



Final Report

In-Use Emissions Evaluation of
Diesel and Propane Terminal
Tractors

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Submitted to

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1 Executive Summary

Energy Environmental Analytics (EEA or E2A) evaluated the real-world tailpipe emissions performance of two yard tractors, one equipped with a Diesel-fueled Compression Ignited (CI) engine and one fitted with a propane-fueled Spark-Ignited (SI) engine. The emissions were evaluated while the tractors were engaged in normal revenue service at the Port Newark Container Terminal (PNCT) in Newark, NJ. Gaseous and particulate phase emissions were quantified using a Portable Emissions Measurement System (PEMS).

Vehicle emissions were characterized according to activity by dividing into discrete vehicle speed bins. Collected data were segregated into “Idle” operation, for vehicle speeds less than 0.93 Miles Per Hour (MPH), and “Urban” operation, for vehicle speeds between 0.93 MPH and 31.3 MPH, which is consistent with published data. Speeds in excess of 31.3 MPH were not encountered during this program, thus no “Rural” or “Highway” operation speed bin was populated.. It shall be noted that both tractors had reasonable parasitic loading during low-speed (idle) operation, often as high as 10% of peak torque. This was attributed to loading associated with on-board hydraulic power systems.

A summary of program emissions results is presented in Table 1-1, below, that support the following conclusions:

- **Total cycle-averaged idle- and brake-specific emissions rates showed over 99% lower NOx emissions for the propane-fueled tractor in comparison to the Diesel-fueled tractor. More importantly, the propane-fueled yard tractor demonstrated near-zero NOx emissions under real-world operating conditions.** Cycle-averaged NOx emissions were approximately 0.0046 g/bhp-hr and 3.838 g/bhp-hr for the Propane-fueled and Diesel-fueled tractors, respectively.
- **Likewise, the propane tractor showed near-zero PM emissions.** Measured PM rates resulted in averages of 0.0086 g/bhp-hr and 0.0022 g/bhp-hr for diesel and propane, respectively.
- For idle operation, the propane-fueled tractor produced higher time-specific CO₂ emissions, when compared to the diesel-fueled tractor. **However, for urban operation, brake-specific CO₂ emissions from the propane-fueled tractor were lower than those of the diesel-fueled tractor by approximately 14%. This would correlate to an approximate 14% reduction in lifecycle CO₂ emissions that would be in addition to the upstream emissions for both fuels, which can be estimated using Argonne National Laboratory’s GREET 2022 model.**
- **THC emission rates were lower by 77% and 51% for the propane tractor in comparison to the Diesel-fueled tractor for idle and urban operation, respectively.**
- On a cycle-average basis, the Diesel tractor showed lower idle and brake-specific CO emissions compared to the propane tractor.

Table 1.1 Summary of Program Emissions Results

	Emission	Units	Cold Start (Diesel 1)	Diesel 2	Diesel 3	Propane 1	Propane 2	Propane 3	Diesel Avg	Propane Avg
Idle (Vehicle Speed < 0.93 Miles Per Hour)	CO ₂	g/hr	7239	5163	5095	10289	9980	10518	5129	10262
	CO	g/hr	21.12	9.27	3.50	15.86	7.33	7.59	6.38	10.26
	THC	g/hr	2.871	1.225	1.082	0.374	0.183	0.213	1.154	0.257
	NOx	g/hr	100.2	91.06	95.96	0.0350	0.0300	0.0942	93.51	0.0531
Urban (0.93 < Vehicle Speed < 31.3 Miles Per Hour)	CO ₂	g/bhp-hr	--	582.9	587.2	506.1	492.0	503.4	585.1	500.5
	CO	g/bhp-hr	--	0.548	0.271	1.366	0.797	0.829	0.410	0.997
	THC	g/bhp-hr	--	0.050	0.040	0.028	0.018	0.021	0.045	0.022
	NOx	g/bhp-hr	--	3.854	3.822	0.0066	0.0014	0.0057	3.838	0.0046
	PM	g/bhp-hr	--	0.0088	0.0084	0.0019	0.0023	0.0020	0.0086	0.0021

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2 Overview

E2A was contracted by the Propane Education & Research Council (PERC) to conduct PEMS testing of two off-road yard tractors (terminal tractors). Collected data were used to compare in-use tailpipe emissions from a Diesel-fueled terminal tractor with those from a Propane-fueled terminal tractor. Emissions measurements, including Oxides of Nitrogen (NO_x), Nitric Oxide (NO), Carbon Monoxide (CO), Carbon Dioxide (CO₂), Total Hydrocarbons (THC) and Particulate Matter (PM) were measured. The terminal tractors were operated over standard revenue routes, with a minimum of three data sets collected from each of the tractors.

3 Test Articles

Two terminal tractors were provided and operated by the Port Newark Container Terminal (PNCT). PNCT staff provided all pre-test maintenance and inspections prior to test commencement. A description of each test article is included below.

3.1 Diesel-Fueled Terminal Tractor (PNCT Unit H37)

PNCT Unit H37 was a Diesel-fueled tractor that was fitted with a QSB 6.7L engine (ESN 73742609), manufactured by Cummins, Inc (Cummins). The engine was a 2014 model that was certified against 40 CFR Parts 60 and 1039 Interim Tier 4 emissions standards and had an emission control system that comprised of Exhaust Gas Recirculation (EGR) and a Diesel Oxidation Catalyst (DOC). The engine employed high-pressure common rail fuel injection and a fixed-geometry turbocharger. Further engine details, including emission certification values for both discrete mode and transient test cycles, are included in Table 3.1.

3.2 Propane-Fueled Terminal Tractor (MAFI Unit H1)

MAFI Unit H1 was a Propane-fueled tractor that was fitted with an 8.8L engine, manufactured by Power Solutions International (PSI). The engine was a 2022 model that was certified against 40 CFR Part 1048 Tier 2 emissions standards and had an emission control system that relied upon dual Three-Way Catalysts. The engine was a naturally aspirated design that employed Sequential Multiport Injection. Further engine details, including emission certification values for both discrete mode and transient test cycles are included in Table 3.1.

Table 3.1 Test Vehicle Specifications

Vehicle Unit Number	H37		H1	
Fuel Type	Diesel		LPG	
Chassis Manufacturer	Kalmar Solutions LLC		MAFI Transport-Systeme GmbH	
Chassis Model	4x2		T230	
Engine Manufacturer	Cummins, Inc.		Power Solutions International	
Engine Model	QSB 6.7-173		Ultra-Low NOx 8.8L	
Displacement	6.7L		8.8L	
Rated Power	173hp @ 2200rpm		265.5hp @ 2600rpm	
Engine Model Year	2014		2022	
Engine Emission Certification Family	ECEXL06.7AAH		NPSIB08.8LPG	
Fuel Injection System	Direct Injection		Sequential Multi-Port	
Exhaust Aftertreatment	EGR, DOC		TWC	
Engine Operating Hours	N/A (80,256 miles, 12,097.5 idle hours)		143.6	
Emission Species	Emissions Certification Values (g/kW-hr)		Emissions Certification Values (g/kW-hr)	
	Nonroad Compression-ignition Composite Transient Cycle	D2 Discrete Mode	Large Spark-ignition (SI) Composite Transient Cycle	C2 Discrete Mode
HC + NOx			0.2	0.1
NMHC	0.05	0.04		
NOx	3.1	2.7		
NMHC + NOx				0.0
CO	0	0	2.6	0.4
CO ₂	826.14	755	770	771.1
PM	0.02	0.02		

4 Test Location

All tests were conducted at the PNCT facility located at 241 Calcutta St, Newark, NJ. Testing occurred between December 28, 2022 and December 30, 2022. For the testing of the propane-fueled tractor (Wednesday December 28th), ambient temperatures varied between -2°C to 9°C, whereas temperatures ranged between 5°C and 17°C for the Diesel-fueled tractor testing (Friday December 30th).

4.1 Test Routes

Emissions data from the yard tractors were collected over normal, in-use operating routes, as the tractors picked up shipping containers from the PNCT Container Terminal and transported them to the PNCT rail terminal via a single overpass (flyover) of Corbin Street. An aerial view of the area traveled for the testing reported herein is included as Figure 4.1.

