 Cummins	n/a	n/a	n/a	n/a		
J&R03	2013 Cummins	550	500	540	480	-2%	-4%
J&R04	2013 Volvo	n/a	n/a	n/a	n/a		
J&R05	2012 Cummins	570	640	520	800	-9%	25%
J&R06	2015 Cummins	510	550	530	460	4%	-16%
J&R07	2014 Volvo	n/a	n/a	n/a	n/a		
J&R09	2012 Cummins	640	720	590	630	-8%	-13%
J&R10	2011 Cummins	520	610	490	570	-6%	-7%
J&R11	2013 Cummins	470	500	450	540	-4%	8%
J&R12	2011 Volvo	n/a	n/a	n/a	n/a		
J&R13	2013 Cummins	470	510	480	540	2%	6%
J&R14	2010 DDC	520	470	530	470	2%	0%
J&R15	2010 Navistar	650		650	520	0%	
J&R16	2010 Mack	n/a	n/a	n/a	n/a		
J&R17	2011 Cummins	590	450	540	470	-8%	4%
J&R18	2014 Cummins	480	500	470	480	-2%	-4%
J&R19	2015 Cummins	500		580	600	16%	
Second visit		590	590	460	490	-22%	-17%
J&R20	2011 Cummins	520	530	480	490	-8%	-8%
J&R21	2013 Cummins	470	480	480	480	2%	0%
J&R22	2013 Cummins	470	510	490	490	4%	-4%
Second visit		360	360	340	340	-6%	-6%
J&R23	2013 Cummins	500	490	460	500	-8%	2%
J&R25	2013 Cummins	480	500	470	490	-2%	-2%
J&R26	2013 Paccar	450	480	470	470	4%	-2%
J&R27	2014 Volvo	n/a	n/a	n/a	n/a		
J&R28	2013 Cummins	n/a	n/a	n/a	n/a		
J&R29	2014 Cummins	480	490	470	490	-2%	0%
J&R30	2013 Cummins	n/a	n/a	n/a	n/a		
J&R31	2013 Cummins	480	500	470	490	-2%	-2%
J&R32	2013 Volvo	n/a	n/a	n/a	n/a		
J&R33	2015 Cummins	n/a	n/a	n/a	n/a		
J&R34	2015 Volvo	n/a	n/a	n/a	n/a		
J&R35	2014 Volvo	n/a	n/a	n/a	n/a		
J&R36	2013 Volvo	610	520	520	540	-15%	4%
J&R37	2016 DDC	n/a	n/a	n/a	n/a		
J&R38	2013 Cummins	n/a	n/a	n/a	n/a		
J&R39	2013 Cummins	480	490	490	500	2%	2%
J&R40	2013 Cummins	540	590	480	490	-11%	-17%
Second visit		n/a	n/a	n/a	n/a		
Third visit		n/a	n/a	n/a	n/a		
J&R41	2014 Paccar	n/a	n/a	n/a	n/a		
J&R42	2013 Cummins	460	490	470	500	2%	2%
J&R43	2014 Cummins	n/a	n/a	n/a	n/a		
J&R44	2014 Volvo	460	470	460	460	0%	-2%
J&R45	2013 Cummins	n/a	n/a	n/a	n/a		
J&R46	2013 Cummins	n/a	n/a	n/a	n/a		
J&R47	2013 Volvo	500	496	479	468	-4%	-6%
J&R48	2013 Maxxforce	602	679	580	556	-4%	-18%

Note: n/a - Not available

4.1.2 Plume Measurement Methods

4.1.2.1 HEAT EDAR Results

The PM, NO, NO_2, and NOx emission results for the EDAR are presented in Table 4-20. These results were obtained by driving the truck (unloaded) past the EDAR at approximately 15 mph in triplicate. These results are the averages of the ratios of each pollutant to CO_2, in mole/mole units. The PM is in nanomole/mole, meaning for a value of one there would be 1 nanomole or 6.022×e14 particles, per mole of CO_2. For the PM emissions, values ranged from 0.19 to 2.10 over the different vehicles and test conditions. The EDAR takes separate readings for NO and NO_2, so these are included in Table 4-20 along with the NOx values. Values for NOx ranged from 0.0027 to 0.123, while values for NO and NO_2 ranged from 0.0024 to 0.0120 and from 0.0001 to 0.0022, respectively.

The EDAR measured relatively higher NOx emissions for J&R04, 06, 07, 10, and 12 than were measured during the chassis dynamometer tests with the MAHA instrument. This was consistent with the higher NOx emissions for J&R04, 06, 07, and 12 from the MAHA measurements on the chassis dynamometer. The MAHA did, however, show lower emissions for J&R10, and higher emissions for J&R09, somewhat opposite with the EDAR results. The MAHA also showed significant NOx emissions reductions for J&R03, 04, 07, 09, and 12 at 30 mph, while the EDAR only showed significant reductions for J&R12 and showed increased NOx emissions for J&R03, 06, and 09.

It should be noted that any differences in the MAHA chassis dynamometer and EDAR readings should be considered cautiously, as the loading and speed profiles between the two measurement was considerably different, as noted in section 3.2.4.3. The differences in loading could also lead to differences in aftertreatment temperatures, which could have an important impact on NOx emissions.

Table 4-20 Pre- and post-repair emissions measured by the EDAR Remote Sensing Device

Vehicle NO.	Pre-repair Emissions (/CO2)				Post-repair Emissions (/CO2)				% difference			
	PM	NO	NO_2	NOx	PM	NO	NO_2	NOx	PM	NO	NO_2	NOx
	nanomole/mole	mole/mole			nanomole/mole	mole/mole						
J&R03	0.302	0.0032	0.0003	0.0036	0.388	0.0120	0.0004	0.0123	28.8%	271.5%	5.6%	246.0%
J&R04	0.409	0.0054	0.0009	0.0063	0.357	0.0045	0.0022	0.0067	-12.8%	-17.4%	157.4%	6.8%
J&R05	0.021	0.0027	0.0006	0.0033	0.302	0.0024	0.0003	0.0027	1349.0%	-10.2%	-41.4%	-15.8%
J&R06	0.244	0.0074	0.0005	0.0079	0.237	0.0089	0.0006	0.0094	-3.1%	20.5%	14.0%	20.1%
J&R07	0.314	0.0078	0.0006	0.0083	0.761	0.0067	0.0013	0.0080	142.4%	-13.5%	130.0%	-3.9%
J&R09	0.059	0.0039	0.0004	0.0043	0.019	0.0053	0.0003	0.0055	-68.0%	36.0%	-30.5%	30.0%
J&R10	0.097	0.0079	0.0001	0.0080	0.171	0.0083	0.0001	0.0084	77.5%	5.4%	19.5%	5.6%
J&R12	2.100	0.0109	0.0001	0.0109	0.480	0.0036	0.0019	0.0055	-77.1%	-67.1%	2999.8%	-49.6%

The EDAR results were also plotted against the dynamometer results collected at both 30 and 50 mph to obtain another perspective, as shown in Figure 4-18. For these plots, the NO and NO_2 results were combined together to make a comparison to the NOx readings from the dynamometer testing. While the data does not necessarily show a strong comparison between the EDAR and the chassis dynamometer testing results, these also do not represent direct comparisons the two methods as the measurements were not done at the same time. The chassis dynamometer tests were run under load, where the RSD tests had to be conducted with no trailer, or a very limited load, due to logistical considerations. As such, it is difficult to make a direct comparison with the between the chassis dynamometer and RSD tests. Discussions with HEAT suggested that the NOx values seem to be comparable to previous studies where loaded trucks were studied. Again, the addition of a load to the current project may have generated higher NOx values than our baseline, but this can not be verified at this time. Additional testing is probably needed to provide a more robust comparison between the RSD and other methodologies, which could include some of the testing discussed in section 2.2.3.1.

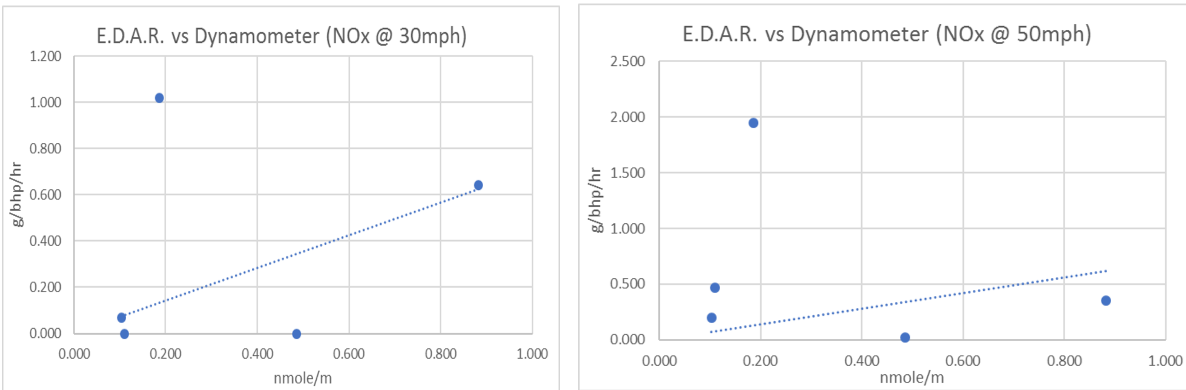


Figure 4-18 Comparison of EDAR vs. chassis dynamometer emission results for MAHA NOx

Additional testing was also done where the EDAR system measured emissions for 62 vehicles that were at the J&R facility for some type of repair. A listing of these vehicles is provided in Appendix H. Of the sixty-two vehicles scanned, twenty-one were suspected of having emission control related issues based on owner complaint and/or illumination of the MIL as indicated on the repair order. It is important to note that the 62 vehicles utilized for this evaluation were selected at random form the vehicles present at the J&R facility, with the majority of the vehicles not being in the main pilot study. These results were obtained by driving the truck without a trailer past the EDAR at approximately 15 mph in triplicate. These vehicles were unloaded, and were not necessarily extensively warmed up during the testing, so the results in terms of absolute magnitudes should be considered cautiously.

These data were examined to determine if the EDAR could identify vehicles whose owners were seeking emissions related repairs and to hypothetically assess the possibility of establishing Pass/Fail points using the EDAR. For purposes of this analysis, simplistic cut-points were established for PM and NO_x emissions based upon the median EDAR readings for the sixty-two-vehicle fleet. The results of this analysis are shown for PM and NOx in Figure 4-19 and Figure 4-20, respectively, where the red dots represent the 21 vehicles that were diagnosed with suspected emission control related issues, the blue dots represent the remaining vehicles that were at the repair facility for a non-emissions related issue, and the blue line connects points with successively higher emissions. The orange line represents the cut points based on the median EDAR readings. It is important to note that one reading was omitted from the PM graph, as it was off-scale with a reading of 96.75.

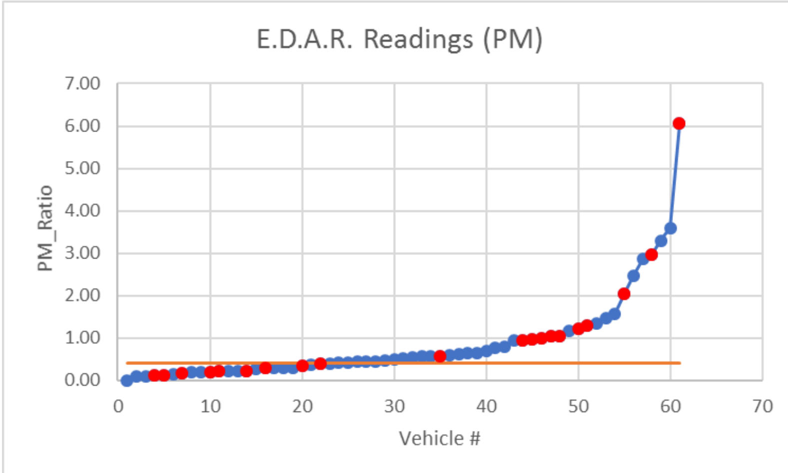


Figure 4-19 PM emissions distribution for 62 vehicle test fleet, where the PM ratio is nanomoles of PM/mole per mole of CO_2.

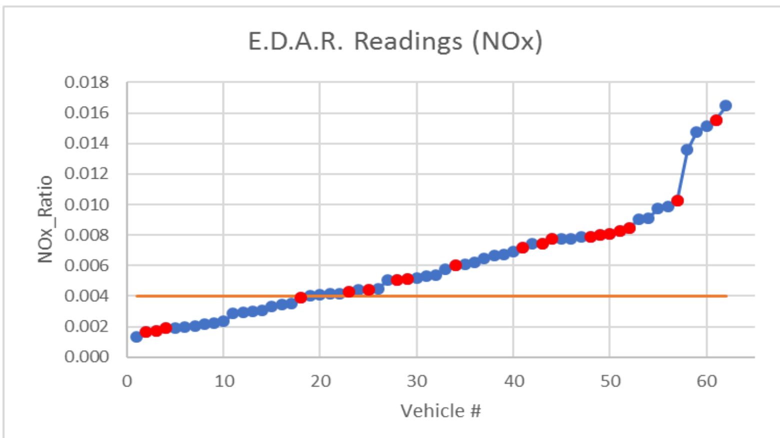


Figure 4-20 NOx emissions distribution for 62 vehicle test fleet, where the NOx ratio is moles of NOx/mole per mole of CO_2.

Under this admittedly simplistic scenario, the EDAR was able to correctly identify sixteen of the twenty-one suspected failures based on NOx emissions, including seven of the eight vehicles that received both dynamometer and EDAR testing. Similarly for PM emissions, the EDAR was able to correctly identify thirteen of the twenty-one suspected failures. It is not possible to determine the incidence of false failures or correct passes that might be anticipated in the absence of additional dynamometer test data. In actual practice, the cut-points would be established in a way that would capture as much of the high emitting fleet as possible, while maximizing Correct Failures and minimizing the False Passes. In particular, the cut-point would have to be selected to minimize false failures, which was not accounted for in the current exercise due to the small data size. For example, the initial cutpoints established for the opacity test conducted by CARB were based on identifying the highest emitting 10% of the fleet, and were refined as more data were collected.

Given the wider distribution of NOx readings compared to that of the PM readings, EDAR tended to correctly identify more potential NOx failures compared to potential PM failures. Again it is important to note that it could not be reliably discerned from the assessment of repair orders what emissions characteristics each vehicle might display. Trucks with high emissions of NO_x are often low emitters of PM and vice versa. The establishment of separate NO_x and PM cut-points essentially doubles the chance of identifying a vehicle that might benefit from repair.

Finally, the EDAR was evaluated with an eye toward measuring emissions under real world conditions. In this assessment, the sixty-two-vehicle fleet discussed earlier was scrutinized. EDAR readings of CO_2 expressed in terms of mole/m, and NO and NO_2 readings expressed in terms of mole/mole of CO_2 were used to estimate grams of NO_x per gallon of fuel, and a fleet average heavy-duty diesel fuel economy estimate from EMFAC2014 was used to convert grams per gallon to grams per mile. Figure 4-21 displays the model year average emission rates as measured by EDAR compared to the 15 miles per hour, model year average emission estimates for NO_x from EMFAC2014. As noted above, some of the differences between these estimates could be attributed true differences in emissions factors, while some of the differences could also be due to the unloaded nature of the test and whether the vehicles were sufficiently warmed up. The small sample size for the EDAR testing would also not necessarily be representative of the full vehicle population represented in EMFAC, especially for the pre-2007 vehicles. Nevertheless, for the post-2007 vehicles, the EDAR emission factors are reasonably comparable with the values used in EMFAC2014.