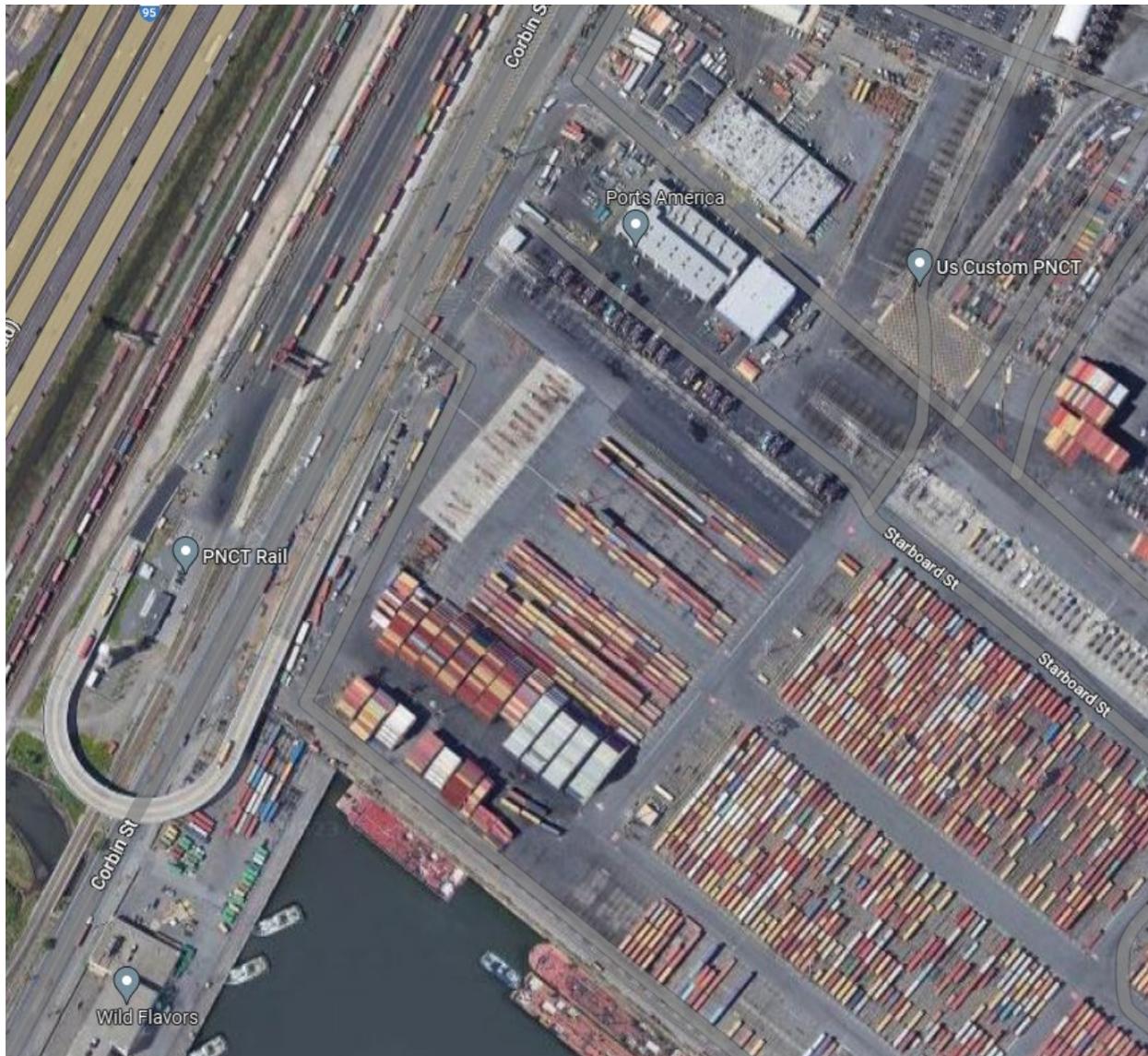


Figure 4.1 Aerial View of PNCT Container Terminal and PNCT Railterminal Facilities.

For each of the tractors, trips were further divided into three main activities. At the start of each test, the test tractor would begin at the PNCT Power Shop (repair facility), where the vehicle had been instrumented and cold-soaked overnight in climate-controlled storage. The vehicle would then proceed to pick up its first load of the test sequence. This “PNCT Power Shop Route” is presented in Figure 4.2

After transporting the container across the flyover to the rail terminal, the vehicle would then travel back across the flyover to the container terminal. Two different locations for container pickup resulted in two distinct routes, denoted the “Short” and “Long” terminal routes, as shown in Figure 4.3 and Figure 4.4, respectively. At the end of the test sequence, the vehicles would travel back to the PNCT Power Shop, where the test sequence was terminated with post-test analyzer drift measurements, and preparations were made for the next test sequence.

Each test sequence was comprised of a PNCT Power Shop Route, then a series of approximately 3-6 Short and/or Long Terminal Routes, depending upon driver schedule and total container daily transport schedule, before concluding with a return Power Shop Route.

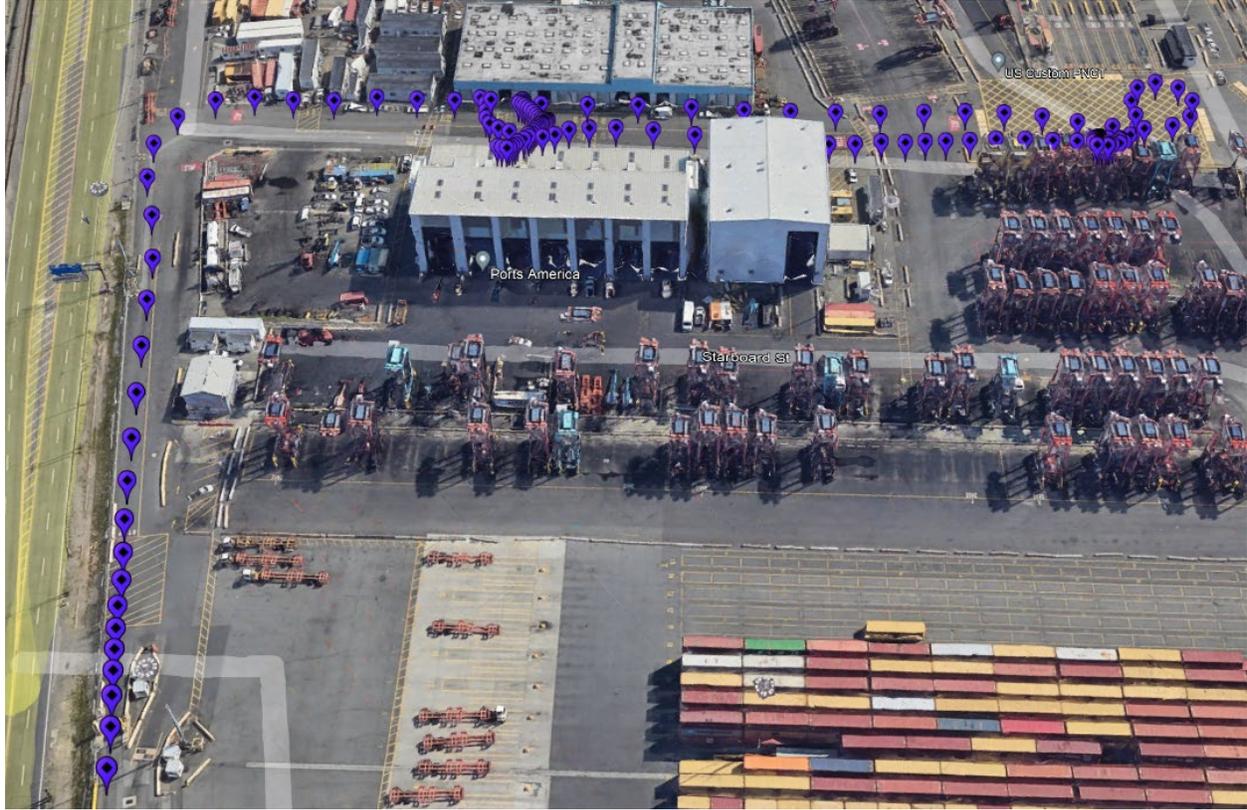


Figure 4.2 PCT PNCT Power Shop Route

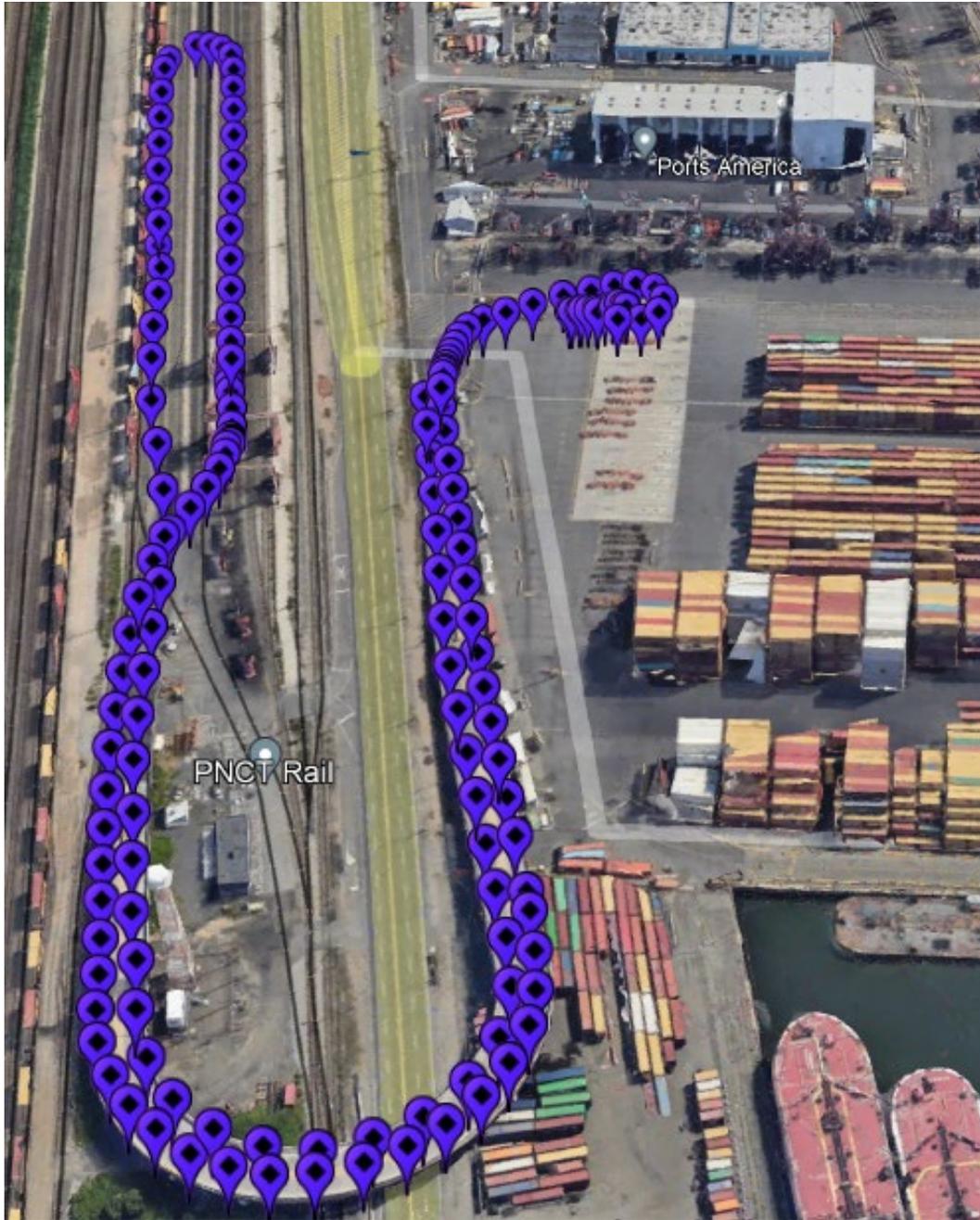


Figure 4.3 PCT Short Terminal Route

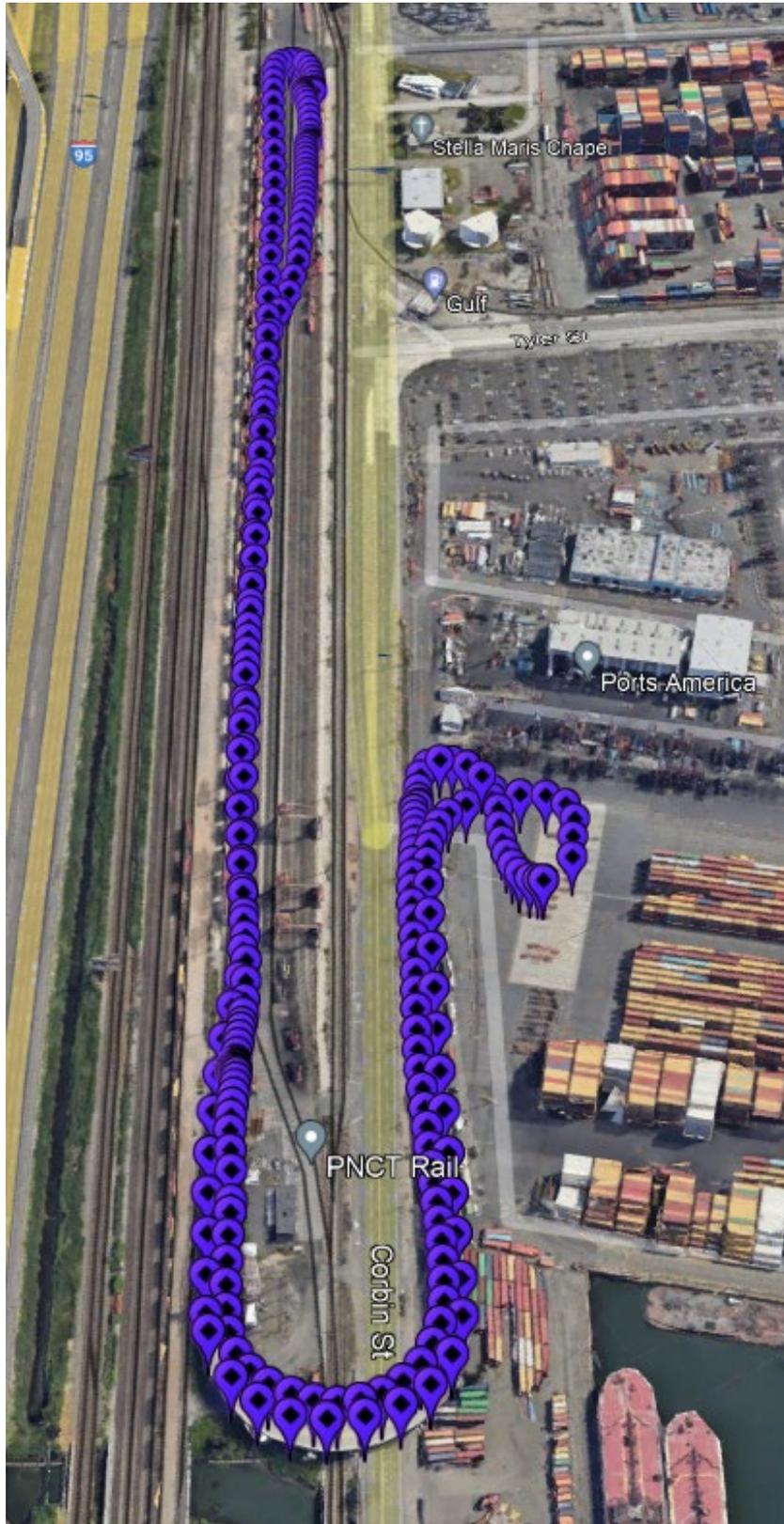


Figure 4.4 PCT Long Terminal Route

5 Test Equipment

For the testing program the following PEMS units were used for the measurement of exhaust emissions from the two test vehicles:

- **PEMS Gaseous Measurement System:** Horiba OBS-ONE Gaseous Portable Emissions Measurement System
- **PEMS Particulate Matter Measurement System:** Sensors Semtech PM2

5.1 Horiba OBS-ONE Gaseous Portable Emissions Measurement System

The Horiba OBS-ONE (**Figure 5-1**) is a laboratory grade portable emissions measurement system (PEMS). It is compliant with the standards set forth CFR Title 40, Part 1065, EC 2017/1151, and in Appendix IV of the MARPOL NO_x Technical Code 2008. The OBS-ONE includes a non-dispersive infrared (NDIR) analyzer for carbon monoxide (CO) and carbon dioxide (CO₂) measurement, a dual heated chemiluminescence detector (CLD) with a NO₂ to NO converter for simultaneous measurement of NO_x and nitric oxide (NO), and dual heated flame ionization detectors (FID) for total hydrocarbon (THC) and methane (CH₄) measurement (summarized in Table 5.1).

5.1.1 Ambient Monitoring

The Horiba OBS-ONE also included an ambient sensor module which provides ambient temperature, pressure, and humidity measurements.



Figure 5.1: Horiba OBS-ONE Gaseous Emissions Analyzer

Table 5.1: Horiba OBS-One Gaseous PEMS Measurement Principles

THC concentration	Heated FID
CH ₄ concentration	Heated FID with non-methane cutter (NMC)
CO concentration	Heated NDIR, wet measurement
NO/NO _x concentration	Heated CLD, wet measurement
NO/NO _x /NO ₂ concentration	Heated CLD, wet measurement
CO ₂ concentration	Heated NDIR, wet measurement

5.2 Sensors SEMTECH® PM2 Portable PM Measurement System

Total particulate matter (TPM) emissions were measured using the Sensors Inc., SEMTECH® PM2 on-board PM-PEMS instrument from Sensors Inc. (Figure 5.2). The SEMTECH® PM2 is a PM mass measurement device that combines real-time and cumulative gravimetric PM measurements. Real-time PM mass information is provided by an ion mobility technique (diffusion charger by Pegasor Oy, Finland), and the cumulative PM mass measurement is based on a traditional gravimetric method using 47 mm flow-through filter media. The SEMTECH® PM2 has received an alternate system approval from the U.S. EPA for field-testing as specified in CFR, Title 40, Part 1065, Subpart J. Table 5.2 provides a summary of the instrument specifications.

The filter media used to collect gravimetric PM were 47mm (i.e. diameter) Pallflex® Emfab™ filter membranes (TX40HI20WW, Pall Life Sciences, Pall Corp., USA). An environmentally controlled clean room (Class Six as specified by ISO 14644-1 or Class 1000 according to the older standard), located at E2A's facility in Morgantown, WV, was utilized for PM filter media handling, storage, pre/post-conditioning and pre/post-weighting for gravimetric analysis. Filter media were pre/post-weighted using a precision micro-balance with an accuracy of 0.1mg (Sartorius, model SE-2F) following conditioning and weighing procedures as outlined in CFR Title 40, Part 1065, §1065.590 and §1065.595.

Table 5.2 Sensors SEMTECH® PM2 Specifications

Measurement Technique Ion mobility & gravimetric PM	Measurement Technique Ion mobility & gravimetric PM
Particle size	Minimum: 10 nm (dependent on selected trap voltage)
	Maximum: 2.5 µm (dependent on measures particle size distribution)
Concentration	From 1 µg/m ³ to 250 µg/m ³
Rise time	< 2.5 seconds
Response Time	< 12 Seconds



Figure 5.2 SEMTECH® PM2 PM Emissions Analyzer

5.3 Exhaust Flow Meter (EFM)

The Horiba exhaust flow meter that was used for this testing was an averaging Pitot-Static design and contained integrated ports for all necessary emissions sample probes and sensors. The flow meter section was adapted to fit near the end of the vehicle exhaust section (tailpipe) using a slip-on connection with band clamps to connect the EFM section to the upstream and downstream exhaust pipes. The same EFM was utilized for both the Diesel-fueled and propane-fueled tractors.

5.4 Gas Bottles

Gas bottles for instrument operation and calibration were transported to the test site in an enclosed trailer, where they were stored for the duration of the test campaign. Calibration gases, typically in the ppm concentration range, are used for zero/span and linearity verification of the gaseous emissions analyzers. Before and after each test sequence, zero/span checks were performed for each analyzer such that measured concentrations could possibly be corrected for instrument drift (if occurred) during data post-processing.

In addition to span gases, Ultra Zero Air (UZA, hydrocarbon-free) and ultra-high purity (UHP) Nitrogen were used to establish analyzer reference (zero) signals as well as provide 'burner air' for the FID analyzers. An FID fuel cylinder, comprised of 60% Helium and 40% Hydrogen, was additionally used to operate the FIDs. UZA and FID fuel bottles were secured to the vehicle for the duration of the tests, while nitrogen and calibration (span) bottles remained at the PNCT Power Shop location. These bottles were connected at the beginning and end of each test sequence.

5.5 Instrument Power

PEMS instrumentation power was provided by portable 120V/60Hz gasoline-fueled generators, rather than extracting power from the terminal tractor's electrical system or installing large battery storage units.

5.6 CAN Data Collection

In addition to PEMS-centric measurements, several other measurements are required to provide for brake-specific emissions, as well as corroborative measurements used for data quality assurance. Data were collected from the J1939 CAN broadcast in order to integrate with emissions measurements during post processing. CAN parameters recorded from the public broadcast are summarized in Table 5.3.