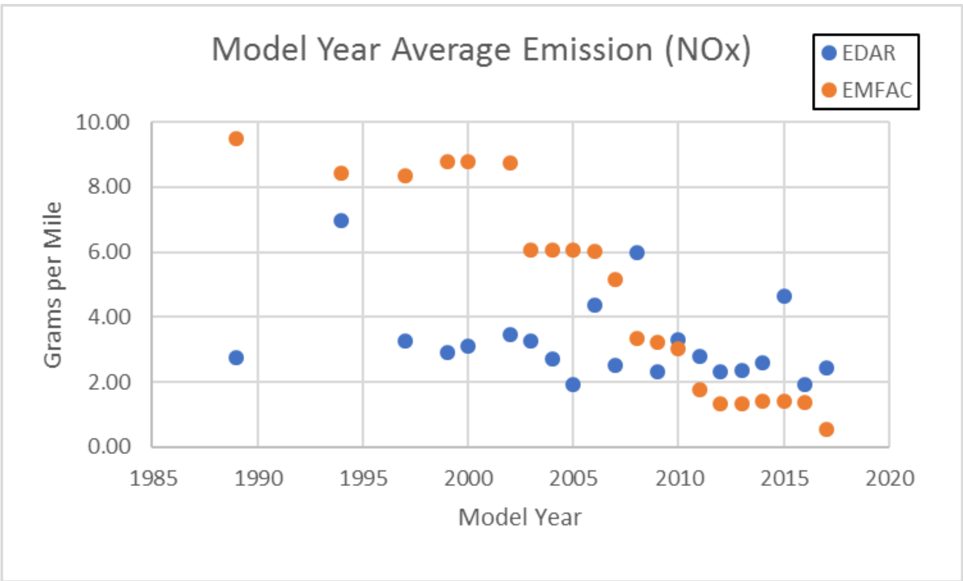


Figure 4-21 Comparison of EDAR NOx emissions readings with EMFAC2014 at 15 mph

Although the pilot study dataset is very limited, examination of this data in the context of the larger dataset of available information on RSD that is being developed worldwide, as discussed in section 2.2.4.1, suggests that the device shows potential in making emissions related pass/fail decisions and in the quantification of fleet emissions and reductions associated with a HD I/M program.

4.1.2.2 PEAQS Results

The results for the PEAQS measurements are provided in Table 4-21 and Table 4-22 and Figure 4-22 to Figure 4-25. Table 4-22 includes the corresponding identification for the corresponding pilot study, as applicable. Note that J&R13 was equipped with a newer engine (as shown in Table 3-3 , where the engine model years are presented) in an older vehicle chassis. A summary of the PEAQS system results is provided below:

- A total of 130 different vehicles were measured: 66 official vehicles passed through PEAQS a minimum of 3 times and 64 additional ‘volunteer’ vehicles (1-3 passes through PEAQS). We report the emissions data from all vehicles measured within the histogram and averages.
- Average, standard error of the average, and maximum EF_{BC} and EF_{NOX} are reported in Table 4-21.
- Data distribution indicates higher emitting vehicles are responsible for the majority of BC emissions (Figure 4-22 and Figure 4-23). Distribution is more highly skewed right for BC over NO_X.
    - 10 of 130 (7.7%) vehicles emitted 51% of BC emissions
    - 43 of 130 (33%) vehicles emitted 57% of NOx emissions
- Strong winds during the week resulted in lower sample resolution for a few measurements, due to added dissipation of the exhaust plume.
- Two vehicles were tested before and after repair during the week for PM related issues (Trucks 3 and 4 in Figure 4-24) and 2 additional vehicles were measured twice (Trucks 1 and 2 in Figure 4-24), presumably before and after repair.
- BC emissions from Trucks 3 and 4 (Figure 4-24) decreased by orders of magnitude following repairs. The AE-33 reported emissions reductions below detection limits after repair for both vehicles, whereas the AE-51 reported 99.9% reduction for vehicle 4 and below detection limit for vehicle 3.
- NOx emissions decreased after repair for Trucks 1-3 (Figure 4-24). Thus, suggesting repairs may have reduced tail-pipe NOx levels. However, the after-treatment temperature was not measured at the time of measurement. The pre-repair and post-repair emissions for Truck 4 did not show differences outside the testing variability.
    - Decreased final NOx levels may be due to elevated after-treatment temperatures following the completion of the dynamometer tests. Initial elevated NO_X emissions could be a function of off-cycle emissions of a cold vehicle, rather than a malfunction or mal-maintenance issue.
    - Information regarding vehicle activity immediately prior to our measurement could give insight to this issue.
- We note no significant trend of emissions with recorded model year (MY) of the 38 vehicles where MY information was available (Figure 4-25).

- Vehicles selected for this study were selected from a fleet at a repair facility, and are not representative of the overall CA heavy-duty fleet. It is highly likely that any vehicle selected has a mechanical issue that may affect emission levels.

Table 4-21 Summary statistics for sampling campaign

		g Pollutant / kg fuel
NO_X		
	Average	17.5 ± 1.22
	Maximum Value	121
	Vehicles with Measurable NO_X	59
BC		
AE-33 Aethalometer	Average	0.816 ± 0.331
	Maximum Value	12.2
	Vehicles with Measurable BC	39

Table 4-22 Repaired vehicle information

	Chassis Make	Engine Make	Chassis Model Year	Mileage	State
Truck 1 – J&R12	Volvo	Volvo	2011	574610	IN
Truck 2*	-	-	-	874946	CA
Truck 3 - J&R09	Kenworth		2012	623976	VA
Truck 4 - J&R13	Volvo	Cummins	2002	99285	MI

*Vehicle information not available

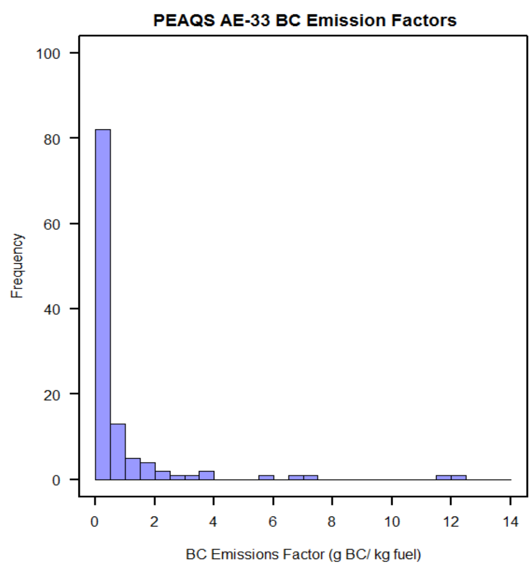


Figure 4-22 Histogram and probability distribution of all collected BC emission factors during the week of November 14th – 18th at the J &R Repair Facility in Bloomington, CA. Measurements presented here were collected with the AE-33 aethalometer. Data includes all runs from each of the 39 vehicles that had measureable BC emissions, as per Table 4-21.

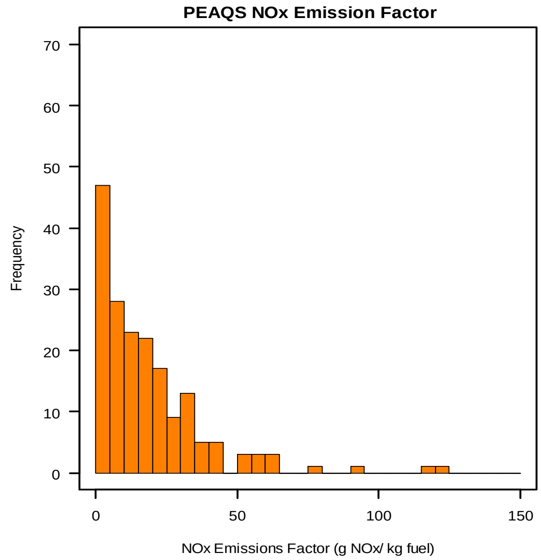


Figure 4-23 Histogram and probability distribution of collected NOx emission factors during the week of November 14th – 18th at the J &R Repair Facility in Bloomington, CA. Measurements were collected with the California Analytical Instruments (CAI) 600 series chemiluminescense detector. Data includes all runs from each vehicle

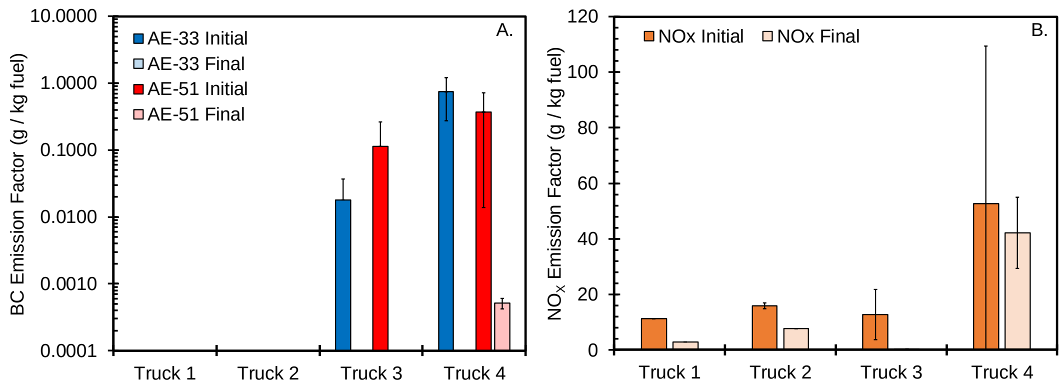


Figure 4-24 Comparison of vehicles before and after repair. Truck 1 had repairs of the DEF lines and a manual regeneration, and showed NOx reductions during the post-repair run. The repairs for truck 2 are unknown, but it showed a reduction for NOx for the post-repair run. Truck 3 underwent repairs associated with frequent regenerations and had an OBD DPF repair light before initial run. Truck 4 had an intake NOx sensor repair. Error bars are the standard deviation associated with multiple passes through PEAQS, an absence of error bars indicates a single pass. "nd" indicates that BC emissions were not detected.

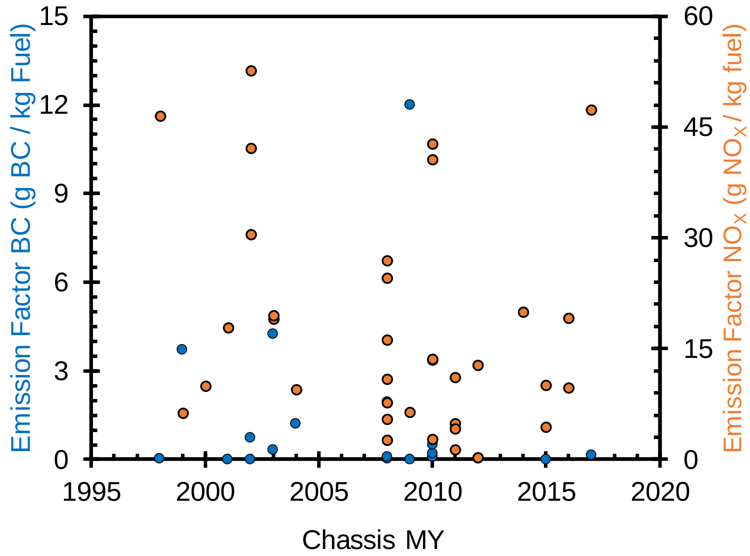


Figure 4-25 Summary of BC (blue points) and NOx (orange points) emission factors for all vehicles with known chassis model year (MY). Information was recorded prior to all tests for 38 of 66 vehicles tested, information was not available for remaining vehicles

4.1.2.3 Broader implications for the use of plume measurement methods in HD I/M

Overall, the HEAT EDAR and PEAQS results suggest the ability to differentiate between vehicles with a range of different PM and NOx emission levels. Coupled with other information from the literature, as discussed in section 2.2.3, this suggests that such methods could provide an important contribution to a HD I/M program. This could include the identification of high emitters for early model year engines that are not equipped with OBD. Further study is probably needed to better understand the correlation of such methods with other tailpipe measurement methods for a full range of higher and lower emitting vehicles to allow for the development of cut points that maximize the correct identification of high emitters, while minimizing false failures.

4.2 Repair costs and repair frequencies from the Pilot Study

Additional analyses were conducted on the pilot study information to evaluate the average repair costs and repair frequencies.

4.2.1 Pilot Study Repair Costs

A summary of the components replaced, performance checks conducted, and total repair costs for each vehicle is provided in Table 4-23. For this table, the repairs are categorized based on the issue that was identified with the vehicle upon its arrival, although the actual repair could often include fixing issues related to a broader range of components. The repair costs covered a range from $250 to approximately $8,660, depending on the extent of the repair needed. The most costly repairs were primarily those associated with the replacement of major parts or systems. This included repairs and replacement of DPFs ($2,687), SCRs ($6,773), and turbochargers ($3,774). Less expensive repairs included those that were sensor replacements, code clearing, or recalibration. It is worth noting that there was a relatively wide range of repair costs, even within a particular repair category. For example, repair costs for an EGR related issue ranged from $511 to $7,638 and those for turbochargers ranged from $393 to $7,155. This again shows that the repair issues identified by the OBD system can range from more minor sensor replacements to the full replacement of a major system, such as the DPF, SCR, or turbocharger. It is also worth noting that a DPF cleaning was frequently used either in conjunction with or as a primary repair during the repair process. Only a small number of DPF cleanings were included in the test matrix to ensure there would be sufficient number of vehicles in other repair categories, and since a DPF cleaning is not a typical OBD related repair.

The average repair costs from the pilot study were determined for both the full test fleet, which was recruited on the basis of have the check engine light on, and for the vehicles that were found to have the DM1 MIL on prior to the repair. These average costs are listed at the bottom of Table 4-23. The average repair costs per vehicle were $1,803 for vehicles with check engine lights on and $2,037 for vehicles where the DM1 MIL was on.

Table 4-23 Repair Costs by Vehicle

Vehicle No.	Repair performed/Parts replaced	Repair cost /$
J&R01	DPF, injector doser, DPF cleaning	4255.00
Cum01	DEF Module Calibration	395.00
Cum02	Injector doser, turbocharger	Warranty Repair
J&R03	SCR temperature sensor connectors	Warranty repair
J&R04	EGR Temperature sensor	252.82
J&R05	Burned DEF system relays, DEF filter	292.72
J&R06	Clean DPF, DPF Temp. sensor, injector doser, SCR Temp. sensor	2300.41
J&R07	Turbo speed sensor	393.49
J&R09	Clean DPF	801.86
J&R10	Outlet NOx sensor	626.33
J&R11	Injector Doser, outlet NOx sensor, DPF cleaning	4580.63
J&R12	DEF lines at dosing valve, manual regen	255.55
J&R13	Intake NOx Sensor, Engine Harness	1505.63
J&R14	Crankcase breather/separator & wiring	717.00
J&R15	Injector doser/DPF clean/fuel line (DPF found to be damaged)	**
J&R16	Turbocharger & injector doser	7,155.38
J&R17	Injector doser, Intake NOx sensor, clean DPF	2,740.22
J&R18	air filter	1158.34
J&R19	DEF harness	802.72
J&R 19, Second visit	DEF Harness	1,437.54
J&R20	Intake NOx sensor	817.77
J&R21	Clean DPF	688.20
J&R22	Exhaust Pressure Sensor	511.29
J&R 22, Second visit	Intake NOx sensor/DEF Filter	1,029.32
J&R23	Clean DPF/Engine Oil Cooler	751.00
J&R25	Short w/ coolant temperature sensor, thermostat	558.95
J&R26	Aftertreatmnet fuel shut-off valve	Warranty Repair
J&R27	Injector Doser, aftertreatment fuel shut off valve, clean DPF	1852.41
J&R 28	DEF harness	505.86
J&R29	Crankcase filter	308.14
J&R30	Corrected/Cleaned DEF pump/harness connections	320.00

** - repair costs not available; warranty – repairs were done as a J&R internal warranty based on a previous repair.

Table 4-23 Repair Costs by Category - Continued

Vehicle No.	Repair performed/Parts replaced	Repair cost /$
J&R31	Replace SCR, Temperture Sensor, Inlet NOx Sensor, Dosing Valve, Clean DF	8,662.24
J&R32	differential pressure sensor	**
J&R33	differential pressure sensor + DPF harness	**
J&R34	aftertreatment fuel valve	921.47
J&R35	Crankcase pressure sensor & oil pressure sensor	485.64
J&R36	Camshaft position sensor	1,252.58
J&R37	EGR cooler, valve assembly, & actuator	7,638.44
J&R38	update ECM	702.67
J&R39	SCR repair	4884.27
J&R40	Wiring for DEF dosing valve & SCR NH3 sensor	490.11
J&R 40, Second visit	DEF dosing valve	**
J&R 40, Third visit	Aftertreatment fuel injector	**
J&R41	EGR valve assembly	2,983.50
J&R42	update ECM, Intake NOx Sensor, SCR Temp Sensor	1,801.69
J&R43	update ECM & timing sensor	718.73
J&R44	DPF Delta Pressure Sensor, clean DPF	1,119.09
J&R45	Fuel injector	1,372.57
J&R46	Intake NOx Sensor	935.91
J&R47	Intake NOx Sensor	1,079.36
J&R48	Engine throttle valve	2,529.67
	Ave.	**1803.00**
	Ave. (DM1=1)	**2037.00**

** - repair costs not available; warranty – repairs were done as a J&R internal warranty based on a previous repair.

4.2.2 Repair Costs for J&R and Cummins Records

An extended J&R repair record database was evaluated to estimate repair costs and provide an estimate of the downtime associated with different types of repair. This database covered repair records from January 2015 to January 2017, and included 2,784, 2010 and newer model year vehicles. For this analysis, the 11 repair categories used were derived from the broader list of Tampering, Mal-maintenance and Malfunction categories used in EMFAC2014. The results of this analysis are provided in Table 4-24. It should be noted that the number of categories was condensed because the repair orders often lacked the specific information needed to match categories classified in EMFAC2014. Therefore, the repair categories presented below represent a broader range of potential repairs within a specific category. For example, the category "NOx" included SCR catalyst issues, as well as various NOx sensors. Both the parts used in the repair of each vehicle and the mechanics comments were considered in determining whether a vehicle would be included in a specific repair category. It was also not unusual for a single vehicle to experience more than one mechanical or emissions related issue simultaneously and therefore to be included in multiple repair categories. The cost estimates and the related downtimes shown below reflect that fact.