Table 5.3 J1939 Parameters Recorded During Testing

Diesel-Fueled Tractor		Propane-Fueled Tractor	
Parameter	Units	Parameter	Units
Engine Speed	[rpm]	Engine Speed	[rpm]
Vehicle Speed	[km/h]	Vehicle Speed	[km/h]
Actual Engine Percent Torque	[%]	Actual Engine Percent Torque	[%]
Boost Pressure	[kPa]	Boost Pressure	[kPa]
Air Inlet Pressure	[kPa]	Air Inlet Pressure	[kPa]
Engine Oil Pressure	[kPa]	Engine Oil Pressure	[kPa]
Engine Coolant Temp.	[deg C]	Engine Coolant Temp.	[deg C]
Intake Manifold 1 Temp.	[deg C]	Intake Manifold 1 Temp.	[deg C]
Throttle Position	[%]	Fuel Temp.	[deg C]
Inlet Air Mass Flow rate	[kg/h]	Throttle Position	[%]
EGR Mass Flow Rate	[kg/h]	Inlet Air Mass Flow rate	[kg/h]
Fuel Rate	[L/h]	Instantaneous Fuel Economy	[km/L]
Nominal Friction Percent Torque	[%]	Engine Fuel Rate	[L/h]
Engine Reference Torque	[Nm]	Nominal Friction Percent Torque	[%]
		Engine Reference Torque	[Nm]
		Front Axle Speed	[km/h]
		Aftertreatment 1 Intake % Oxygen 1	[%]
		Aftertreatment 2 Intake % Oxygen 1	[%]
		Aftertreatment 1 Outlet % Oxygen 1	[%]
		Aftertreatment 2 Outlet % Oxygen 1	[%]
		Engine Desired Air Fuel Ratio	[#]
		Engine Fuel Control Mode	[#]
		Engine Protection Timer State	[#]
		Engine Protection System approaching Shutdown	[#]

6 Fuel Analysis

Fuel samples were collected from the tractor’s fuel tank at the end of each test day. Analyses of these fuel samples were not conducted, as nominal (default) values of fuel properties, provided in 40 CFR Part 1065, were used for the calculation of emission quantities.

7 Emissions Reporting

Emissions data were collected and reported according to relevant requirements of 40 CFR Subchapter U, Parts 1039, 1048 and 1065. Emissions Calculations and Data Processing. Calculation of emissions mass rates and integrated emissions factors from measured raw emissions concentrations and exhaust flow meter data using the PEMS instrument was performed following recommendations outlined in CFR, title 40, part 1065. Analyzer linearization verifications and checks according to CFR, Title 40, Part 1065 were conducted prior to installation of the PEMS instrument using NIST-traceable calibration gas cylinders. A ‘quad-blend’ cylinder was used to provide span gases, including THC, NO, CO₂, and CO, for periodic analyzer span checks and calibrations during testing, whereas a compressed ultra-zero air (UZA) cylinder (i.e. ‘zero air’) was used for period zero checks. The following provides additional information regarding calculations of time- [g/hr] and work-specific [g/kWh] emissions rates from the gaseous and PM PEMS systems.

7.1 Gaseous Emissions Calculations

Continuous gaseous emissions mass rates in [g/s] were calculated using the Horiba® OBS-One post-processing software (Version-#: V3.0.0). Results from the actual fuel analysis were added to the parameter setting screen of the software prior to reducing data. Pre- and post zero/span check values were used by

the Horiba® software to automatically perform a drift correction of the gaseous concentrations following CFR, title 40, §1065.672, while setting the $x_{prezero}$ value to 0 and the $x_{prespan}$ value to the concentration of the span bottle. This was done since the instrument was calibrated just before starting the test.

In case of hourly zero/adjustment checks, the intermediate $x_{postspan}$ values were assumed to have drifted by the same amount as the measured zero drift and thus, used accordingly in the drift correction function. Only at the very end an actual span check with a span bottle was performed. Also, note that intermediate zero-drift checks and adjustments were performed with an ultra-zero-air (UZA) gas bottle connected to the PEMS, and thus, justifying that zero-drift adjustments after each periodic zero-drift check were made.

Total NO_x emission concentration values were further corrected for intake air humidity ($x_{NO_x, Kh}$) by the Horiba® software following Eq. 1065.670-1 described in CFR, title 40, §1065.670 using measured ambient air conditions. Both uncorrected and corrected NO_x concentrations will be reported separately in this report.

The Horiba® OBS-One PEMS measures all constituents on a 'wet' basis and thus, no 'dry-to-wet' correction (Kw) of the measured raw concentrations was necessary.

To calculate final emissions mass rates in [g/s], exhaust concentration data were aligned with exhaust flow data inside the Horiba® post-processing software using a least-square optimization approach. NO₂ and NO_x emissions mass rates were calculated using the molecular weight of NO₂ (46.0055 g/mol), whereas NO was calculated using the respective molecular weight of NO (30.0061 g/mol). All molecular weight information is taken from CFR, title 40, §1065.1005(f)(2).

The integration of the continuous emissions mass rates that were calculated with use of the Horiba® post-processing software, were performed in a Matlab® environment. Mass rates were only integrated during periods of engine operation (identified by the ECU engine speed parameter) and when the PEMS instrument was not undergoing an automated periodic zero-drift check/adjustment event.

7.2 Particulate Matter Mass Emissions Calculations

Particulate matter mass emissions in [g] per test cycle were calculated partially using Sensor Inc.'s SEMTECH PM2® reduction software (Version-#: V1.0.1.8) and E2A's in-house reduction code in a Matlab® environment. Since the exhaust flow meter data were recorded with the Horiba® OBS-One, the exhaust flow was merged with results provided by the SEMTECH reduction software to calculate the total mass of PM in the exhaust stream for the duration of the test.

7.3 Test Work and Test Duration Calculations

Total test cycle work to calculate work-specific emissions was derived from engine broadcast ECU parameters as shown by Equations 1 through 3, where T_{ref} is the broadcast reference torque in [Nm], $Act.\%torque$ the actual engine percent torque in [%], $Fric.\%torque$ the nominal friction percent torque in [%], and n_{engine} the engine speed in [rpm]. Equation 1 is based on the SAE J1939-71 documentation.

$$T_{brake-net}[Nm] = \frac{(Act.\%torque - Fric.\%torque)}{100} * T_{ref}[Nm] \quad \text{Eq. 1}$$

$$P[kW] = T_{brake-net}[Nm] * \frac{n_{engine}[rpm]}{60} * 2 * \pi \quad \text{Eq. 2}$$

$$W[kWh] = \frac{\sum P}{3600} \quad \text{Eq. 3}$$

8 Test Methodology

8.1 Equipment Installation

Prior to arriving on-site, EEA conducted required calibration and verification checkouts, pursuant to CFR Title 40 Part 1065. PEMS instrumentation was mounted on the test article along with a portable generator. The PEMS exhaust flow meter assembly was adapted to the exhaust of the test article, as approved by PNCT staff. Compressed gas bottles for FID fuel (hydrogen/helium blend), span (calibration) and nitrogen/hydrocarbon-free air were additionally affixed to the test article. The test article was then photographed, and relevant data were recorded.

8.2 • PEMS Installation

Gaseous and PM PEMS instrumentation were mounted onto the exterior surfaces of the two yard tractors. Exhaust flow meters were installed after removing muffler sections of the tractors. Generators were mounted to power the PEMS so that additional electrical loading was not imposed by the testing equipment. In addition, fuel for the FID analyzer (hydrogen/helium blend) and zero air were mounted to the vehicle so that the gaseous PEMS could perform periodic (1-hour) analyzer zero calibration to mitigate drift concerns, per manufacturer specifications.

8.2.1 PEMS Installation on Diesel-Fueled Tractor

Gaseous and PM PEMS were secured to the right front fender area of PNCT Unit H37, as shown in Figure 8.1. The EFM was installed at the exit of the tractor's muffler and a 90-degree elbow was affixed to the end of the EFM test section. A single Honda EU2200i inverter generator was installed at the left rear of the tractor cab.