The results from the facility repair record analysis generally suggest higher average repair costs than were observed for the fleet of vehicles in the pilot study. This could be due to the generally older age of the vehicles in the repair records (average age of 2012), whereas the majority of the vehicles in the pilot study were 2013 and newer. For the major EMFAC categories, the total repair order (RO) costs are on the order of or exceed $2,000 for all of the repair categories, which is slightly higher than the average repair costs found for the pilot study vehicles. This could be due to repair categories in the pilot study that represented more minor repairs that do not represent a significant contribution to the EMFAC TM&M rates. The repair record analysis also showed typical repair costs above $4,000 for the turbo, NOx, fuel pressure, and engine categories, indicating that these are more major repairs that likely require the replacement of a major component.

Table 4-24 Repair Costs and Estimated Downtimes for Different Repair Types from the J&R extended repair records

Failure	**DPF**	**Catalyst**	**ECM**	**Turbo**	**NOx**	**Fuel Pressure**	**Air**	**Engine**	**EGR**	**Timing**	**Oil**
Number (2010+)	1124	442	235	343	209	35	3864	1642	400	42	1357
Labor ($)	661.19	673.53	853.96	1,705.16	1,199.64	1,162.79	546.35	2,007.91	777.00	821.86	749.29
Materials ($)	1,524.47	1,834.15	1,230.35	4,706.31	2,910.20	3,078.53	1,295.44	4,450.90	1,749.21	1,694.97	1,317.40
Tax ($)	123.90	148.34	93.45	373.20	228.28	239.28	104.06	348.25	138.05	139.40	106.32
RO ($)	2,334.13	2,664.16	2,078.68	6,687.87	4,250.31	4,365.58	1,951.40	6,625.82	2,606.48	2,697.13	2,173.60
Downtime	2	2	3	3	3	2	2	2	3	2	3

***Number is the number of records, Downtime is expressed in days, RO = repair order, which represents the total cost of the repair order including labor, parts, and tax.**

A subset of repair records was also obtained from Cummins Pacific in Bloomington, CA. This included records for 2,855 vehicles, spanning a period from January to May 2016. A breakdown of the repair records and the repair costs is provided in Table 4-25. The breakdown shows the distribution of vehicles based on chassis type and engine type on the left side of the table, while the right side of the table shows a breakdown based on different types of repairs. It should be noted that as a Cummins dealer, the Cummins Pacific facility provides warranty service that is incorporated in the repair records, so the total average repair costs represent only the costs for the non-warranty repairs. As such, the repair costs for more major repairs may not be fully represented in the real average repair costs. It should also be noted that the average parts and labor costs do include costs associated with warranty repairs for accounting purposes, even for warranty items that are not included on the final bill to the truck owner.

As shown, the average non-warranty repair costs to the customer range from approximately $529 to $4,325, depending on the specific engine/chassis. For most engines/chassis, the average non-warranty repair costs were generally below $2,000, and were generally below the values found in the pilot study. This suggests that many of the major service items being serviced by Cummins Pacific may fall under warranty repair. The most common repairs include those related to the ECM, catalyst, EGR, and the turbocharger. Other repairs include SCR issues, air cleaners, fault codes, injector doser, and manifold issues. For the average parts and labor, which include warranty repairs, the values typically ranged between $1,000 and $2,000 for both parts and labor, suggesting that the actual total cost of the repairs being conducted, when warranty repairs are taken into account, would be higher than the costs found for the pilot study fleet.

Table 4-25 List of the repairs and corresponding repair costs from Cummins Pacific Repair records

	PETERBILT	KENWORTH	FREIGHTLINER	VOLVO	INTERNATIONAL	VANHOOL	MACK	Total	
XTA15-E10	250	198	180	130	0	0	0	758	159,839
XTA15-E13	223	267	113	103	527	0	0	1233	162,432
ISX15 425ST	5	5	19	11	1	0	0	41	159,486
ISX15 450	36	20	15	4	20	0	0	95	161,152
ISX15 500	8	0	7	29	0	0	0	44	160,844
ISX15 485	42	18	5	0	0	0	0	65	160,275
ISX15 550V	8	4	0	0	0	0	0	12	160,795
ISX15 525V	7	5	0	0	4	0	0	16	162,305
STX12-E13	29	3	3	0	0	4	0	39	160,044
ISX 425	5	3	0	1	0	0	0	9	159,356
ISX15 525	1	4	0	0	0	0	0	5	39,932
ISX15 400ST	21	48	22	21	13	0	0	125	162,010
ISX 400ST	19	35	6	61	14	0	0	135	158,923
ISX 400	3	13	1	12	11	0	0	40	160,194
G6LTAA8.9E	55	3	166	0	9	0	5	238	161,805
Total	712	626	537	372	599	4	5	2855	161,169
Avg Odometer	160,501	160,736	160,511	161,027	162,119	160,047	160,518		
Avg Parts	$2,087.22	$1,702.17	$2,275.32	$2,374.66	$ 1,327.26	$ 230.26	$1,905.56		
Avg Labor	$1,563.71	$1,304.37	$1,852.10	$1,615.36	$ 1,052.93	$1,077.54	$1,493.34		
Avg Total Cost	$1,757.59	$1,655.23	$1,476.94	$1,488.74	$ 1,021.53	$ 37.63	$ 708.92		

	O2	FUEL INJECTOR	AIR CLEANER	FAULT CODE	EGR	DOSER	TURBO	ECM	EXHUAST MANIFOLD	DPF	CAT	NOX	CODES	SCR	TEMP SENSOR	MANIFOLD	WARRANTY	AVG PARTS	AVG LABOR	AVG TOTAL
XTA15-E10	0	42	177	125	226	143	209	184	4	240	300	72	160	65	30	101	117	$2,260.92	$1,736.48	$ 1,740.18
XTA15-E13	1	33	289	138	201	104	279	598	4	209	513	225	296	81	25	91	164	$1,807.91	$1,408.17	$ 728.15
ISX15 425ST	0	2	5	14	16	9	11	13	0	13	9	6	11	6	1	10	1	$2,371.43	$1,875.70	$ 3,309.34
ISX15 450	0	4	12	14	24	13	19	33	0	24	29	23	15	9	6	11	18	$1,399.30	$1,232.76	$ 1,154.10
ISX15 500	1	2	7	17	11	7	17	12	0	13	13	3	20	3	2	8	4	$1,389.37	$1,574.09	$ 1,484.56
ISX15 485	0	0	10	8	10	12	19	17	0	16	15	9	8	11	2	7	25	$1,866.19	$1,240.20	$ 2,408.17
ISX15 550V	0	0	1	2	3	4	6	5	0	8	5	3	1	4	1	2	3	$3,810.52	$1,430.05	$ 4,239.52
ISX15 525V	0	0	2	2	5	3	5	3	1	4	1	2	3	2	0	3	3	$2,153.17	$2,222.87	$ 4,324.72
STX12-E13	0	0	8	3	11	5	11	14	1	5	14	3	4	4	0	3	21	$1,049.42	$1,484.86	$ 624.97
ISX 425	0	0	0	1	1	1	3	2	0	3	1	0	1	0	0	2	3	$1,633.05	$ 664.84	$ 735.69
ISX15 525	0	0	0	2	2	1	1	3	0	2	2	0	1	1	2	0	1	$1,676.02	$1,229.16	$ 771.25
ISX15 400ST	0	5	30	12	28	7	24	56	0	15	69	10	47	14	2	10	12	$1,617.87	$1,137.52	$ 679.72
ISX 400ST	0	4	28	10	25	27	46	45	0	48	44	4	18	2	5	11	10	$1,572.12	$ 999.44	$ 1,358.40
ISX 400	0	2	6	3	8	4	7	14	0	13	7	0	4	1	1	5	1	$1,066.14	$1,026.93	$ 1,297.82
G6LTAA8.9E	134	0	187	90	506	0	374	488	2	0	307	8	224	47	24	280	47	$1,903.38	$1,578.82	$ 529.75
Total	136	94	762	441	1077	340	1031	1487	12	613	1329	368	813	250	101	544	430			

4.2.3 Discussion of Pilot Study Repair Cost Results

Coupling the repair cost estimates from the pilot study test fleet with those of the repair records, it can be seen that a wide range of repair costs can be found in real-world operation. The average repair costs per vehicle of $1,803 for vehicles with check engine lights on and $2,037 for vehicles with the DM1 MIL on for the pilot study fleet are in the same range as those found from the repair records. They do tend to be lower than those found for the major repair categories for the J & R facility, but slightly higher than those found for the non-warranty repairs for the Cummins Pacific facility. It is expected that the costs associated with OBD-related repairs could span a relatively wide range, as OBD is designed to identify issues with different components before they become catastrophic failures in addition to components that have actually failed. To the extent that OBD successfully identified component failures in an earlier stage, this could ultimately lead to lower total repair costs.

Another important finding of this study is that in many cases multiple emissions-related issues were identified and repaired while the vehicle was in for servicing. This observation is consistent both for the repairs that were conducted as part of the pilot study, and for the more extensive repair records that were obtained from J&R. So, it is felt that this phenomena is representative of real-world repair situations. The potential for multiple and more complex repairs could be attributed to the more extensive systems that are utilized on the latest technology trucks. In that regard, OBD can provide information to facilitate repairs and to identify needed maintenance on different engine systems.

4.2.4 Repair Frequencies

In attempting to predict the failure rate in the future heavy-duty fleet, an analysis was performed on the repair records obtained from the J&R facility. Specifically, the analysis focused on the J&R mechanic's comments recorded on each repair order which stated the reasons for repair. As the proposed method of identifying potentially high emitting trucks in I/M is through an assessment of the trucks' OBD systems, the coded comments for a total of 2,784 model-year 2010 and newer trucks were examined.

The clearest indication that repairs were emissions related and prompted by the OBD system was a notation by the mechanic that the Check Engine Light was on when the vehicle was initially brought in for service. However, vehicles were also counted as potential failures if mechanics noted they had found stored fault codes. These notations were considered less reliable because the OBD system may have been queried in the course of investigating other problems rather than being primary reason for seeking repair. As an example, the operator of a truck may seek repair because of loss of power. While the Check Engine light may not be illuminated, the mechanic may seek insight into the problem by querying the OBD system for stored codes.

Yet another subset of vehicle owners were advised by the J&R mechanics that the Check Engine Light was on and that emissions related repair were needed, however the owners/operators declined service believing that the needed repairs could/should be performed under warranty. It is important to note that J&R is not authorized by engine manufacturers to perform warranty work and the emission reductions related to repairs performed under warranty cannot be attributed to I/M at the risk of double counting. It is also important to note that the vehicles undergoing emissions related repairs at the J&R facility were doing so in the absence of I/M.

A total of 723 vehicles, or 26% of the 2010 and newer model year vehicles were identified as potential failures under the proposed I/M criteria relating to the check engine light. The average mileage of the J&R fleet was about 522,000 miles. The corresponding failure rates from the J&R fleet are estimated at 27% and 24%, respectively for 2010 to 2012, and 2013 and newer trucks after half a million miles of travel. CARB assumes linear growth in the incidence of tampering and mal-maintenance and reports fleet failure rate at 1,000,000 miles for the EMFAC model. Extrapolating these rates to 1,000,000 miles, the failures rates become 52% and 46%, respectively, for 2010-2012 and 2013 and newer vehicles. Figure 4-26 presents the failing vehicles identified in the J&R fleet as a function of mileage. Note that the failure rates for the J&R fleet do not show the increasing trend utilized in EMFAC above 500,000 miles. While one might think that failure rates might increase with increasing mileage, at the same time, only vehicles that are well maintained can be kept operational at higher mileages. As such, vehicles that have frequent failures at higher mileages tend to be taken out of in-use service.

Failure rate frequencies were also estimated for the DM1 MIL on vehicles. As the J&R repair records do not provide information related to the status of the DM1 MIL, failure rates were obtained through a combination of the J&R repair records and the pilot study data. As discussed above in section 3.2.2, the DM1 MIL was on for 30 of 48 repair visits (62.5%) for the pilot (excluding visits where the DM1 MIL data was not available), with would represent approximately 16% of the 2010 in-use fleet at 522,000 miles. The is further broken down to be 5 of 10 2010-12 vehicles (50%), and 25 of 38 2013 and newer vehicles (66%). Since the check engine light on was a criteria for recruitment for the pilot study, it was assumed that the fraction of check engine light on vehicles that would also have the DM1 MIL on would be the fraction identified in the pilot study. As such, the failure rates for the DM1 MIL on vehicles at 1,000,000 miles would be 52% x 50% = 26% for 2010-2012 vehicles and 46% x 66% = 30% for 2013 and newer vehicles. It should be noted, however, that this does not necessarily represent the fraction of check engine lights and DM1 MILs on in the on-road HDV fleet, as vehicles needing repairs would be preferentially found at repair facilities. It should be noted that the HEM data logger used was not designed for reading diagnostic messages, and the Silver Scan Tool was an older version that did not have the latest software updates, which could have caused some issues in determining the DM1 MIL status, although in most cases the MIL status identified by the HEM data loggers and Silver Scan Tool was the same.

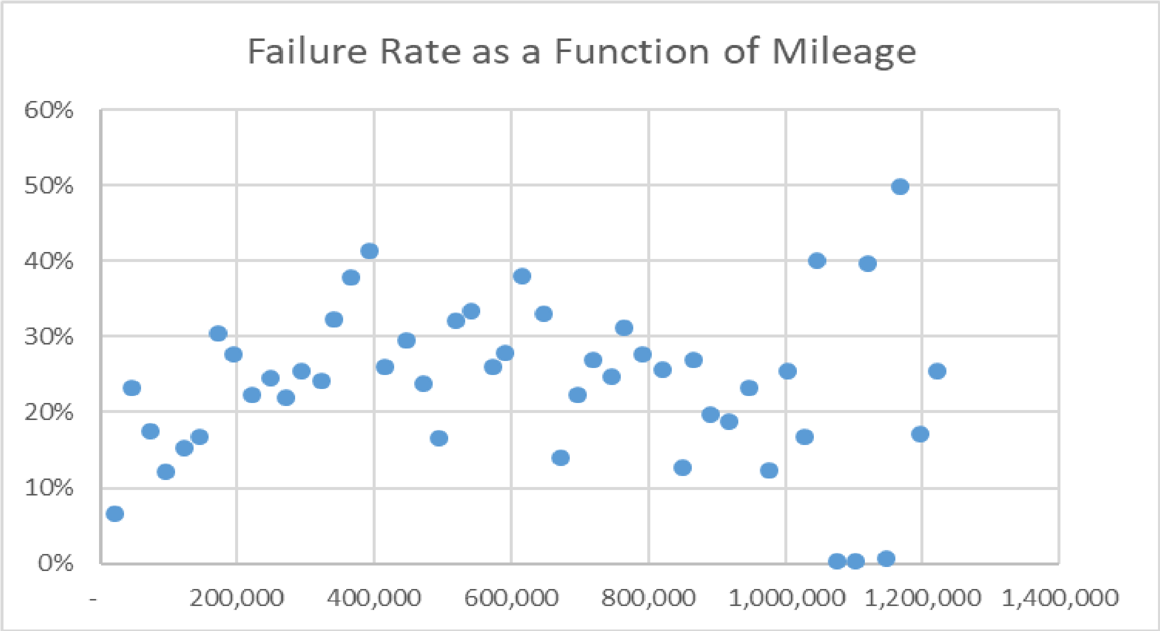
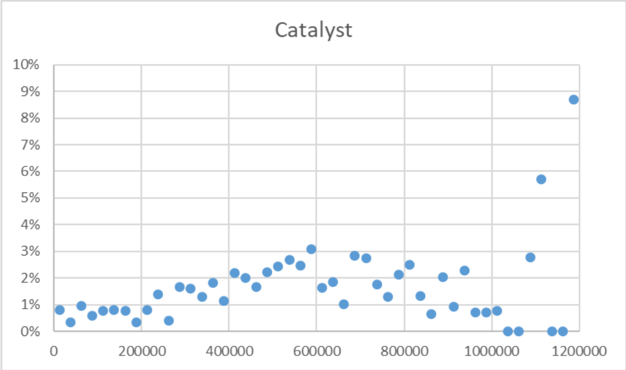
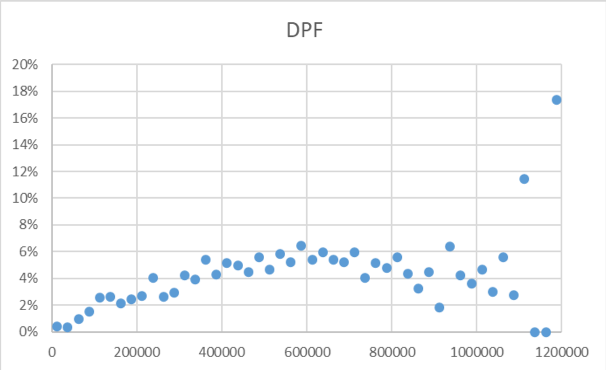


Figure 4-26 Check Engine Light On rates as a function of mileage for different repair types

Additional analyses were conducted to determine the repair rates as a function of different repair categories. For different repair categories, failure rates as a function of mileage were determined by stratifying the fleet by mileage into 25,000-mile intervals (from 0 to 1,225,000 miles). At each interval, the number of failing vehicles was assessed against the total number of vehicles in each interval. These failure rates are plotted in Figure 4-27. Additional analyses were conducted to evaluate the frequency of DPF replacements. This was done be evaluating the parts replacement fields of the J&R data to find incidences that could indicate major work on the DPF system. This analysis came up with 142 2010 and newer vehicles that appear to have had a DPF replacement This broke down to 6% of 2010 to 2012 vehicles and 3% of 2013+ model year vehicles. It should be noted that in general the failure rates found for the J&R fleet should not be assumed to be representative of the on-road fleet at large, as the J&R fleet is skewed toward vehicles in need of repair and owner/operators seeking non-warranty repairs.