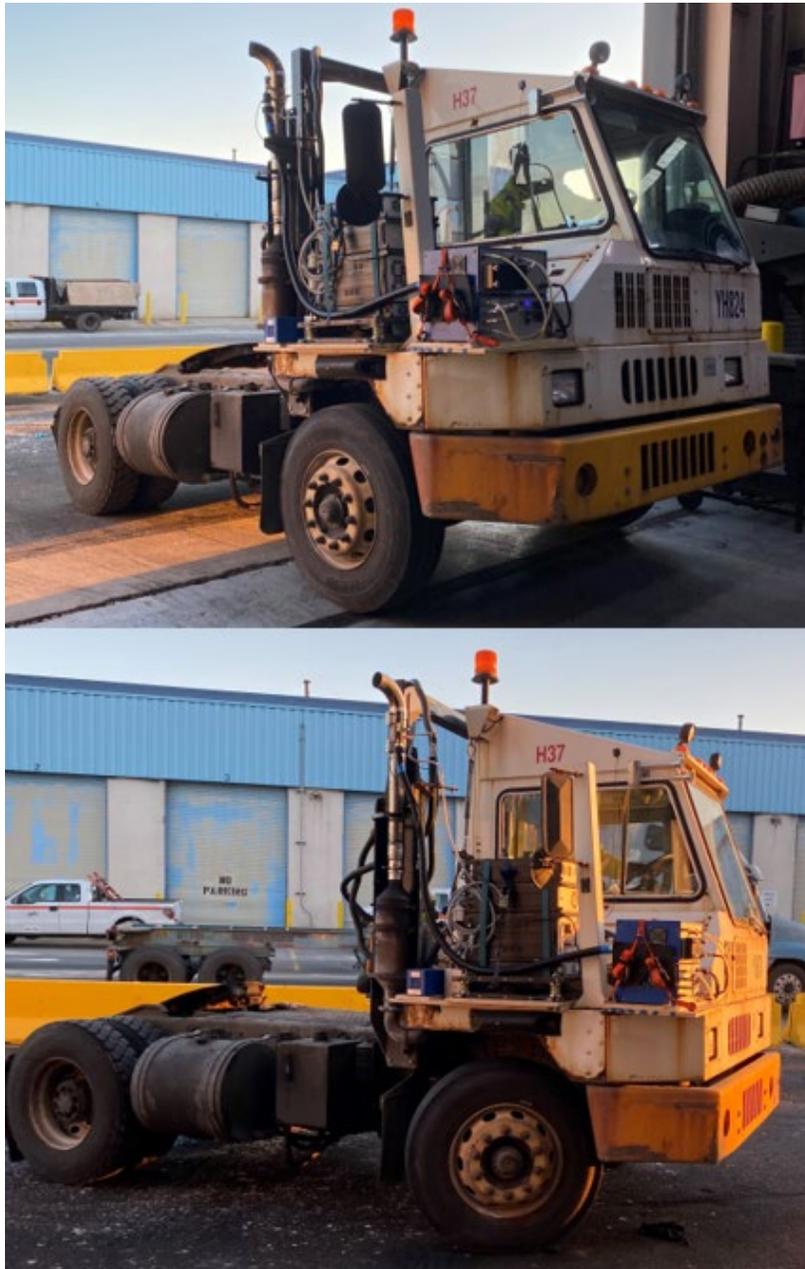


Figure 8.1 PEMS Installation on PNCT Diesel-Fueled Port Tractor H37

8.2.2 MAFI Propane-Fueled Port Tractor H1

Gaseous and PM PEMS were secured to the catwalk area at the rear of the tractor cab of MAFI Unit H1, as shown in Figure 8.2. A single Honda EU2200i inverter generator was installed at the right front fender section of the tractor cab.



Figure 8.2 PEMS Installation on MAFI Propane-Fueled Port Tractor H1

The MAFI H1 tractor had a dual exhaust design (four cylinders per exhaust pathway) that utilized a transverse-mounted muffler that combined both exhaust paths at a location immediately downstream of the TWC (see Figure 8.3). The muffler was a common-core design that mixed both exhaust paths and then directed them to symmetrical exits (turn-downs) at each side of the vehicle. Figure 8.3 illustrates the common cavity of the internal muffler (lower right image) as well as the low exit location of the dual exhaust tailpipes.



Figure 8.3 Exhaust System Components of MAFI Port Tractor H1

8.2.2.1 Exhaust Flow Meter Installation on MAFI Propane-Fueled Port Tractor H1

The exhaust system design of the MAFI H1 tractor presented significant challenges in attaching the EFM at a position downstream of the vehicle's muffler. As such, the muffler was removed, and a test section was fabricated in such a manner as to facilitate the integration of each exhaust pathway prior to the EFM test section (see Figure 8.4). The integration section, which comprised two 3" (nominal) exhaust tubes were combined prior to a 5" 90-degree elbow that was then attached to a reducing section that resulted in a slip-on connection for the 3.5" (nominal) EFM test section (identified by red oval in Figure 8.4). A 90-degree elbow was affixed to the end of the EFM test section, forming the tailpipe of the exhaust path.

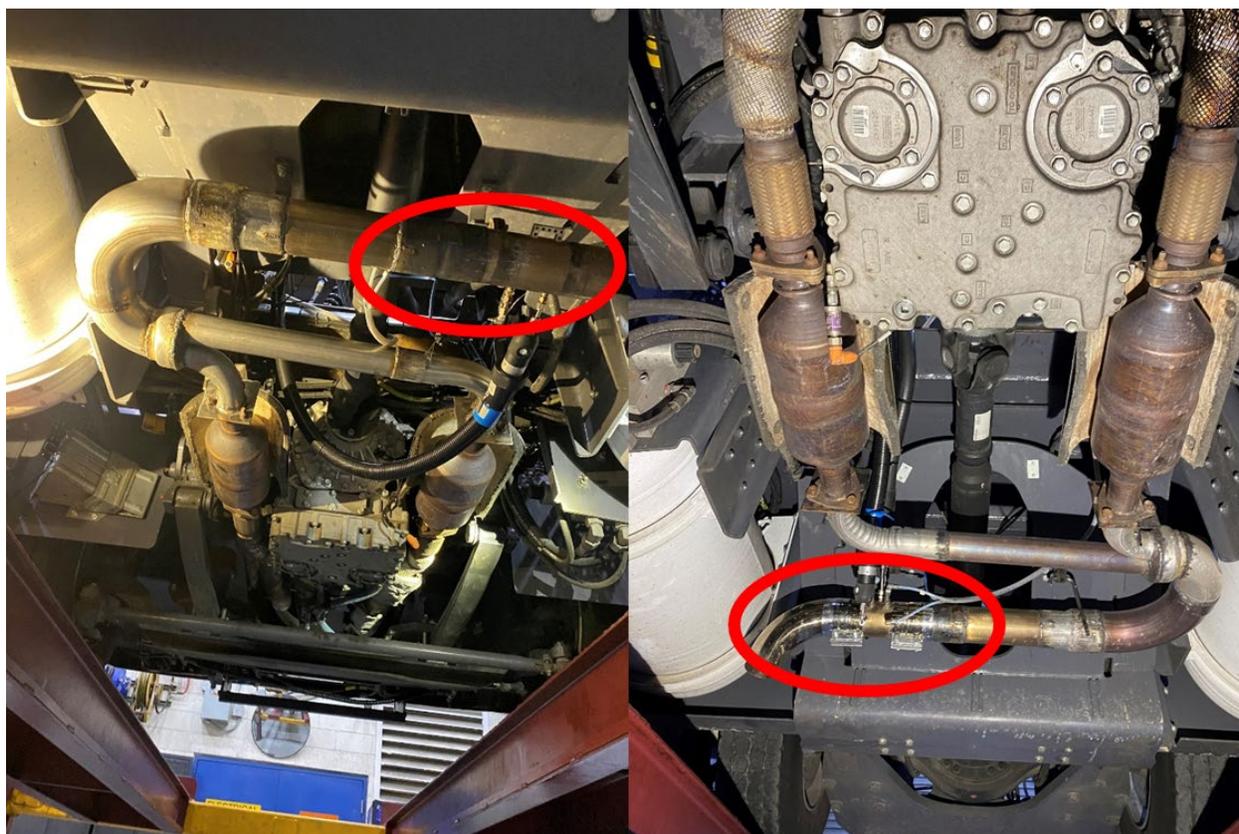


Figure 8.4 PEMS Flow Meter Installation on MAFI Port Tractor H1

8.3 Test Procedure

The test article was fueled by PNCT staff at the start of each test day. Data recording was initiated prior to vehicle start-up to capture cold-start operation. Periodic (nominally 1-hour intervals) zero reference and/or span verifications were conducted, per PEMS manufacturer recommendations. The operation of the test article was not limited or halted during these periods.

As described previously in “Test Routes,” each of the test sequences began at the PNCT Power Shop (repair facility), where the vehicle had been instrumented and cold-soaked overnight in climate-controlled storage. The vehicle would then proceed to pick up its first load of the test sequence. After transporting the container across the flyover to the rail terminal, the vehicle would then travel back across the flyover to the container terminal. At the end of the test sequence, the vehicles would travel back to the PNCT Power Shop, where the test sequence was terminated with post-test analyzer drift measurements, and preparations were made for the next test sequence. Three test sequences were collected for each tractor, designated as “Diesel 1,” “Diesel 2,” and “Diesel 3” and “Propane 1,” “Propane 2,” and “Propane 3.” However, for the first test of the Diesel-fueled tractor, a failure occurred in the cable that connected the CAN protocol adapter to the data acquisition PC. As a result, minimal CAN data were collected during this test sequence. Due to the minimal CAN data for “Diesel 1” combined with lunch breaks between tractor testing, the first four minutes of each test, apart from “Diesel 1”, was removed to avoid discrepancies between the tests. Resulting in only the first four minutes of “Diesel 1” being used as cold start results, noted as “Diesel Cold Start” throughout the report.

At the conclusion of the testing, the PEMS equipment and associated support components were removed from the tractors. After returning the exhaust systems of the tractors to their original configuration, PNCT representatives inspected the vehicles prior to returning them to routine service.

9 Results and Discussion

9.1 Data Format and Binning

All recorded and calculated data were published in Microsoft Excel® files. One sheet consisted of all the “raw” data recorded from the OBS-ONE, while the second sheet was used to transfer these “raw” OBS data and perform the necessary calculations described in “Emissions Reporting.”

Data were calculated on distance-, time- and brake-specific formats, depending upon the appropriate mode of operation. Using the MATLAB® function “readcell”, each excel file was then imported into MATLAB® where those data were binned according to vehicle speed. Data were segregated into “Idle” operation, for vehicle speeds less than 0.93 Miles Per Hour (MPH), and “Urban” operation, for vehicle speeds between 0.93 MPH and 31.3 MPH, which are consistent with published data. Speeds in excess of 31.3 MPH were not encountered during this program. It shall be noted that both tractors had reasonable parasitic loading during low-speed (idle) operation, often as high as 10% of peak torque. This was attributed to loading associated with on-board hydraulic power systems.

9.2 Exhaust Flow Meter Data

Exhaust flow meter data collected from the Diesel-powered tractor is illustrated in Figure 9.1. These data points are quite representative of data commonly collected from diesel-powered vehicles. The exhaust flow meter data collected from the propane-powered tractor is included in Figure 9.2. As indicated, the exhaust flow meter data had excessive noise, which is often encountered with those data collected from spark-ignited stoichiometric engines. The combination of throttled intake air and high water content in the exhaust stream often poses challenges to the differential pressure measurement that provides the basis for the exhaust flow rate data. A significant problem arises since the resulting flow rate data often include negative values. As such, E2A elected to derive a surrogate exhaust flow meter signal by integrating the CAN-based Mass Air Flowrate (MAF) signal, provided by SAE J1939 Suspect Parameter Number (SPN) 132, with a fuel flow rate signal. This method is a provision included in 40CFR Part 1065.230. Data calculated as this surrogate exhaust flow rate are included in Figure 9.3 for the same test as depicted in Figure 9.2. The result provided a much more stable exhaust flow rate signal.