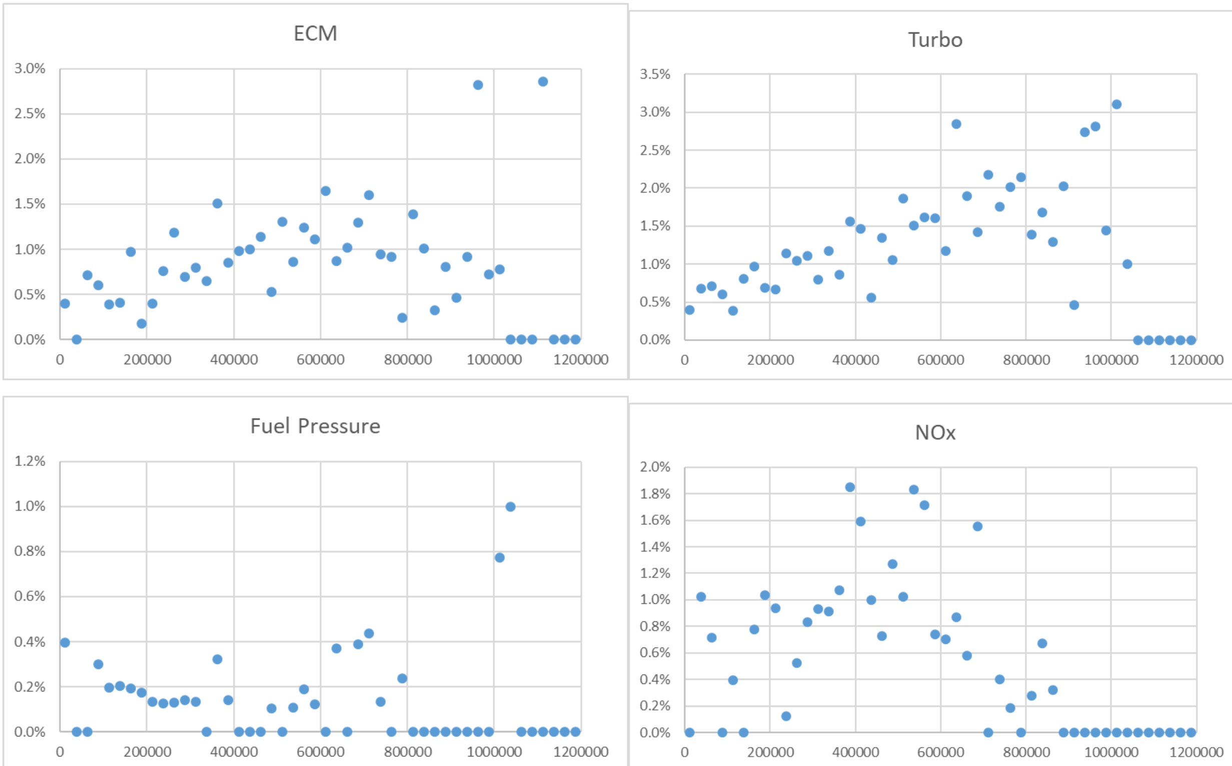
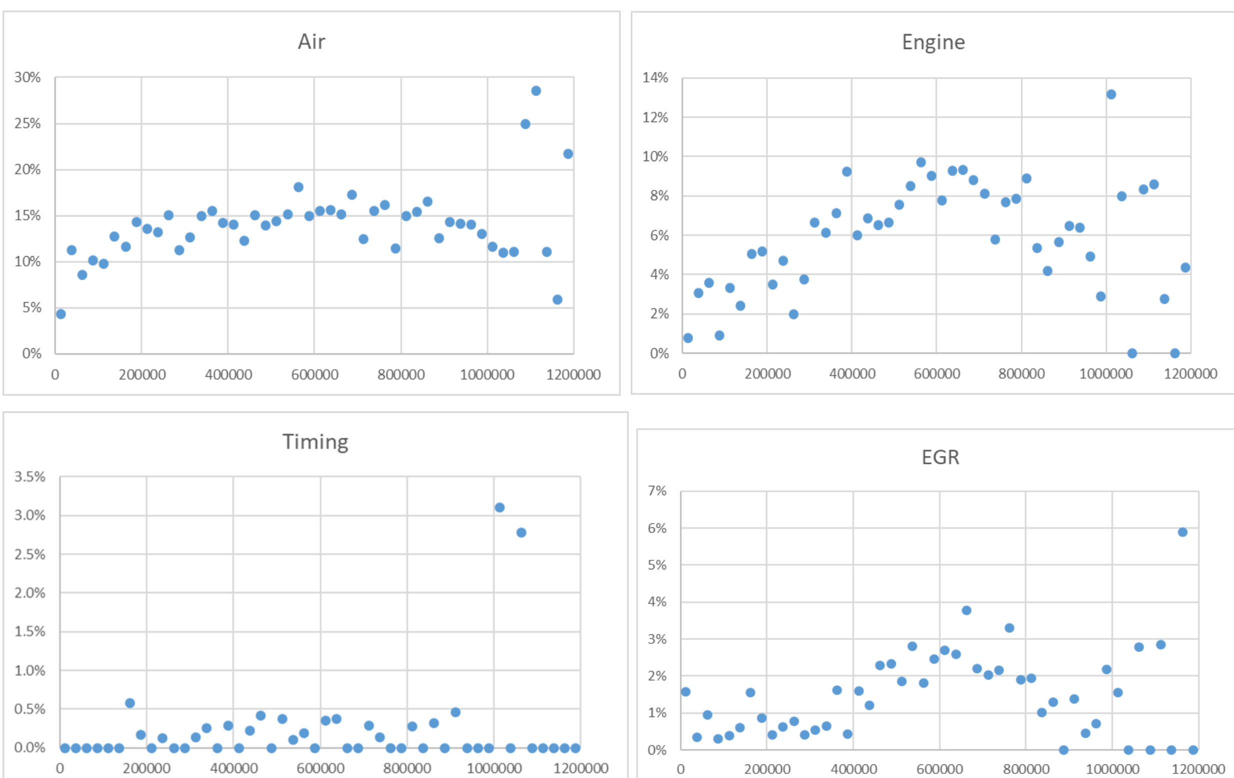


Figure 4-27 Failure rates as a function of mileage for different repair types



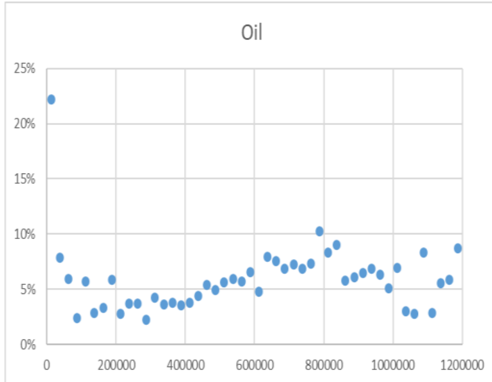


Figure 4-27 cont. Failure rates as a function of mileage for different repair types (continued)

5 Conclusions and Recommendations

The objective of this study was to develop, evaluate, and assess options for a more comprehensive HD I/M program for vehicles over 14,000 pounds GVWR, and to provide recommendations for the implementation of a full-scale program. This effort included a literature review, and a demonstration and evaluation of a prototype I/M program. Based on these results, recommendations for a comprehensive HD I/M program were provided.

5.1 Summary and Conclusions

The results from the literature review, pilot study, and pilot study analysis are summarized as follows:

5.1.1 Literature Review

The main emphasis of the literature review was to evaluate potential methodologies and instruments that could be utilized for a HD I/M program and propose a framework for a prototype HD I/M program that could be evaluated as part of this project. A summary of the main features and costs of different methodologies is provided in Table 5-1. A summary of the results of this literature review portion of the study for the different methods is as follows.

5.1.1.1 Tailpipe Emissions Measurements

Tailpipe emission measurement methodologies that were evaluated included chassis dynamometer emissions measurements, portable emissions measurement systems (PEMS), and remote sensing devices (RSD). Dynamometer testing represents one of the most comprehensive methods that could be utilized for a HD I/M program, and provides the best potential to correlate with laboratory grade emission measurements. However, the implementation of a dynamometer based inspection system that could service the full population of trucks in California, and the burden that would be associated with pulling vehicles out of service to go to such facilities on an annual basis make this option impractical for a full HD I/M program implementation.

PEMS can include both fully 1065-compliant PEMS, which are used in compliance testing, and smaller mini-PEMS that are designed to provide quality measurements without meeting full regulatory requirements. The cost and level of intrusion on the HD vehicle operator is still an issue with fully 1065-compliant PEMS, with the capital costs ranging from $100,000 to $120,000 for a gas-phase PEMS and from $200,000 to $220,000 for a PM PEMS. Mini-PEMS can be more readily deployed, and are considered as a possible method to validate high emissions identified from other methods. Costs of mini-PEMS can vary greatly from $30,000 to $50,000 for a more complete sensor-based type of mini-PEMS with the ability to measure multiple components or designed to meet a traceable metric, such solid PN. RSD or PEAQS-like systems have the advantage of being non-invasive, having the ability to capture the emissions of vehicles as they are driven by the owner/operator under real-world conditions. Capital costs for such systems could range from $100,000 or more depending on the complexity of the system design.

Table 5-1 Summary of Main Features of Various I/M Methodologies

Methodology	Pollutants	Ease of Use/Test time	Initial Capital Costs
Repair grade chassis dyno with I/M grade analyzers	NOx, PM, THC, CO, CO_2	Requires reporting to station location, 30 minutes to 1 hour for set up and actual testing	$170k for dynamometer with installation and I/M grade analyzers
1065-compliant PEMS	NOx, PM, THC, CO, CO_2	Requires mounting PEMS and driving truck, several hours to a full day	$100k to $120k for gas-phase $200k to $220k for gas-phase + PM
Mini-PEMS (sensor-based or solid PN)	NOx, PM, THC, CO, CO_2 for full system or a PM/PN only system	Testing under idle or snap acceleration conditions could take 10 minutes. Tests that require driving with mini-PEMS could be longer and prohibitively inconvenient	$30k to $50k
Remote Sensing Devices	NOx, PM, THC, CO, CO_2	Test conducted while truck is driven by and could be unmanned	$20k to 200k and upwards depending on complexity of set-up
OBD – repair station scan	Monitors system components related to NOx, PM, and HC emissions	10 to 20 minutes to conduct and record scan	OBD incorporated onto truck
OBD – kiosk system (physical connection)	Monitors system components related to NOx, PM, and HC emissions	Cable to download data from truck	Capital costs for a kiosk would be ~$50k with another ~$50k for installation
OBD – remote transmission methods	Monitors system components related to	Wireless transmission to a designated database	$50-$100 per unit for dongle

	NOx, PM, and HC emissions		Minimal costs for Wi-Fi data transmission
OBD – remote continuous monitoring	Monitors system components related to NOx, PM, and HC emissions	Data transmission through a cellular network	~ $17 per month per vehicle beyond the cost of the dongle

* Note that the capital costs reflect the costs for the purchase of major pieces of equipment. The actual per test cost would be considerably less than that and would depend on many factors, including the volume of the testing, the specifics of the testing requirements, and other items.

5.1.1.2 On-Board Diagnostics

OBD monitors all emissions critical devices and systems, stores diagnostic trouble code(s) (DTC) and illuminates a malfunction indicator light (MIL) when a problem is detected. A key advantage of OBD is that the vehicle's emission control system is continuously monitored as the vehicle is driven under real-world conditions. An OBD I/M test could be relatively quick, convenient to the owner operator, and the per test costs could be considerably lower than dynamometer or PEMs based alternatives for the full fleet. OBD can also be remotely monitored using telematics, which could allow the I/M program to be administered with little intrusion for the owner operator. The OBD system itself is already integrated into the engine design for 2013 and newer vehicles. Therefore, the only owner-related costs for an OBD-based HD I/M would be those associated with the visit to the repair station, centralized or decentralized inspection facility, or a kiosk, resembling a "drive up" ATM in size, with a physical connection.

Upgrading the OBD to remote OBD could be done for less than $100. With a remote OBD system, the OBD scan could be performed by a kiosk or other some other roadside antenna through a wireless local area network (Wi-Fi). Data transmission cost would be minimal in this case. Alternatively, OBD scan data could be transmitted on a continuous basis through a cellular network. This option would allow for the OBD system to be queried at any time, regardless of time or location. The costs of data transmission for continuous monitoring would be approximately $17 per vehicle per month.

5.1.1.3 Recommendations

Based on the literature review, it was suggested that both OBD and RSD or PEAQS-like technologies be used in implementing an enhanced, statewide I/M program for the on-road HDV fleet. Unmanned RSD devices and automated diagnostic and repair code readers could be deployed at state operated weigh stations, border crossings, cargo terminals and other strategic locations that could include traffic for both gasoline and diesel powered vehicle and those without or equipped with OBD. The deployment of the combination of on-site RSD/PEAQS and OBD would provide advantages in terms of both comprehensiveness and cost effectiveness in terms of monitoring the fleet as these vehicles are operated under real world conditions. Mini-PEMS could potentially also be incorporated into a HD I/M program as a verification of the pass/fail determinations, in a manner comparable to that of opacity testing in the current California program, either on a limited basis for confirmatory roadside testing or for fleets under a PSIP type of program.

5.1.2 Pilot Study

A pilot study was conducted to evaluate methods of emissions measurement that might be used in a full I/M program, emissions reductions from OBD-related repairs, and the associated repair costs. The exploratory pilot program consisted of testing 47 vehicles before and after repair on a chassis dynamometer. The testing included OBD scans, chassis dynamometer testing with I/M grade emissions analyzers and a number of mini-PEMS, and some RSD and PEAQS measurements before and after the repair.

5.1.2.1 Emissions Measurements Results

The pre-repair MAHA NOx emissions results showed that a number of vehicles had NOx emissions higher than 0.20 g/bhp-hr for both the initial 30 and 50 mph tests. However, it is acknowledged that the results should not be directly compared to certification standards, which are set for engine dynamometer testing that was not performed in the pilot study. The results showed that NOx reductions of greater than 80% were found for 43% of the 30 mph tests and 28% of the 50 mph tests after repair, with the highest emitters showed greater than 80% NOx reductions under all test conditions. The mini-PEMS generally showed relatively high NOx emissions for some of the same vehicles that showed high NOx emissions for the MAHA analyzer. SCR efficiency calculations were also made based on readings from the inlet and outlet NOx sensors for a subset of 9 vehicles. SCR efficiencies varied from vehicle-to-vehicle. For one engine manufacturer, SCR efficiencies were greater than 75%, and for another engine manufacturer some vehicles had efficiencies higher than 84% and others had pre-repair efficiencies below 70%, including two vehicles with SCR efficiencies below 15% pre-repair. The SCR efficiencies for the two vehicles with very low values improved to greater than 90% for most test conditions after repair.

The results for the NOx running exhaust emissions repair benefits for the vehicles in the broader categories having their check engine light on and for having the DM1 MIL on pre-repair provided in Table 5-2. Having the check engine light on is an indication that the ECM has identified a repair or maintenance need in one of the 22 target categories, and this was the criteria for recruiting all vehicles into the pilot study. The subset of vehicles where the DM1 MIL was on all had active diagnostic trouble codes (DTCs) indicating an emissions-related malfunction in addition to having the check engine light on. These values include only those vehicles for which the DM1 MIL was off post-repair, which would signify that the vehicle has sufficiently completed what would be the repair process for a HD I/M program. The results also exclude two trucks with Navistar engines that did not utilize SCR aftertreatment, and are estimated to represent only a very small fraction of the fleet by 2025. For the vehicles that were recruited based on the check engine light being on, the fleet average NOx emissions reductions were 75% at 30 mph and 46% at 50 mph. For the vehicles with the DM1 MIL on pre-repair, the fleet average NOx emissions reductions were 81% at 30 mph and 53% at 50 mph. The mini-PEMS generally were successful in detecting vehicles that showed high NOx emissions for the chassis dynamometer measurements with the I/M repair grade instrument. This suggests the mini-PEMS show the potential for identifying high NOx emitters.

The pre-repair opacity were 5% or less for all but 8 vehicles. Of the 8 vehicles with pre-repair opacity readings that were above 5%, 6 vehicles showed reductions in opacity to below the 5% level for the post-repair tests. Fleet average reductions of 43% in opacity were found for both all vehicles with the check engine light on pre-repair and for vehicles that also had the DM1 MIL on, excluding the Navistar trucks and the vehicles where the DM1 MIL was on for the post-repair test.

PM measurements during the 30 and 50 mph tests were relatively low and could not be adequately measured with some of the PM instruments. Solid PN and PM instruments showed greater sensitivity in measuring at such low PM levels. Although a DPF was replaced on one vehicle, the other vehicles did not appear to have catastrophic DPF failures. It was also difficult to quantify PM repair benefits because the DPF is often still capable of physically capturing excess PM even if a PM-repair failure is present. The impact of repairs on soot loading and regeneration frequency and improved maintenance in preventing more catastrophic failures was also not evaluated. It is suggested that further studies be conducted to better understand potential PM repair benefits for 2010+ vehicle technologies.

In comparing between the different instruments that were used for the measurement of PM and PN, the results were more complicated than for the NOx instrument comparisons. In particular, the opacity, PM mass, and PN measurements generally did not show a strong correlation for measurements on different test vehicles. This is likely due in part to the low PM levels that were found for the test vehicles and the small sample size. The opacity measurements were also done under snap accelerations, whereas the other instruments measured under steady state or idle conditions. Also, the fact that the PM instruments measure different characteristics of PM (mass vs. number), different properties (total vs. solid PM), and different particle size ranges, can influence comparisons between instruments. Most of the PM instruments were generally light weight, easy to use, and had short warmup times. It is suggested that a more systematic study may be needed to better understand the types of instruments that would be most appropriate for identifying PM failures for DPF-equipped vehicles, although other studies have suggested that PN may be the best metric for this application.

Measurements were also made for THC, CO, and CO_2 emissions. THC emissions were generally low and fell within a narrow range, but did not show consistent reductions in post-repair emissions. CO emissions were also low, and while some vehicles showed reductions in CO emissions after repair, these reductions generally represented very small changes on an absolute level. Although some differences in CO_2 emissions were seen between pre- and post-repair testing, the changes in CO_2 emissions could be due to changes in the dynamometer loading, which precluded the characterization of more precise changes in fuel economy.

Table 5-2 NOx Emission Reductions from Pilot Study

Failure Category	Pollutant	Emission Reduction (30 mph)	Emission Reductions (50 mph)
Check Engine Lights	NOx	75%	46%
DM1 MIL on	NOx	81%	53%

5.1.2.2 Repair Costs

The repair costs from the pilot study ranged from $250 to approximately $8,660, depending on the extent of the repair needed. The most costly repairs were primarily those associated with the replacement of more major parts, such as the DPF, SCR, turbocharger, or injector doser. Less expensive repairs included those that were sensor replacements or recalibration. It is expected that the costs associated with OBD-related repairs could span a relatively wide range, as OBD is designed to identify issues with different components before they become catastrophic failures in addition to components that have actually failed. Based on these estimates, the average repair cost per vehicle for a heavy-duty I/M would be $1,803 for vehicles with check engine lights on and $2,037 for vehicles with the DM1 MIL on.

In terms of failure rates in future heavy-duty fleet, an analysis was performed on a repair record database obtained from the main repair facility for a two-year period. This analysis indicated that 26% of the 2010+ vehicles, which had an average mileage of 522,000 miles, had their check engine light on upon arrival at the repair facility. The corresponding percentages of check engine lights being on were 27% and 24%, respectively, for 2010 to 2012, and 2013 and newer trucks. Based on estimates from the pilot study, is estimated that approximately 62.5% of vehicles recruited with the check engine light on, also had the DM1 MIL on. This would represent approximately 16% of the 2010+ in-use fleet at 522,000 miles. It should be noted, however, that this does not necessarily represent the fraction of check engine lights and DM1 MILs on in the on-road HDV fleet, as vehicles needing repairs would be preferentially found at repair facilities.

5.2 Recommendations

Based on a review of the potential methods, it is proposed that a revised HD I/M program incorporate both OBD and tailpipe methods, in manner that is cost effective and that provides cross confirmation between the different methods.

5.2.1 OBD as the Primary Methodology of HD I/M

HD OBD systems were designed in anticipation of statewide I/M. Phased in beginning with 2010 model year engines, OBD is required on all 2013 and newer model year heavy-duty vehicles. The advantages of the use of these systems in an enhanced I/M program are numerous. All emissions critical components are monitored continuously by OBD while the vehicles are in service, as such the vehicles and engines are by definition being tested under “real world” driving conditions. An OBD-based test would be relatively quick, convenient to the owner operator, and the pre-test costs are considerably lower than the dynamometer or PEMS-based alternatives. The algorithms used to illuminate the MIL are intrinsic to the vehicle and are based upon its certified level of emissions, thus eliminating the need to establish either representative driving cycles or pass/fail cut-points. OBD also has the greatest potential for shortening the interval between emission control system malfunction, detection, and vehicle repair. In contrast to alternative strategies, OBD provides diagnostic and repair information which should prove invaluable to the repair and maintenance community compared to reports of levels of pollutant that they may not be familiar with. It should also be noted that the use of OBD minimizes the potential liability borne by the state associated with dynamometer testing, requiring a vehicle to be driven over a uniform route, or the installation and removal of portable emissions measurement equipment on privately owned vehicles by agents of the state.

Given that the state owns and operates weigh stations strategically located throughout the state and that CARB staff already uses the weigh station infrastructure, in conjunction with the California Highway Patrol, for roadside heavy-duty vehicle testing, it is suggested that site-based OBD information collection systems be installed at these locations. In as much the same manner that light-duty kiosks have been established in some states for periodic inspection of the fleet, trucks would be automatically scanned when passing through or by the weigh stations. The cost per transaction (communication from the vehicle to the reader) is estimated be pennies per vehicle and would not represent additional owner/operators cost or inconvenience given existing requirements to visit the scales. It is suggested that site-based remote OBD readers be considered for deployment at other strategic locations including major cargo terminals and border crossings. Aftermarket "plug-in" remote OBD devices are currently commercially available for less than $100/unit which utilize either blue-tooth or SIM based technology for communications purposes. This technological choice could be ideal for monitoring out-of-state vehicles and those that may routinely avoid control locations. Alternatively, data could be monitored continuously through transmissions through a cellular network, although subjecting vehicle owners to continuous monitoring could be more difficult to implement from a practical standpoint.

Particular concerns regarding enhanced statewide HD I/M include the monitoring of out-of-state vehicles, and vehicles that can perform their normal operations without reporting to a designated point of control such as a weigh station, terminal, or border crossing. It is also anticipated that a significant portion of the heavy-duty fleet will be OBD II equipped when enhancements to HD I/M are anticipated to be enacted. In each of these instances, the use of remotely monitored OBD should be considered.

5.2.2 Coupling of an OBD-based HD I/M with roadside monitoring with a remote sensing methodology

It will be important to have a validation testing element as a supplement to OBD within a comprehensive HD I/M program, particularly since some portion of the fleet will not be equipped with OBD. It is suggested that one component of a HD I/M program include the implementation of RSD/OHMS/PEAQS-like systems. The advantages of RSD/OHMS/PEAQS-like systems include the fact that the devices are non-invasive, and have the ability to capture emissions of vehicles as they are driven by the owner/operator under real-world conditions. Such systems should also provide the potential to measure HC, NOx, PM, CO, and CO_2, speed information, and vehicle identification information. To eliminate the need for trucks to report to a centralized facility, RSD/OHMS/PEAQS could be set up at truck weighing stations or other locations where there is a high incidence of HDV traffic throughout the state. This could include the 51 weigh stations at 37 locations that the state currently owns. Such a system that can be operated at a low cost and largely unmanned for extended hours could be key for this implementation. One disadvantage of such systems is that they only evaluate over the limited operating conditions that occur while the HDV is passing through the system. This could lead to conditions where some high emission failures could be missed, while the HDV might also be operated in a manner that might trigger high emissions that could not otherwise be seen under typical operations.

5.2.3 A comprehensive HD I/M program with OBD as the primary methodology, remote sensing and mini-PEMS for validation testing

Although the coupling of OBD with remote sensing will provide for a relatively comprehensive HD I/M program, there are some conditions that may still require additional resolution beyond what could be captured in a pure OBD+remote sensing program. This could include repair/maintenance issues that lead to high emissions that don't trigger the OBD MIL and are also not detectable at the limited conditions evaluated by RSD. Mini-PEMS could be used on a more limited basis to verify emissions readings or the effectiveness of RSD in identifying high emitters. Mini-PEMS could be utilized at weigh stations or in fleets similar to the PSIP for this purpose, and could provide significant advantages in sensitivity compared to current opacity testing. This could be similar to the solid PN instruments that are being used in Europe under Swiss Regulation 941.242 for non-road equipment. Such testing would need to be designed so that it could be completed in a short period of time (~10 minutes), under conditions that do not require the instrument to be mounted on the vehicle (such as idle or snap accelerations), and by operators that do not have significant training. As the results of the pilot study did not show consistent trends between the different PM/PN mini-PEMS, additional study in this area is suggested to identify a suitable mini-PEMS for this application. It is expected that over the next 8 years that mini-PEMS technology will continue to improve, and that such mini-PEMS could potentially provide sufficient accuracy to distinguish between failing and non-failing vehicles in this capacity.

Chassis dynamometer and fully 1065-compliant PEMS methods were also considered in this capacity, but would likely be more burdensome in terms of the need for vehicles to be taken out of service to report to a centralized location, the more extensive requirements in terms of setting up and conducting the testing, and the greater capital costs associated with the test equipment. Additionally, an extensive network of chassis dynamometers would need to be established throughout the state to fully service the vehicles. The feasibility of establishing such a network and the associated testing costs would need to be investigated further to determine the feasibility of implementing a chassis dynamometer-based HD I/M program. Chassis dynamometer and 1065-compliant PEMS would, however, continue to play an important role in terms of in-use surveillance testing and in-use regulatory testing of manufacturer trucks.

5.3 Overall Conclusion

Overall, the testing results suggest that a HD I/M program will provide significant and tangible emission benefits and can be an integral component of California's ability to meet federally-mandated ambient air quality standards, and CARB's overall air quality, sustainable freight, and climate goals.

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Appendix A. Vehicle-Repair Selection Test Report Form

Vehicle Description

Vehicle no. ____________Date___________ Repair shop: J&R / Cummins Pacific

Engine mfr______________ Vehicle mfr________________________________

Engine MY_______ Vehicle MY______ Vehicle type (tractor, bus, etc.)_____________

Engine model___________ Engine family number_________________________

Displacement_______ # Cylinders _____ Max. Power/Torque____________________

Vehicle Mileage_______ Vehicle VIN_______________________ LPN___________

Comments____

____

Diagnosis and Repairs

Customer's stated reason for requesting vehicle service (including owner/driver complaints)?

____

Did vehicle come in for service with MIL illuminated? YES_______NO_____________

If NO, could MIL be commanded on through OBD system? YES_______NO________

Repair facility's diagnosed reason(s) for repair:_________________________

____

OBD check:____

Which SAE OBD protocol was used for the OBD check? J1939_______J1979_______

Visual inspection:____

Functional inspection:____

Any performance checks:____

Actual components to be replaced:____

____

Repair Cost (s):___________________________________Warranty: ______________

Comments____

Appendix B. Description of Chassis Dynamometer Test Facilities

J&R Heavy-Duty Chassis Dynamometer Laboratory

J&R has installed a heavy-duty tandem axle truck chassis dynamometer in the facility's research area, in conjunction with Taylor Dynamometer. The development of the chassis dynamometer design was based on target vehicles in the medium to heavy-duty diesel vehicle range. This high performance 48" Electric Chassis Dynamometer has Dual Direct Connected. The roll brakes are pneumatically-actuated disc. The dynamometer is capable of simulating exacting road load & inertia forces to a vehicle operating over a range of different driving conditions including highway cruise, urban driving, and other typical on road driving conditions. The robust dynamometer can continuously absorb/motor loads of 1100 HP at 35 mph. The dynamometer is able perform vehicle inertia simulation across a vehicle weight up to 120,000 lb.

Appendix C. Emissions Analyzers for Chassis Dynamometer Measurements

MAHA MGT 5 Emissions Tester

The MAHA MGT 5 Emissions Tester is a 5 gas analyzer capable of measuring HC, CO, NOx, CO_2, and O_2. The specifications for the analyses for each of these pollutants is provided in the Table C-1 below. The instrument is shown in Figure C-1.

Table C-1 Specifications for Emissions Analyzers

Meassurement gas	CO	CO_2	HC	O_2	NO_x
Measurement range	0…15 Vol %	0…20 Vol %	0…2000 ppm Vol (Hexan), 0…4000 ppm Vol (Propan)	0…25 Vol %	0…5000 ppm Vol
Measurement accuracy **absolute or 5 % of the measurement value (the higher value is decisive)**	0.03 Vol %	0.5 Vol %	10 ppm Vol	0.1 Vol %	32…120 ppm Vol (dependent upon measurement range)
Measurement principle	infrared	infrared	infrared	electro-chemical	electro-chemical
Measurement value resolution	0.001 Vol %	0.01 Vol %	0.1 ppm Vol	0.01 Vol %	1 ppm Vol

Figure C-1 Emissions Analyzers for Chassis Dynamometer Measurements

MAHA MDO2-LON Diesel Opacity meter

The MAHA MDO2-LON Diesel Opacity meter utilizes absorption photometry for the measurement/estimation of particle emissions. The instrument uses a pulsed green 567 nm wavelength LED-light source. The detector is a temperature compensated photo diode. The unit is pictured in Figure C-2.

Figure C-2 MAHA MDO2-LON Diesel Opacity meter

Appendix D. Chassis Dynamometer Test Cycles

The following are descriptions of different chassis dynamometer test.[3]

D550 Short Test

The D550 test is detailed in Anyon P, 1995, *Diesel Inspection and Maintenance. The D550 Short Test*. Emissions sampling occurs during the last 30 seconds of the test cycle as illustrated in Figure D-1 below. This Steady-state test is carried out at a dynamometer load equivalent to a fully laden vehicle driving up a 5% gradient at 50 km/h. This represents a near full-load condition for most vehicles. As it is a constant load, constant-speed test, it requires only a simple power dynamometer. The test is designed so that there is no need to establish maximum power or torque outputs, unlike the lug-down and 2-speed tests described later.