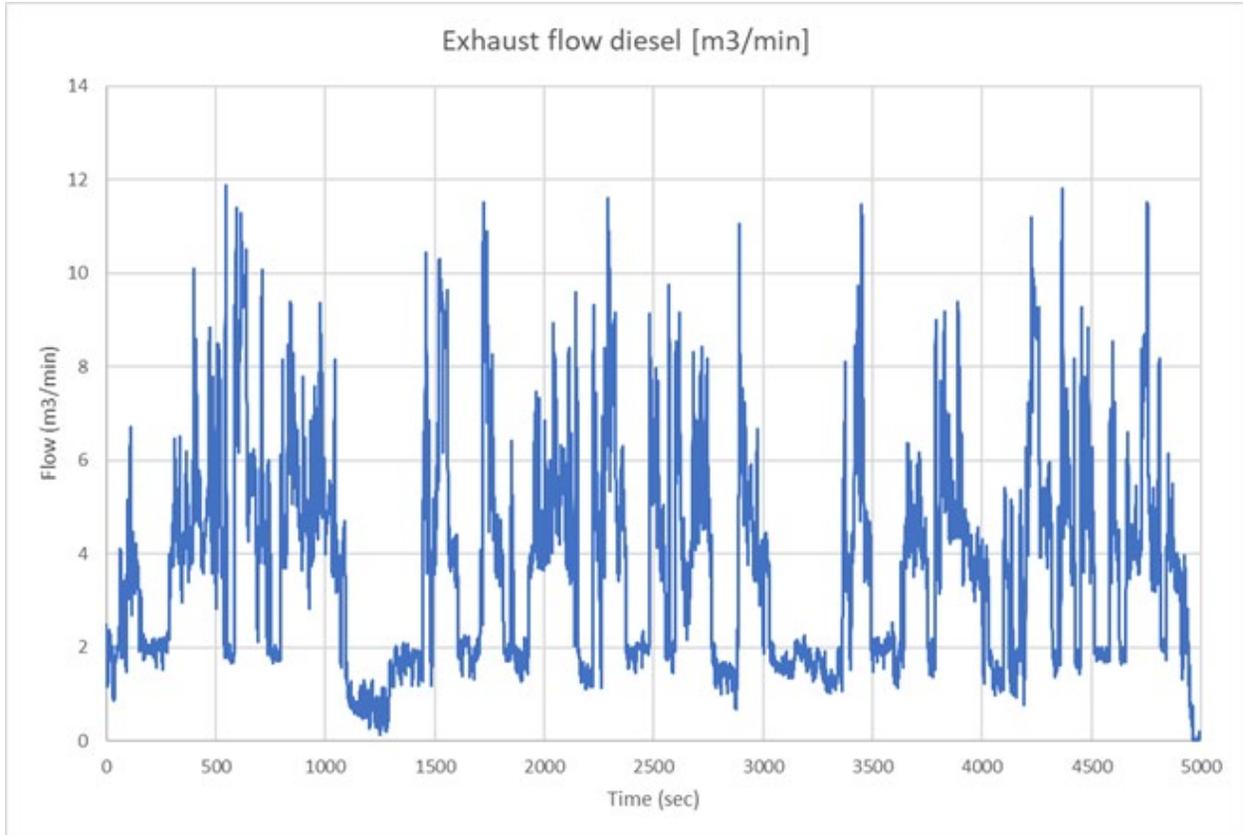


Figure 9.1 Exhaust Flow Rate Data Collected from Diesel-Powered Tractor

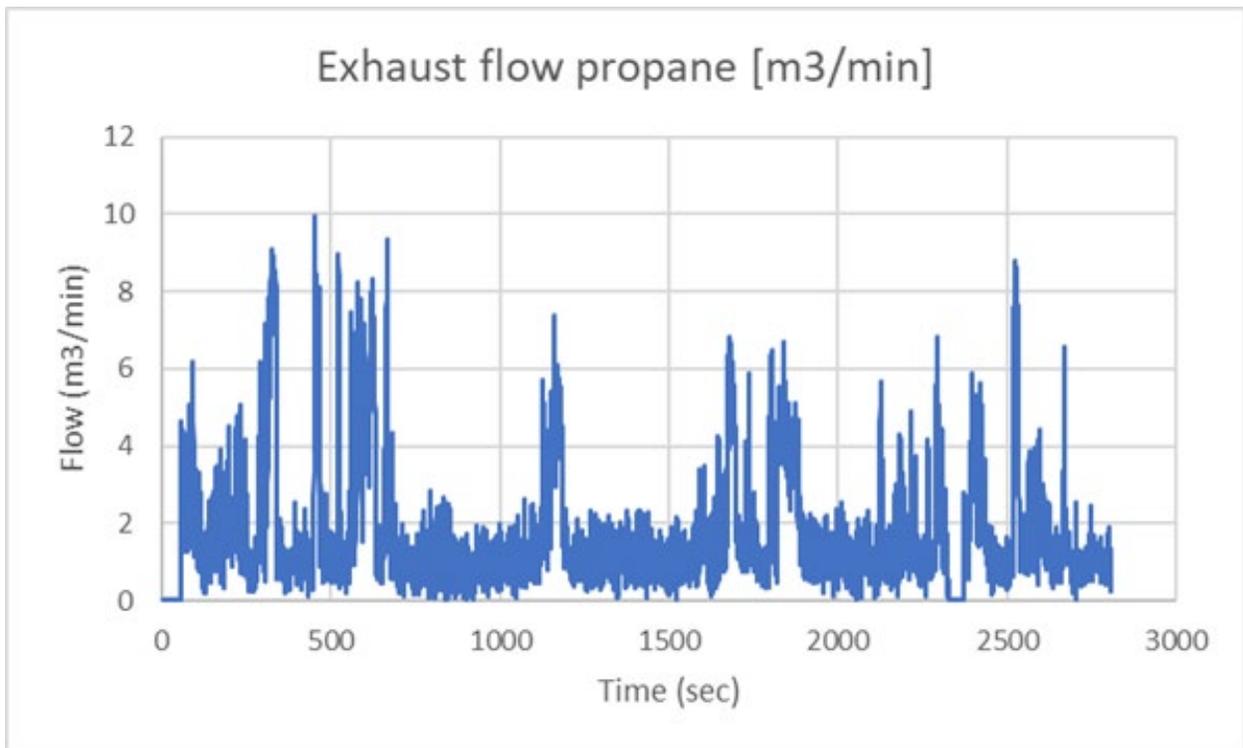


Figure 9.2 Exhaust Flow Rate Data Collected from Propane-Powered Tractor

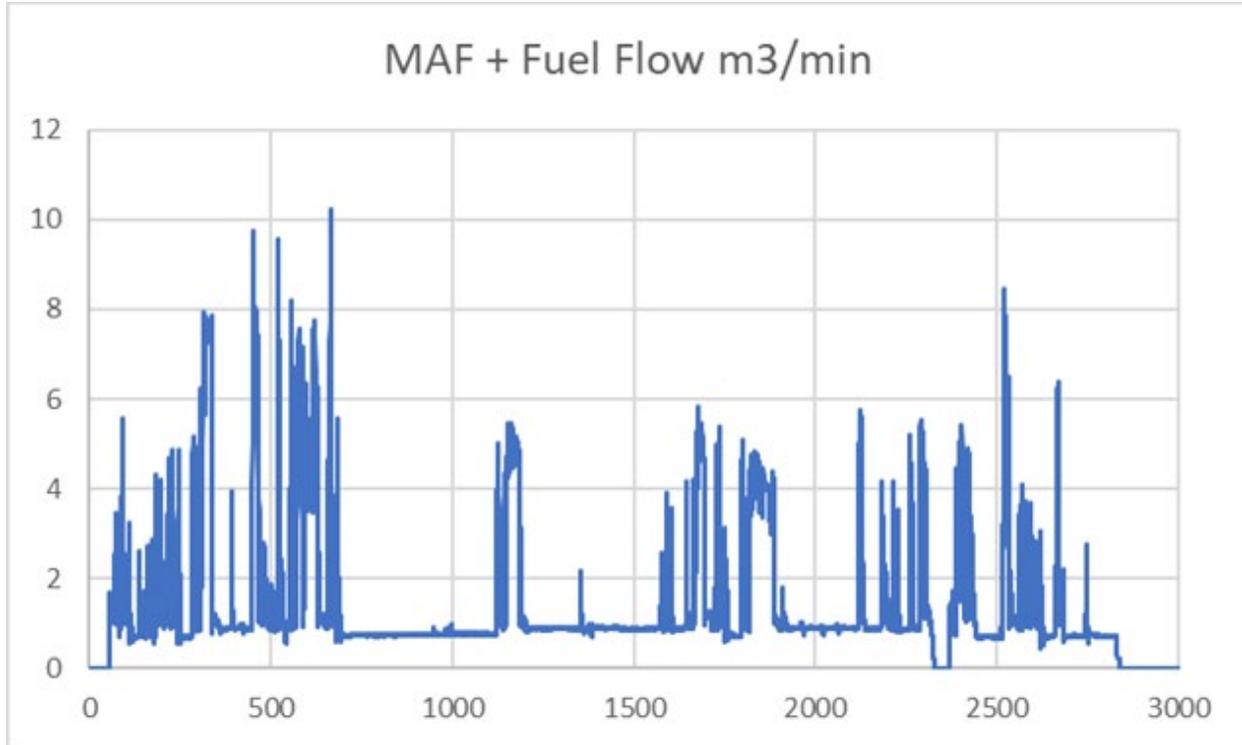


Figure 9.3 Surrogate Exhaust Flow Rate Data - MAF + Fuel

Fuel flow rate data, collected as Engine Fuel Rate (SPN 183) from the J1939 CAN broadcast, was initially used for the fuel term of the surrogate exhaust flow rate signal. However, CAN-data of this parameter were only present for 1 of the 3 tests conducted on the propane-fueled tractor. Moreover, the resultant Brake-Specific Fuel Consumption (BSFC) of the CAN data for Engine Fuel Rate (SPN 183) and the calculated work, derived from Actual Engine Torque, Frictional Torque and Reference Torque, as discussed in “Test Work and Test Duration Calculations” above, resulted in unrealistically low values (0.234 kg/kW-hr). After consulting with representatives from PSI, E2A combined a stoichiometric air-fuel ratio (A/F) of 15.7:1 for propane combustion, as recommended by PSI, with recorded MAF data to provide a surrogate exhaust flow rate, as illustrated in Figure 9.3. This approach was validated by the collected data, which exhibit nearly zero deviation from the stoichiometric value, as indicated by the CO₂ data presented in Figure 9.4.