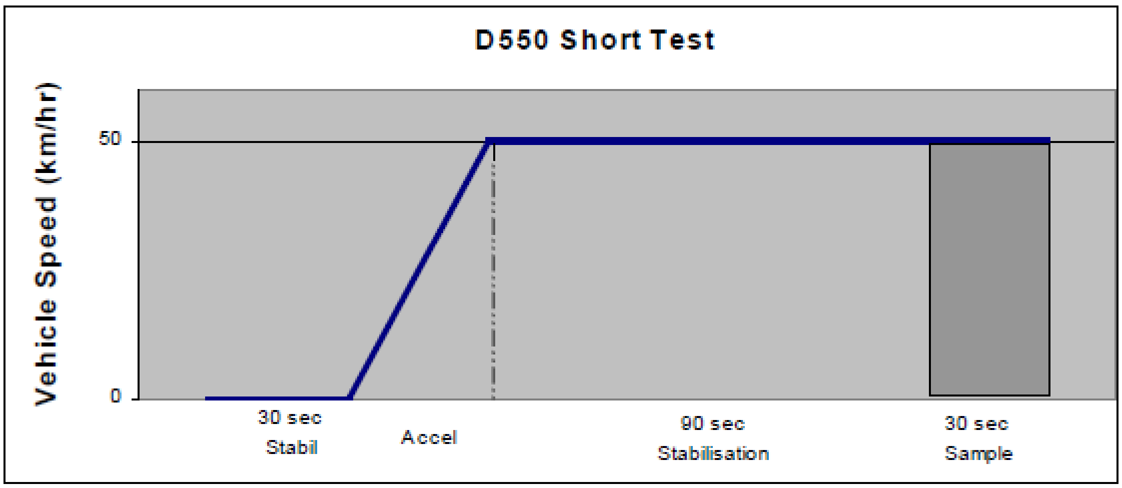


Figure D-1: D550 Short Test

Two-Speed Short Test

The Two-Speed Test (Figure D-2) is designed for measurement of emissions under steady-state conditions replicating two of the four test points in the engine dynamometer tests carried out for ADR 30 (Diesel Engine Smoke Emissions). Emissions are sampled at two points (rated speed and intermediate speed) for 30 seconds each. The test is carried out under full-load conditions using a simple power dynamometer.

[3] Anyon P, Brown S, Pattison D, Beville-Anderson J, Walls G, Mowle M, 2000, Proposed Diesel Vehicle Emissions National Environment Protection Measure Preparatory Work, In-Service Emissions Performance - Phase 2: Vehicle Testing, Prepared for the National Environment Protection Council by Parson, Inc., November.

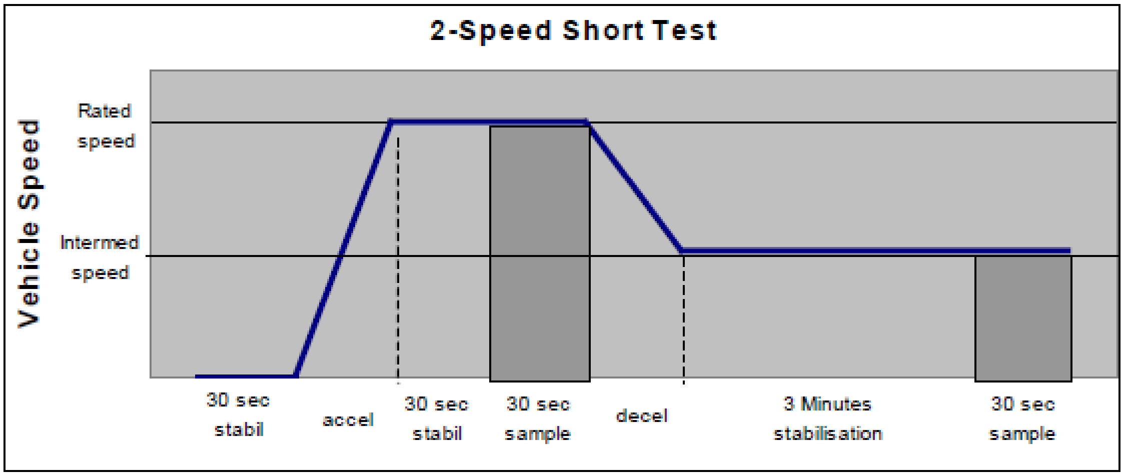


Figure D-2: 2-Speed Short Test

Snap Idle Short Test

The Snap-Idle (or 'Snap Acceleration' or 'Free Acceleration') test (Figure D-3) is variously described in Regulations and standards in USA, Europe, Japan and a number of other countries. The most detailed specification for the test is given in Society of Automotive Engineers, 1996, *Surface Vehicle Recommended Practice J1667 Snap Acceleration Smoke Test for Heavy-Duty Diesel Powered Vehicles*. The test is very simple to perform, and requires no dynamometer. Emissions are sampled during the period from 0 to 100 % full throttle.

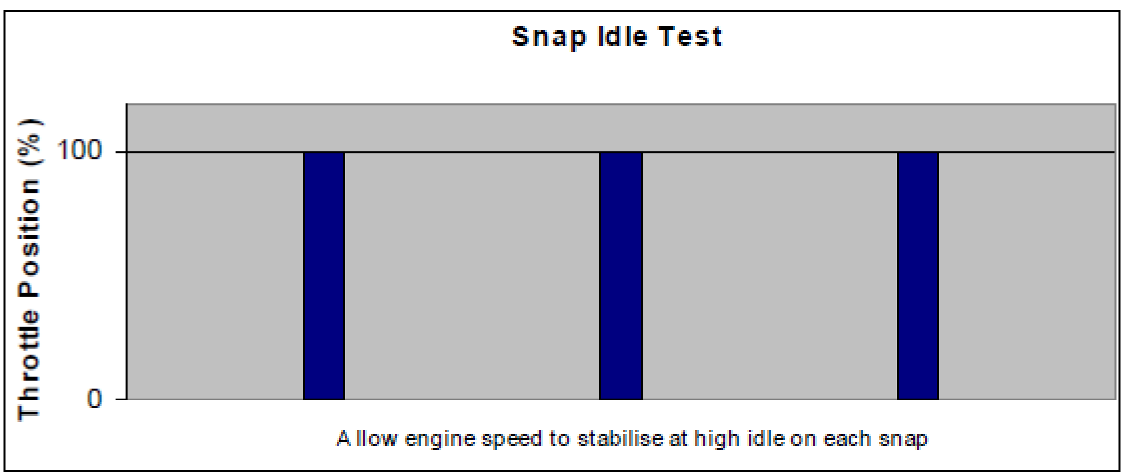


Figure D-3: Snap Idle Short Test

Lug-Down Short Test

The lug down test (Figure D-4) is based upon similar tests carried out for smoke emissions specified in the *State of Colorado – Regulation 12 'the Reduction of Diesel Vehicle Emissions'*. The test is carried out at full load, requiring a relatively simple power dynamometer and control system at four steady state points during which time emissions are sampled for 30 seconds.

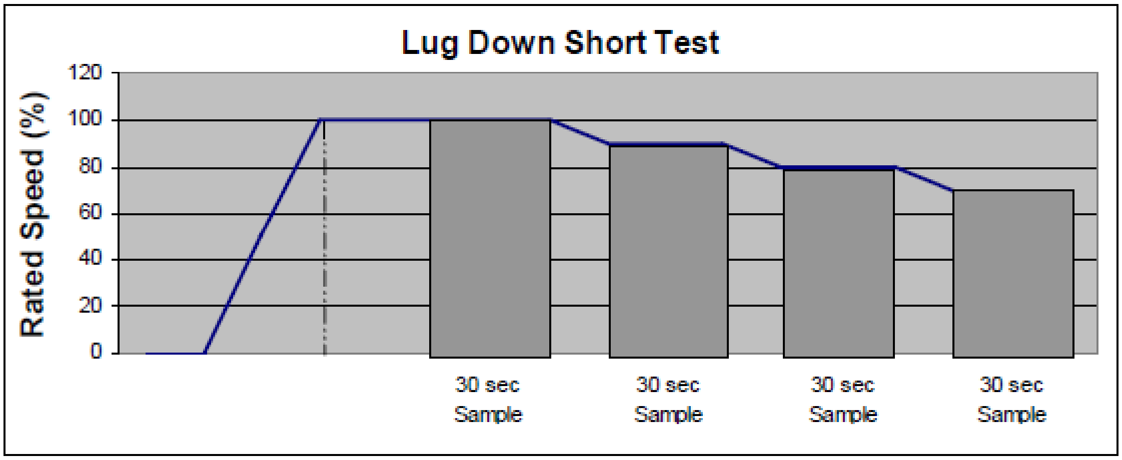


Figure D-4: Lug Down Short Test

DT80 Short Test

The DT80 Test (Figure D-5) is a relatively aggressive mixed-mode test, having three full-load accelerations, as well as a steady-state 80 km/h cruise. The test requires the use of a dynamometer with inertia simulation. Emissions are sampled during the entire cycle.

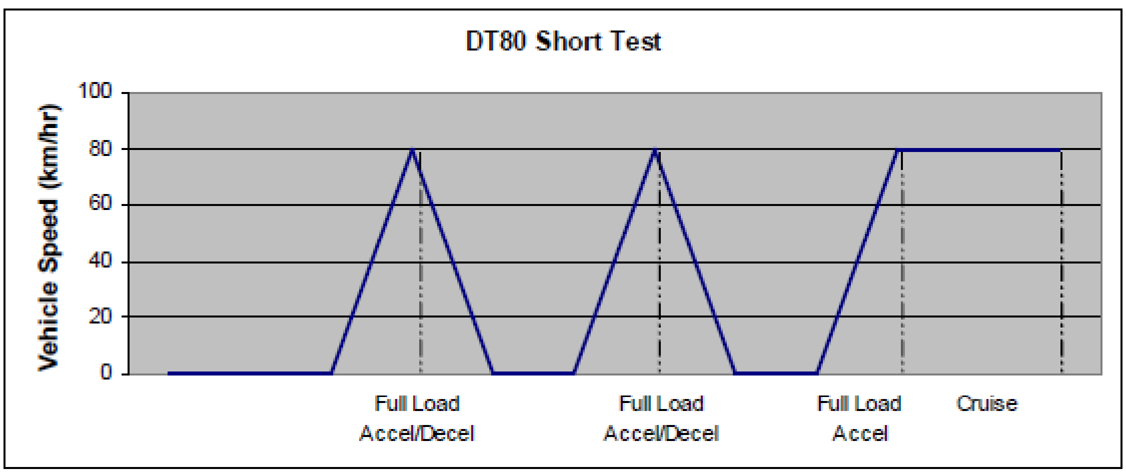


Figure D-5: DT80 Short Test

AC50/80 Short Test

The AC50/80 (Figure D-6) is a mixed-mode test having two full-load accelerations and two steady-state cruises. It is less aggressive than the DT80, but emissions are sampled during the full period of the cycle like the DT80. It requires the use of an inertia-simulating dynamometer.

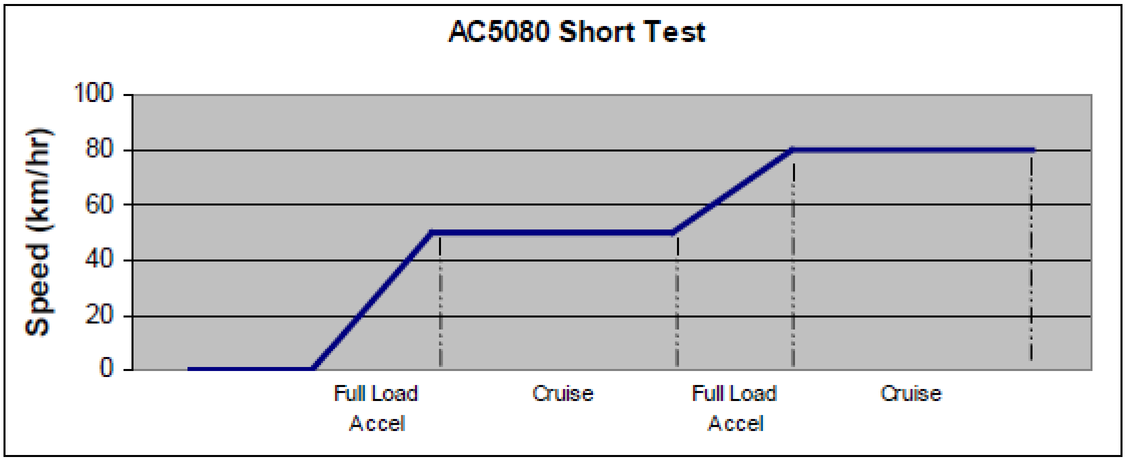


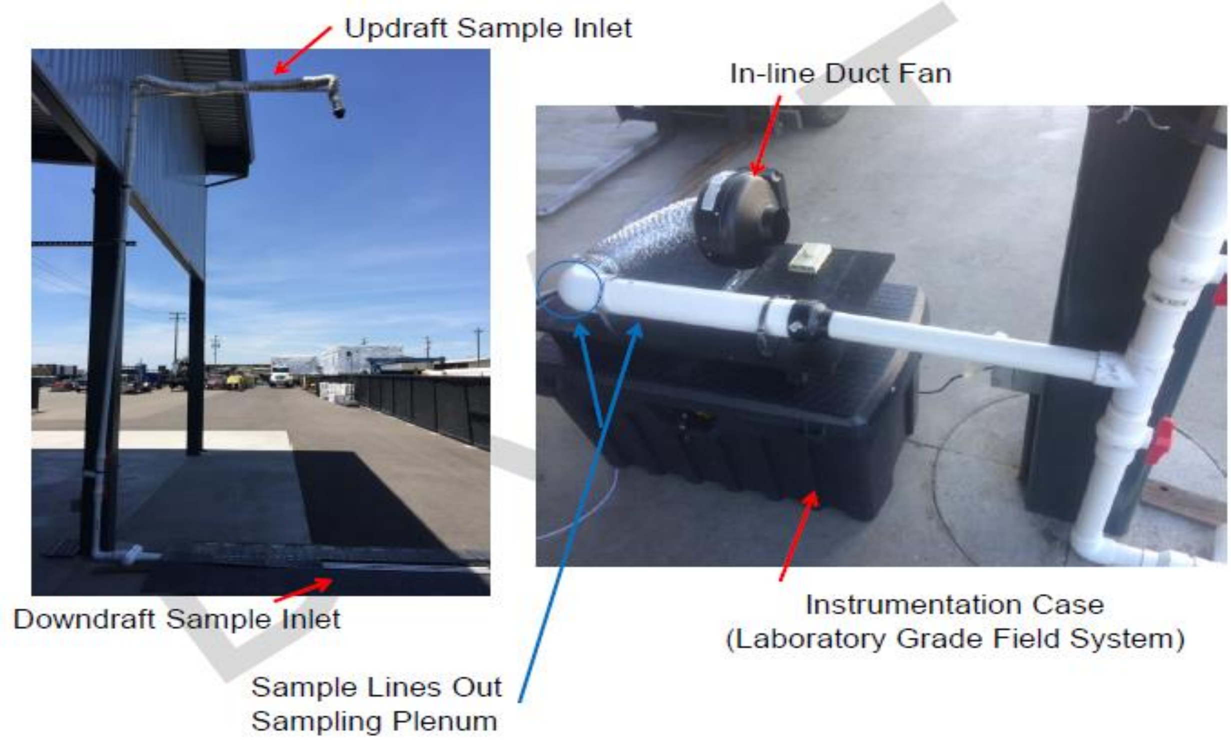
Figure D-6: AC50/80 Short Test

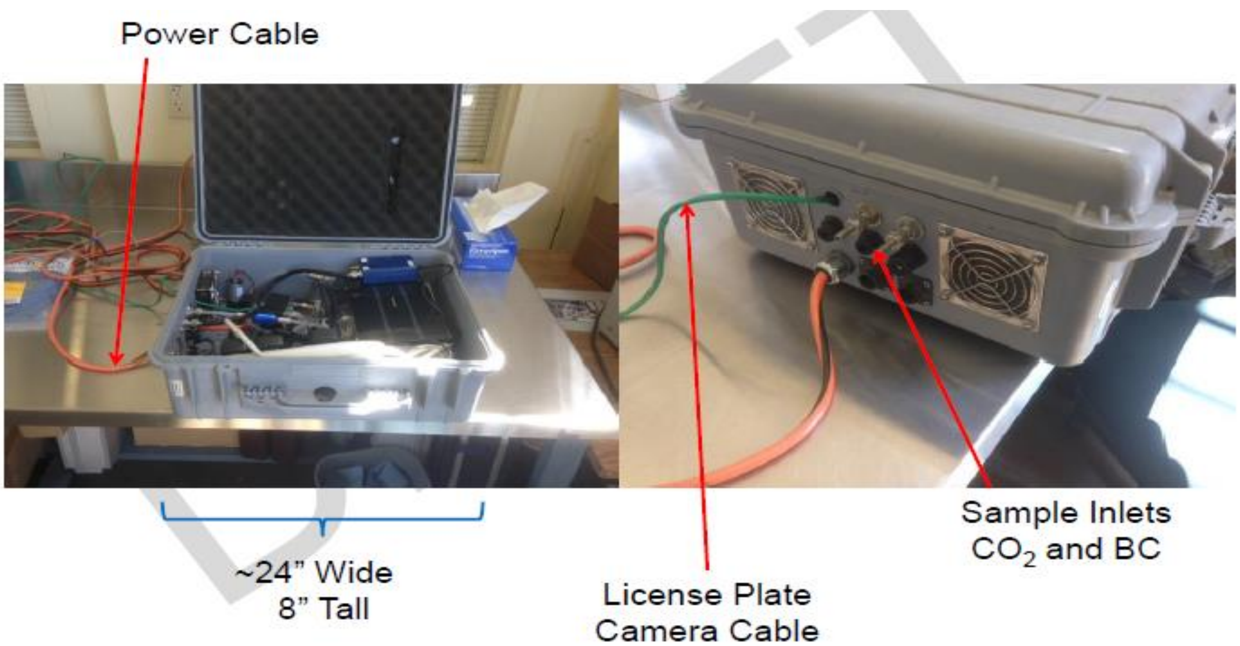
Appendix E. HEAT EDAR Remote Sensing Device

Hager Environmental & Atmospheric Technologies, LLC (Hager Environmental) was founded in 2009 to develop an advanced and unique technology aimed at revolutionizing the Vehicle Emission Testing Industry. This technology, EDAR (Emissions Detecting And Reporting), is an eye safe laser-based technology capable of remotely detecting and measuring the infrared absorption of environmentally critical gases coming out of a moving vehicle. EDAR contains a multi-patented system of hardware and software, which allows for a multi spectral 3-dimensional image of the entire exhaust plume of a moving vehicle. Additionally, The EDAR technology is designed to collect data on various gases (CO, CO_2, NOx, HC and Particulate Matter (PM)) as part of an unmanned system. Since EDAR uses remote sensing technology, these units require only periodic maintenance that is performed by a third-party maintenance company. The technology behind EDAR eliminates the need for Calibration, which allows for it to be an unmanned system with one footprint for both heavy and light duty vehicles.