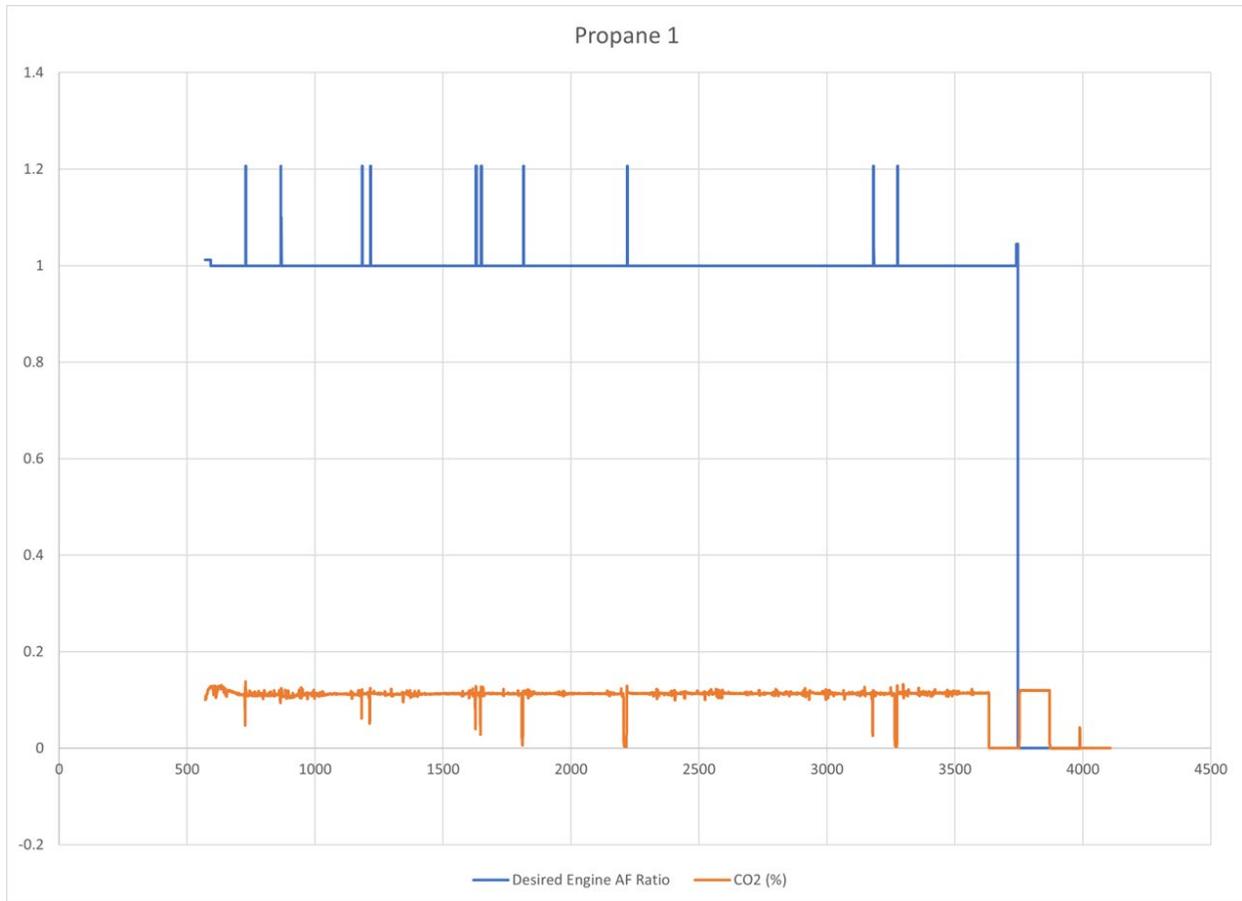


Figure 9.4 Air-Fuel Ratio and CO₂ from Propane-Fueled Vehicle Test

Table 9.1 presents fuel consumption results from the test sequences collected from the two tractors. CAN-reported fuel consumption was derived from SPN 183 for the Diesel-fueled tractor, while data for the propane-fueled vehicle were derived from the MAF and A/F ratio, as discussed above. The green annotated value for “Propane 3” was derived from SPN 183, resulting in an average difference of 8.22% when compared to the MAF and A/F derived fuel consumption for the Propane 3 test sequence. Table 9.1 additionally includes carbon-derived fuel consumption, inferred from measured exhaust emission rates, presented on an equivalent fuel volume basis. The percent differences presented in Table 9.1 were derived from comparing CAN-broadcast fuel consumption with emissions-derived (carbon balance) fuel consumption. Typically, data collected from engine fueling CAN broadcast corroborate well (within 5%) with carbon balance data derived from exhaust emissions measurements. As Table 9.1 indicates, those data collected from the Diesel-fueled tractor were well within this range, while the propane-fueled tractor results deviated only slightly for test sequence Propane 1.

Table 9.1 Fuel Consumption Results from the Test Vehicles

	Diesel 2	Diesel 3	Propane 1	Propane 2	Propane 3
CAN Derived Fuel Consumption (L)	8.1787	10.805	15.342	9.859	14.549 *13.399
Carbon Balance Fuel Consumption (L)	8.3004	10.837	14.414	9.361	13.888
Percent difference (%)	1.477	0.296	6.237	5.182	4.649

9.3 Monte Carlo Simulation of Exhaust Flowrate and Engine Torques Estimates for Propane Tractor

For the propane-fueled vehicle data, additional data analysis was performed, at the request of PERC. After consultation with PSI, accuracy margins for the MAF and actual torque data were used to simulate the impact on results using a Monte-Carlo approach. For each of the propane tractor test sequences, a margin of +/- 5% for MAF data were used to derive exhaust flow rate accuracy margins, which should linearly impact mass emission rates. For each value of the recorded Engine Intake Air Mass Flow Rate (SPN 132), which was recorded at a 10Hz frequency, a randomized number between the -10% and +10% of that value was generated using the 'randbetween' function (normal distribution) in Microsoft Excel® and used to replace each of the respective original data points. Since the 'randbetween' function only rounds to the nearest whole number, data points were scaled prior to this randomization step, and then re-scaled accordingly. After applying this procedure to the emission mass rate calculations, the actual engine percent torque was also randomized, based upon a margin recommendation of +/-10%, provided by PSI. As with the MAF data, for each value of the recorded Actual Engine Torque (SPN 513), which were recorded at a 10Hz frequency, a randomized number between the -10% and +10% of that value was generated using the 'randbetween' function in Microsoft Excel® and used to replace each of the respective original data points.

Randomized values for MAF and percent torque were reprocessed using the EEA MATLAB® emissions reduction code. These data were then speed-binned in order to segregate vehicle operation. This process was repeated ten times for the three propane tests to create simulated distance-, time- and brake-specific data that would provide a reference of sensitivity of those results with respect to the reported accuracy of those two parameters. These ten randomized data sets were then used to calculate a standard deviation and geometric mean for each time-, distance- and brake-specific result.

9.3.1 Monte Carlo Simulation Results

The mean values of the ten randomized data sets were very well-represented by the original data values. The largest percent difference occurred at a value of 0.56% for idle THC emissions, collected from the "Propane 3" test sequence. The smallest percent difference was observed at idle conditions during the "Propane 1" test sequence, with CO results exhibiting a difference of 0.0015%.

Standard deviation showed comparable results to that of the percent difference. Idle CO2 experienced the greatest standard deviation with an average standard deviation of 2.37. Distance-specific NOx experienced the lowest standard deviation with an average standard deviation of 0.00005.