Appendix F. CARB Portable Emissions AcQuisition System (PEAQS)

The PEAQS system consists of two sampling lines (one 'updraft' pipes and one for 'downdraft' pipes), connected to some emissions analyzers, and a license plate reader (LPR). Pictures of the PEAQS system are provided below.





Appendix G. Description of Mini-PEMS

This Appendix describes the measurement principles of the different mini-PEMS instruments that were utilized in this study. The technical specifications of the instruments are provided at the end of this section.

Pegasor has developed a PM sensor that is being used in a variety of applications.[4] The Pegasor PPS-M is a PM sensor module. The operation of the PPS-M sensor is based on electrical charging and detection of the charged aerosol particles. The design combines a sheath air-assisted corona charger with an ejector pump. Clean air is ionized via a positive corona needle and mixed with the sample, charging the particles. The positively charged particles enter and escape a Faraday cup creating a net total charge that is proportional to particle concentration. As such, it can be used to measure particle mass and number concentration. The sensor can be used as an independent module, but has also been integrated into a more complete PEMS system. Systems that incorporate the Pegasor PM sensor include the NTK system, the SEMTECH CPM system, and the Control System unit from Italy.

NTK has developed a small PEMS system called the NTK Compact Emissions Meter (NCEM).[5] The system can be used to measure PM and particle number (PN), NOx and O_2, and air/fuel ratio. The system weights about 12 kg and measures 340 mm by 280 mm by 270 mm. It can be set up in approximately 5 minutes. It is powered by a DC12/24V vehicle battery and draws less than 10Amp to operate. The PM/PN sensor is based on the Pegasor technology. The NOx sensor detects NOx by measuring disassociated O_2 ions from NOx in a second chamber. UC Riverside conducted some comparison tests with the NTK system for both an on-road and marine engine. For the on-road engine, the NTK NOx values were within 20% of UCR Mobile Emissions Laboratory (MEL) results, with the NTK NOx measurements generally being lower than the MEL reference method. PM values were within 70% with PM2.5 for engine dyno test. For the marine engine, NOx emissions showed a good correlation with a CLD-NOx in a bypass mode. PN Compared Well with CPC Results of the Marine engine for the Catalytic Stripper Mode. NTK vs CVS PN Differences resulted from organic condensation formation in CVS, as the NTK measurement represents a solid PN.

TSI has developed a Nanoparticle Emissions Tester (NPET) that has been used in studies to identify high emitting vehicles.[6] The NPET measures total solid particle number emissions, and can be used with a variety of applications, including buses, construction equipment, and others. This unit is designed to sample raw exhaust directly from the tailpipe downstream of a DPF to evaluate the condition of the DPF for in-use after-treatment certification, inspection and maintenance, and emissions research. The NPET includes a 10:1 diluter with a dryer for the recirculating dilution flow, a catalytic stripper heated to 350C to evaporate, oxidize, and remove volatile particles, and a condensation particle counter (CPC) for counting the particles. The NPET

[4] Saukko, E., Järvinen, A., Wihersaari, H., Rönkkö, T., Janka, K., and Keskinen, J., 2016, Expanded Capabilities of Dual Pegasor PPS-M Sensor in PEMS Measurements Beyond PN, PM and Particle Size, PEMS Workshop 2016, UC Riverside, Riverside, CA, March.

[5] Jiang, Y., Johnson, K.C., Durbin, T.D., and Yang, J., 2016, Evaluation of NTK Compact Emission Meter (NCEM), PEMS Workshop 2016, UC Riverside, Riverside, CA, March.

[6] TSI Incorporated, 2015, Nanoparticle Emissions Tester Model 3795 brochure and website, www.tsi.com/NPET.

is certified by the Swiss institute of metrology (METAS) to test to Swiss Regulation 941.242, which mandates the bi-annual testing of all non-road mobile machinery (NRMM) to ensure that the DPFs are continuing to function throughout the life of the equipment. The unit has been used in Santiago, Chile to evaluate the effectiveness of DPFs that have been installed on buses. In one testing campaign, five buses were measured on route and with the 40-second official SR 941.242 test with the NPET, as well as with a free acceleration opacity test. Of the five buses tested, all five passed the existing opacity standard of 0.24 m^{-1} while only three of the five passed the Swiss standard of 2.5 x 105 cm^{-3}. Additionally, one of the buses failing the Swiss test, had opacity reading very similar to those passing the Swiss test. The NPET has also been utilized for measurements of a DPF-equipped John Deere 6068TF275 diesel engine stationary generator.

The Testo Portable Emission Particle Analyzers (PEPA) is a particle number instrument designed for vehicle type approval in Europe. The PEPA measures the number concentration and diameter of nanometer sized particles in the size range 10 – 500 nm. The instrument is based on a diffusion charging technology and uses electrical charging to count particles. The unit also incorporates a PMP-compliant volatile particle remover. The instrumentation is compact, easily portable and provides on-line response. Due to these properties it is a suitable technology for particle number concentration measurements in non-laboratory settings. It is battery operated and therefore appropriate for on-board and field measurements.

The 3DATX Corporation has developed a smaller size integrated portable emissions measurement systems (iPEMS). The systems are called the parSYNC® and parSYNC® PLUS and are designed to provide a lower cost option to full 1065 compliant PEMS.[7] Both the parSYNC® and the parSYNC® PLUS utilize a miniaturized multi-chamber and replaceable (patents pending) “Sensor Cartridge” designed to obtain real-time PM/PN performance data from diesel engines either in a dedicated “pass/fail” lane testing configuration or in a field unit PEMS/PAMS approach. In addition, the parSYNC® PLUS adds a NO/NO_2 (NOx)/CO_2 GasMOD™ Sensor Cartridge. The 3DATX Corporation has also developed a particle generator called the CA/GE™ System that is designed to produce a controlled size-disbursed/distributed aerosol combination of non-toxic particles and vapor in the required size range. This provides a calibration method suitable for verification and certification programs and allows for ambient particle testing in areas where a normal particle count is not sufficient.

[7] Ropkins, K., Li, H., and Andrew Burnette, A., 2016, Next Generation (Smaller, Lower Cost, Lower Energy Consumption) Portable Emissions Measurement Systems, PEMS Workshop 2016, UC Riverside, Riverside, CA, March.

Appendix H. Supporting Data

Table H-1 Pre- and post-repair for CO_2 emissions from MAHA and parSYNC® PLUS for each vehicle

Vehicle NO.	Manufacture	Pre-repair CO_2 Emissions %				Post-repair CO_2 Emissions %				% difference			
		30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle	30 mph	50 mph	Idle	High Idle
J&R01	2011 Cummins	5.2	6.9	1.5		7.9	9.5	1.9		52%	39%	30%	
Cum01	2015 Cummins	6.6	8.6	1.8	2.6	7.2	8.4	2.2	3.6	10%	-2%	25%	42%
Cum02	2010 Cummins	8.9	8.2	3.2	5.2	8.6	9.6	7.6	4.7				
J&R03	2013 Cummins	9.0	8.7	4.1		9.5	8.9	3.8		6%	2%	-7%	
J&R04	2013 Volvo	9.2	10.0	4.3		7.6	9.5	2.8		-18%	-5%	-35%	
J&R05	2012 Cummins	8.2	9.0	6.6		7.8	10.3	4.9		-5%	14%	-25%	
J&R06	2015 Cummins	6.5	9.1	2.6		8.1	8.9	2.5		24%	-3%	-4%	
J&R07	2014 Volvo	6.9	8.9	2.8		7.6	8.7	2.8		10%	-2%	-1%	
J&R09	2012 Cummins	10.1	11.1	7.0	6.4	6.7	9.6	3.9	3.3	-33%	-13%	-44%	-49%
J&R10	2011 Cummins	7.1	9.3	2.7	3.3	8.9	9.4	2.7	4.0	26%	1%	-1%	21%
J&R11	2013 Cummins	7.3	9.5	4.4	3.3	6.3	9.1	3.8	2.2	-15%	-4%	-14%	-33%
J&R12	2011 Volvo	6.4	9.8	2.8	2.7	6.9	9.4	2.8	3.0	8%	-4%	3%	10%
J&R13	2013 Cummins	4.7	6.8	1.8	2.2	5.4	6.9	2.0	2.0	15%	3%	10%	-7%
J&R14	2010 DDC	8.5	8.6	2.1	2.3	8.9	8.4	2.4	2.3	5%	-2%	15%	0%
J&R15	2010 Navistar	10.8	12.5	4.5	4.7	13.8	13.1	5.3	6.2	28%	6%	18%	33%
J&R16	2010 Mack	8.4	8.5	6.2	4.0	8.4	8.1	4.4	4.5	0%	-4%	-29%	11%
J&R17	2011 Cummins	6.4	6.0	1.4	2.1	8.4	7.9	1.8	2.6	30%	32%	27%	21%
J&R18	2014 Cummins	7.8	8.8	3.2	2.1	7.8	9.6	3.3	2.2	-1%	9%	3%	2%
J&R19	2015 Cummins	9.5	8.7	5.2	3.1	9.9	9.1	5.0	3.1	4%	4%	-4%	-2%
Second visit		9.9	9.1	5.0	3.1	9.5	10.5	3.5	3.9	-4%	15%	-29%	27%
J&R20	2011 Cummins	8.5	8.9	6.2	4.1	9.4	10.1	6.4	3.7	11%	14%	3%	-9%
J&R21	2013 Cummins	7.4	8.9	3.3	2.8	8.0	9.0	3.5	2.8	9%	2%	6%	3%
J&R22	2013 Cummins	6.5	6.7	1.9	2.5	7.5	9.3	4.0	3.0	16%	39%	114%	19%
Second visit		7.5	9.3	4.0	3.0	8.2	8.9	3.6	4.1	9%	-5%	-9%	39%
J&R23	2013 Cummins	8.0	9.2	3.8	3.6	8.9	9.6	3.6	3.3	12%	4%	-7%	-7%
J&R25	2013 Cummins	8.86	10.29	4.03	2.61	8.48	10.25	4.04	2.62	-4%	0%	0%	0%
J&R26	2013 Paccar	9.81	10.94	3.92	2.53	10.26	10.31	4.62	2.71	5%	-6%	18%	7%
J&R27	2014 Volvo	9.54	7.84	2.87	2.77	8.65	8.09	2.45	2.59	-9%	3%	-15%	-7%
J&R28	2013 Cummins	9.53	9.94	4.71	3.50	7.45	9.24	3.66	2.38	-22%	-7%	-22%	-32%
J&R29	2014 Cummins	8.37	8.60	4.44	3.46	7.22	8.70	4.58	2.47	-14%	1%	3%	-29%
J&R30	2013 Cummins	6.98	8.65	4.32	3.49	7.47	8.57	4.20	3.18	7%	-1%	-3%	-9%
J&R31	2013 Cummins	8.16	9.42	4.41	3.38	8.09	9.34	3.79	2.50	-1%	-1%	-14%	-26%
J&R32	2013 Volvo	8.81	11.39	3.98	4.92	9.12	10.63	3.77	2.02	3%	-7%	-5%	-59%
J&R33	2015 Cummins	8.06	8.23	4.57	2.28	7.34	8.54	4.55	2.31	-9%	4%	0%	1%
J&R34	2015 Volvo	8.04	8.18	2.42	2.30	8.74	8.67	2.50	2.35	9%	6%	3%	2%
J&R35	2014 Volvo	9.37	9.19	2.76	2.59	8.43	9.38	2.63	2.54	-10%	2%	-5%	-2%
J&R36	2013 Volvo	9.69	7.71	3.48	3.06	7.92	7.72	3.64	2.92	-18%	0%	5%	-5%
J&R37	2016 DDC	6.58	6.03	1.75	2.75	9.45	8.03	2.62	2.54	44%	33%	49%	-8%
J&R38	2013 Cummins	6.12	8.21	3.27	2.64	5.89	7.46	3.29	2.57	-4%	-9%	0%	-2%
J&R39	2013 Cummins	6.66	8.28	3.49	2.19	6.83	8.26	3.99	3.61	3%	0%	15%	65%
J&R40	2013 Cummins	9.03	9.89	3.77	2.74	7.30	9.05	3.29	2.73	-19%	-8%	-13%	0%
Second visit		7.28	9.10	3.29	2.73	7.43	7.70	3.22	2.56	2%	-15%	-2%	-6%
Third visit		7.45	7.70	3.22	2.56	6.71	9.12	3.75	4.21	-10%	18%	17%	65%
J&R41	2014 Paccar	9.86	10.79	6.39	2.75	10.22	11.14	5.76	2.70	4%	3%	-10%	-2%
J&R42	2013 Cummins	7.44	8.69	4.81	2.77	8.22	9.45	4.74	2.71	11%	9%	-1%	-2%
J&R43	2014 Cummins	6.61	9.48	3.33	3.04	7.06	9.33	4.37	4.60	7%	-2%	31%	51%
J&R44	2014 Volvo	8.44	8.79	2.78	2.34	9.64	9.66	2.51	2.75	14%	10%	-10%	18%
J&R45	2013 Cummins	7.13	8.91	3.54	2.55	6.63	8.76	4.30	3.42	-7%	-2%	22%	34%
J&R46	2013 Cummins	7.49	8.40	3.84	2.88	8.13	8.30	3.85	3.12	9%	-1%	0%	8%
J&R47	2013 Volvo	8.57	7.97	3.54	2.51	7.45	7.65	2.75	1.63	-13%	-4%	-22%	-35%
J&R48	2013 Maxxforce	5.58	8.57	1.44	5.07	7.22	5.50	2.11	4.52	29%	-36%	47%	-11%
3DATX													
J&R01	2011 Cummins	3.5	4.5	1.0		3.1	3.9			-10%	-13%		
J&R03	2013 Cummins	2.5	2.7	1.3									

Table H-2 Pre- and post-repair for THC emissions for each vehicle on a g/bhp-hr basis

Vehicle NO.	Engine Year & Make	**Pre-repair THC Emissions (g/bhp-hr)**		**Post-repair THC Emissions (g/bhp-hr)**	
		30 mph	50 mph	30 mph	50 mph
J&R01	2011 Cummins	0.022	0.023	0.018	0.007
Cum01	2015 Cummins	0.013	0.012	0.018	0.012
Cum02	2010 Cummins	n/a	n/a	n/a	n/a
J&R03	2013 Cummins	0.015	0.015	0.010	0.009
J&R04	2013 Volvo	n/a	n/a	n/a	n/a
J&R05	2012 Cummins	0.018	0.013	0.017	0.007
J&R06	2015 Cummins	0.019	0.014	0.008	0.003
J&R07	2014 Volvo	n/a	n/a	n/a	n/a
J&R09	2012 Cummins	0.032	0.063	0.015	0.002
J&R10	2011 Cummins	0.021	0.015	0.012	0.010
J&R11	2013 Cummins	0.010	0.008	0.017	0.009
J&R12	2011 Volvo	n/a	n/a	n/a	n/a
J&R13	2013 Cummins	0.012	0.003	0.019	0.007
J&R14	2010 DDC	n/a	n/a	n/a	n/a
J&R15	2010 Navistar	0.023	0.008	0.001	0.003
J&R16	2010 Mack	n/a	n/a	n/a	n/a
J&R17	2011 Cummins	0.016	0.021	0.007	0.013
J&R18	2014 Cummins	0.007	0.010	0.015	0.011
J&R19	2015 Cummins	0.015	0.018	0.010	0.015
Second visit		0.010	0.015	0.004	0.007
J&R20	2011 Cummins	0.009	0.011	0.001	0.002
J&R21	2013 Cummins	0.004	0.005	0.000	0.000
J&R22	2013 Cummins	0.029	0.029	0.003	0.006
Second visit		0.002	0.004	0.000	0.000
J&R23	2013 Cummins	0.011	0.013	0.000	0.000
J&R25	2013 Cummins	0.003	0.001	0.012	0.011
J&R26	2013 Paccar	0.010	0.012	0.002	0.003
J&R27	2014 Volvo	n/a	n/a	n/a	n/a
J&R28	2013 Cummins	n/a	n/a	n/a	n/a
J&R29	2014 Cummins	0.008	0.006	0.013	0.014
J&R30	2013 Cummins	n/a	n/a	n/a	n/a
J&R31	2013 Cummins	0.007	0.004	0.017	0.014
J&R32	2013 Volvo	n/a	n/a	n/a	n/a
J&R33	2015 Cummins	n/a	n/a	n/a	n/a
J&R34	2015 Volvo	n/a	n/a	n/a	n/a
J&R35	2014 Volvo	n/a	n/a	n/a	n/a
J&R36	2013 Volvo	0.006	0.057	0.009	0.011
J&R37	2016 DDC	n/a	n/a	n/a	n/a
J&R38	2013 Cummins	n/a	n/a	n/a	n/a
J&R39	2013 Cummins	0.007	0.007	0.012	0.011
J&R40	2013 Cummins	0.019	0.018	0.011	0.011
Second visit		n/a	n/a	n/a	n/a
Third visit		n/a	n/a	n/a	n/a
J&R41	2014 Paccar	0.005	0.005	0.007	0.005
J&R42	2013 Cummins	n/a	n/a	0.015	0.013
J&R43	2014 Cummins	0.015	0.013	n/a	n/a
J&R44	2014 Volvo	n/a	n/a	n/a	n/a
J&R45	2013 Cummins	0.012	0.009	n/a	n/a
J&R46	2013 Cummins	n/a	n/a	0.015	0.016
J&R47	2013 Volvo	n/a	n/a	n/a	n/a
J&R48	2013 Maxxforce	0.021	0.016	0.023	0.015

Note: n/a - Not available

Table H-3 Pre- and post-repair for CO emissions for each vehicle on a g/bhp-hr basis

Vehicle NO.	Engine Year & Make	**Pre-repair CO Emissions (g/bhp-hr)**		**Post-repair CO Emissions (g/bhp-hr)**	
		30 mph	50 mph	30 mph	50 mph
J&R01	2011 Cummins	0.00005	0.00007	0.00018	0.00018
Cum01	2015 Cummins	0.00006	0.00007	0.00011	0.00009
Cum02	2010 Cummins	n/a	n/a	n/a	n/a
J&R03	2013 Cummins	0.00007	0.00008	0.00003	0.00004
J&R04	2013 Volvo	n/a	n/a	n/a	n/a
J&R05	2012 Cummins	0.00010	0.00011	0.00007	0.00004
J&R06	2015 Cummins	0.00005	0.00004	0.00004	0.00004
J&R07	2014 Volvo	n/a	n/a	n/a	n/a
J&R09	2012 Cummins	0.00005	0.00016	0.00005	0.00004
J&R10	2011 Cummins	0.00006	0.00004	0.00004	0.00004
J&R11	2013 Cummins	0.00004	0.00003	0.00005	0.00003
J&R12	2011 Volvo	n/a	n/a	n/a	n/a
J&R13	2013 Cummins	0.00021	0.00013	0.00005	0.00003
J&R14	2010 DDC	0.00006	0.00011	0.00016	0.00005
J&R15	2010 Navistar	0.00008	0.00004	0.00000	0.00000
J&R16	2010 Mack	n/a	n/a	n/a	n/a
J&R17	2011 Cummins	0.00005	0.00008	0.00004	0.00001
J&R18	2014 Cummins	0.00008	0.00003	0.00004	0.00001
J&R19	2015 Cummins	0.00004	0.00004	0.00001	0.00000
Second visit		0.00001	0.00000	0.00006	0.00001
J&R20	2011 Cummins	0.00024	0.00025	0.00022	0.00021
J&R21	2013 Cummins	0.00004	0.00003	0.00011	0.00010
J&R22	2013 Cummins	0.00016	0.00016	0.00005	0.00000
Second visit		0.00004	0.00000	0.00010	0.00008
J&R23	2013 Cummins	0.00004	0.00003	0.00011	0.00007
J&R25	2013 Cummins	0.00004	0.00001	0.00012	0.00002
J&R26	2013 Paccar	0.00004	0.00003	0.00006	0.00006
J&R27	2014 Volvo	n/a	n/a	n/a	n/a
J&R28	2013 Cummins	n/a	n/a	n/a	n/a
J&R29	2014 Cummins	0.00000	0.00000	0.00002	0.00000
J&R30	2013 Cummins	n/a	n/a	n/a	n/a
J&R31	2013 Cummins	0.00004	0.00001	0.00007	0.00001
J&R32	2013 Volvo	n/a	n/a	n/a	n/a
J&R33	2015 Cummins	n/a	n/a	n/a	n/a
J&R34	2015 Volvo	n/a	n/a	n/a	n/a
J&R35	2014 Volvo	n/a	n/a	n/a	n/a
J&R36	2013 Volvo	0.02211	0.00250	0.00862	0.00430
J&R37	2016 DDC	n/a	n/a	n/a	n/a
J&R38	2013 Cummins	n/a	n/a	n/a	n/a
J&R39	2013 Cummins	0.00004	0.00000	0.00005	0.00003
J&R40	2013 Cummins	0.00005	0.00004	0.00004	0.00003
Second visit		n/a	n/a	n/a	n/a
Third visit		n/a	n/a	n/a	n/a
J&R41	2014 Paccar	0.00004	0.00003	0.00011	0.00007
J&R42	2013 Cummins	n/a	n/a	0.00004	0.00002
J&R43	2014 Cummins	n/a	n/a	0.00004	0.00002
J&R44	2014 Volvo	n/a	n/a	n/a	n/a
J&R45	2013 Cummins	0.00008	0.00006	n/a	n/a
J&R46	2013 Cummins	n/a	n/a	0.00008	0.00005
J&R47	2013 Volvo	n/a	n/a	n/a	n/a
J&R48	2013 Maxxforce	0.00001	0.00001	0.00001	0.00001

Note: n/a - Not available

Table H-4 Test vehicles for HEAT RSD testing.

License Plate	Invoice	Year	Make	Model	Engine	Odometer	CO2 mole/m	PM_ratio	PM nmole/m	NO_ratio	NO mole/m	NO2_ratio	NO2 mole/m
81484	J&R_3	2014	Kenworth	T680	ISX	401,079	60.04	0.225	13.536	0.002	0.093	0.000	0.011
276460	261159	2009	Volvo	630	Volvo	513,939	76.08	1.162	88.400	0.003	0.000	0.000	0.000
2487314	J&R_12	2011	Volvo	670	Volvo	574,610	18.600	2.973	55.300	0.010	0.187	0.000	0.003
2487409	261272	2010	Volvo	670	Volvo	569,223	72.48	3.596	260.620	0.006	0.436	0.000	0.006
02691RP	260531	1994	Ford	Aeroma	Detroit	235,879	53.83	0.542	29.180	0.014	0.780	0.000	0.014
18969PR	260902	1989	Freightliner	Fld	Catepillar	300,149	31.61	3.293	104.090	0.005	0.143	0.001	0.027
51AP0J	261201	2003	Volvo	770	Cummins	909,284	50.5	0.188	9.500	0.009	0.472	0.001	0.026
55739A	261170	2011	Volvo	670	Volvo	725,484	38.95	0.087	3.390	0.007	0.288	0.000	0.001
6H14048	261118	2000	Western Star		Cummins	514,218	19.02	0.425	8.080	0.007	0.126	0.001	0.023
86457PR	261039	2000	Sterling		Cummins		33.02	0.573	18.910	0.008	0.262	0.000	0.003
8945PY	J&R_9	2012	Kenworth	T660	ISX	623,968	43.415	0.165	7.145	0.004	0.169	0.000	0.017
92AS4N	J&R_4	2014	Volvo		Volvo	491,635	30.12	1.037	31.244	0.007	0.221	0.000	0.003
9C38345	261217	2009	International	ProStar	ISX	486,768	31.02	0.511	15.840	0.013	0.409	0.000	0.012
9E66655	261221	2004	Peterbilt	379	Catepillar	95,110	30.25	2.461	74.460	0.006	0.185	0.001	0.018
9E68636	261290	2011	Volvo	670	Volvo	723,037	106.67	0.292	31.140	0.004	0.469	0.000	0.000
9E93069	261205	2009	Freightliner	Cascad	Detroit	887,552	44.61	0.562	25.050	0.001	0.058	0.000	0.002
9F68224	261166	2009	Freightliner	Cascad	Detroit	463,044	41.56	1.286	53.460	0.002	0.064	0.000	0.005
AG45406	261130	2010	International	Prostar6	ISX	977,314	46.79	0.084	3.940	0.016	0.744	0.001	0.027
AG83049	261065	2016	Volvo		ISX	110,920	38.65	0.140	5.410	0.006	0.233	0.000	0.006
F9444W	261220	2008	Freightliner	Columb	Detroit	955,065	24.91	0.400	9.970	0.008	0.196	0.001	0.029
P497790	261266	2002	Volvo	770	Cummins	384,854	34.27	1.041	35.660	0.007	0.233	0.000	0.014
P724100	261267	2011	Freightliner	Cascad	Detroit	1,257,308	42.27	0.654	27.640	0.004	0.161	0.000	0.013
P814100	261096	2010	Freightliner	Cascad	Detroit	753,997	29.13	0.446	12.990	0.003	0.091	0.000	0.006
P827827	261259	2010	Freightliner	Cascad	Detroit	686,264	90.29	1.576	142.280	0.002	0.167	0.000	0.004
P887051	261270	2016	Freightliner	Cascad	Detroit	190,156	65.89	0.471	31.030	0.003	0.225	0.000	0.004
P911497	261258	2016	Peterbilt		ISX	35,771	35.87	0.572	20.500	0.004	0.140	0.001	0.021
P915452	261053	2016	Freightliner	Cascad	Detroit	60,802	59.89	0.491	29.380	0.002	0.118	0.000	0.001
P915472	261161	2012	Volvo		ISX	460,174	27.69	0.963	26.680	0.008	0.227	0.000	0.001
PVZ2150	257357	2011	Volvo	670	Volvo	636,621	69.41	0.208	14.450	0.003	0.215	0.000	0.023
R084520	260297	1999	Freightliner	Century	Detroit	2,261,250	55.95	0.288	16.110	0.006	0.321	0.000	0.016
R275064	261148	2013	Peterbilt	587	ISX	459,336	22.48	1.473	33.120	0.007	0.162	0.001	0.012
R812192	261137	2006	Freightliner		Detroit	940,590	39.1	0.627	24.530	0.009	0.337	0.000	0.019
Temp 326610	261037	2012	Kenworth	T700	ISX	530,562	28.48	0.338	9.640	0.004	0.111	0.000	0.000
UP93164	261189	2000	Volvo	660	Detroit	306,871	16.54	96.752	1599.810	0.002	0.031	0.001	0.016
VP02833	261034	2005	Peterbilt	387	Catepillar	1,372,887	21.99	2.855	62.780	0.004	0.084	0.000	0.004
VP52830	261156	2003	Peterbilt		Catepillar	428,492	10.35	0.434	4.490	0.008	0.078	0.000	0.002
VP93242	261014	2004	Peterbilt	379	Catepillar	391,592	13.85	0.936	12.970	0.004	0.055	0.000	0.006
VP95025	260876	2008	Kenworth	T2000	ISX	630,050	21.34	0.124	2.650	0.015	0.317	0.001	0.015
VP98372	261133	2009	International	Prostar	ISX	887,097	42.27	1.334	56.390	0.007	0.275	0.000	0.007
WP14963	260952	2010	Freightliner	Cascad	Detroit	952,953	48.36	0.225	10.870	0.002	0.101	0.000	0.006
WP26956	261229	2011	Peterbilt	386	Paccar	714,793	100.58	0.300	30.210	0.003	0.303	0.000	0.003
WP27468	261134	2013	Freightliner	Cascad	Detroit	235,137	84.17	0.221	18.630	0.002	0.169	0.000	0.001
WP28005	261102	2009	Volvo	670	ISX	812,147	40.99	0.431	17.650	0.006	0.252	0.001	0.033
WP28232	261079	2010	Volvo		Volvo	761,633	48.59	0.360	17.480	0.014	0.704	0.001	0.031
WP29822	261278	2014	Kenworth	T680	Paccar	301,359	26.32	0.632	16.640	0.004	0.109	0.000	0.000
WP39831	260618	2009	Freightliner	Century	Detroit	?	16.33	2.049	33.470	0.005	0.079	0.000	0.003
WP40189	261190	1997	Volvo	Vnl 64T	Cummins	80,826	52.13	0.935	48.720	0.006	0.290	0.001	0.047
WP45961	261153	2007	Peterbilt		Caterpillar	894,020	3.83	6.055	23.200	0.005	0.018	0.001	0.002
WP48686	261179	2009	Peterbilt	389	ISX	990,329	43.52	0.299	13.030	0.005	0.211	0.000	0.009
WP51521	261090	2010	Freightliner	Cascad	Detroit	82,675	39.71	0.197	7.820	0.004	0.139	0.000	0.000
WP51791	J&R_5	2011	Kenworth	T660	ISX	486,149	14.32	1.211	17.332	0.007	0.104	0.000	0.007
WP51925	261104	2015	Volvo		Volvo	284,674	65.39	0.604	39.510	0.009	0.610	0.000	0.027
WP61469	261262	2012	Freightliner	Cascad	Detroit	637,613	68.94	0.406	27.960	0.003	0.207	0.000	0.000
WP66361	261232	2003	Freightliner	Century	Detroit	144,870	58.28	0.998	58.150	0.005	0.273	0.001	0.037
WP73577	261040	2011	Freightliner	Cascad	Detroit	577,456	85.58	0.803	68.750	0.002	0.199	0.000	0.002
WP73657	J&R_7	2014	Volvo	670	Volvo	368,066	60.04	0.380	22.822	0.008	0.479	0.000	0.027
WP79805	261180	2009	Freightliner	Cascad	Detroit	1,464,956	31.84	0.698	22.220	0.005	0.158	0.001	0.026
WP80208	261085	2009	Freightliner	Cascad	Detroit	874,901	63.19	0.004	0.260	0.002	0.127	0.000	0.010
WP85865	261150	2017	Kenworth	T680	ISX	54,151	51.96	0.279	14.510	0.005	0.267	0.000	0.002
WP90583	J&R_10	2011	Kenworth	T660	ISX	929,354	61.504	0.111	6.802	0.008	0.476	0.000	0.009
WP93747	J&R_6	2011	Kenworth	T660	ISX	740,881	109.39	0.200	21.914	0.007	0.820	0.001	0.062
YAHR507	261292	2003	Freightliner	Columb	Detroit	90,759	52.82	0.768	40.570	0.004	0.209	0.000	0.010