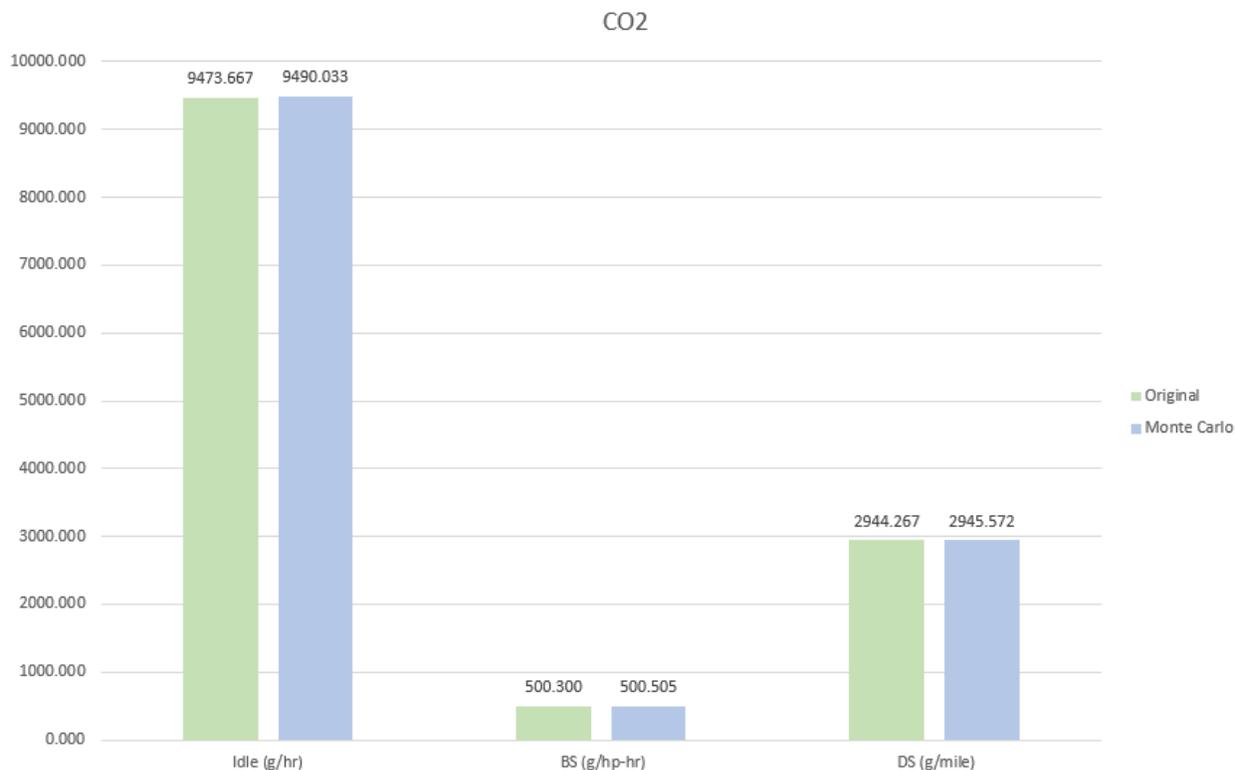


Figure 9.5 Comparison of Original Data with Simulated Data for CO₂ Emissions

As CO₂ comprises the largest weighted term in the iterative carbon balance procedure that is used to calculate molar exhaust flow rate, the variation of the simulated results of this parameter would have the most pronounced effect on subsequent overall emission results. As indicated in Figure 9.5, the mean original propane data resulted in an idle value of 9473.67 g/hr while the simulated data resulted in 9490.03 g/hr. A comparison of the percent difference of simulated results and the original data results for gaseous emissions are presented in Figure 9.6 - Figure 9.9. As indicated, simulated data were well within a +/-1% margin, hence those results were used to represent emissions results for the propane-fueled tractor, as presented in the following section.

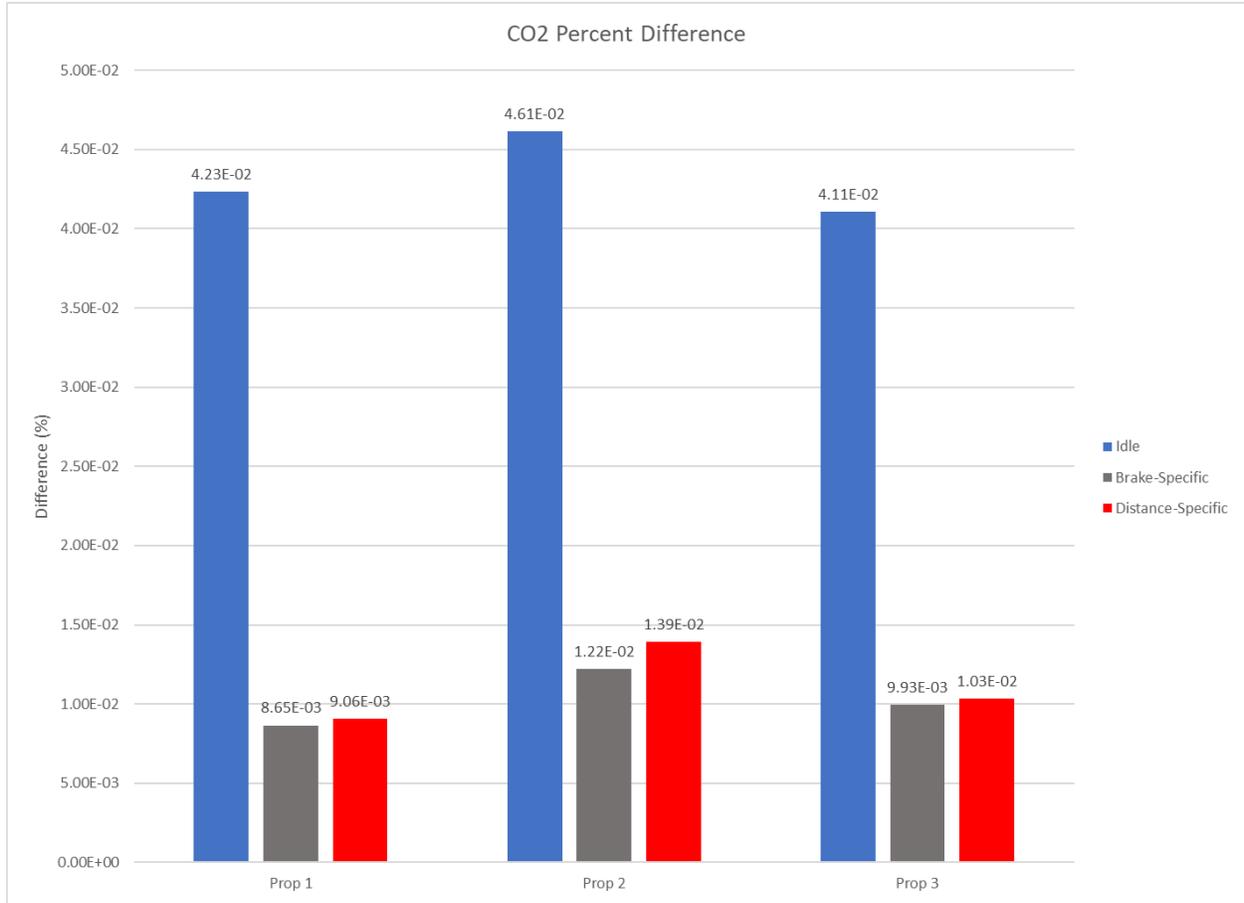


Figure 9.6 Percent Differences in Simulated Data and Original Data for CO₂ Emissions

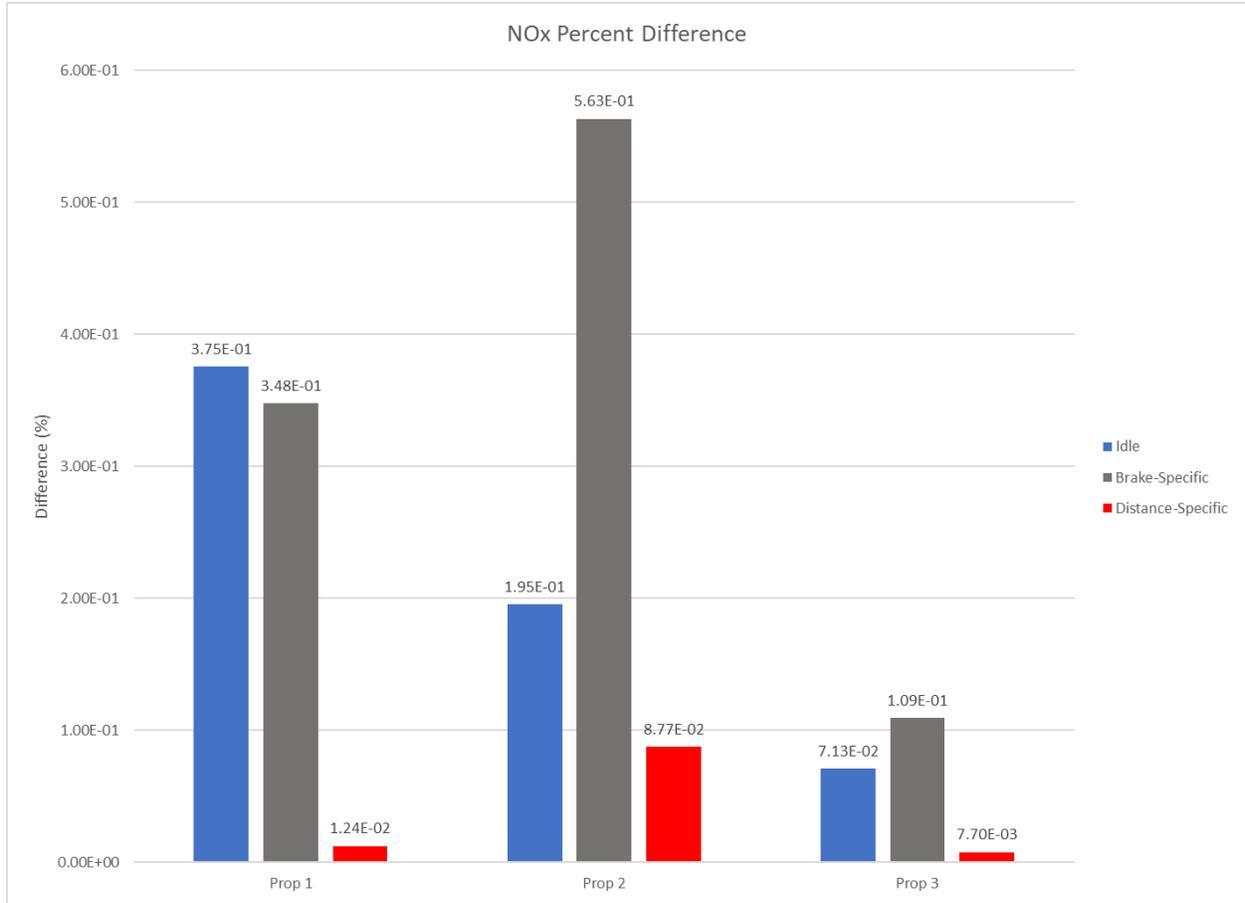


Figure 9.7 Percent Differences in Simulated Data and Original Data for NOx Emissions

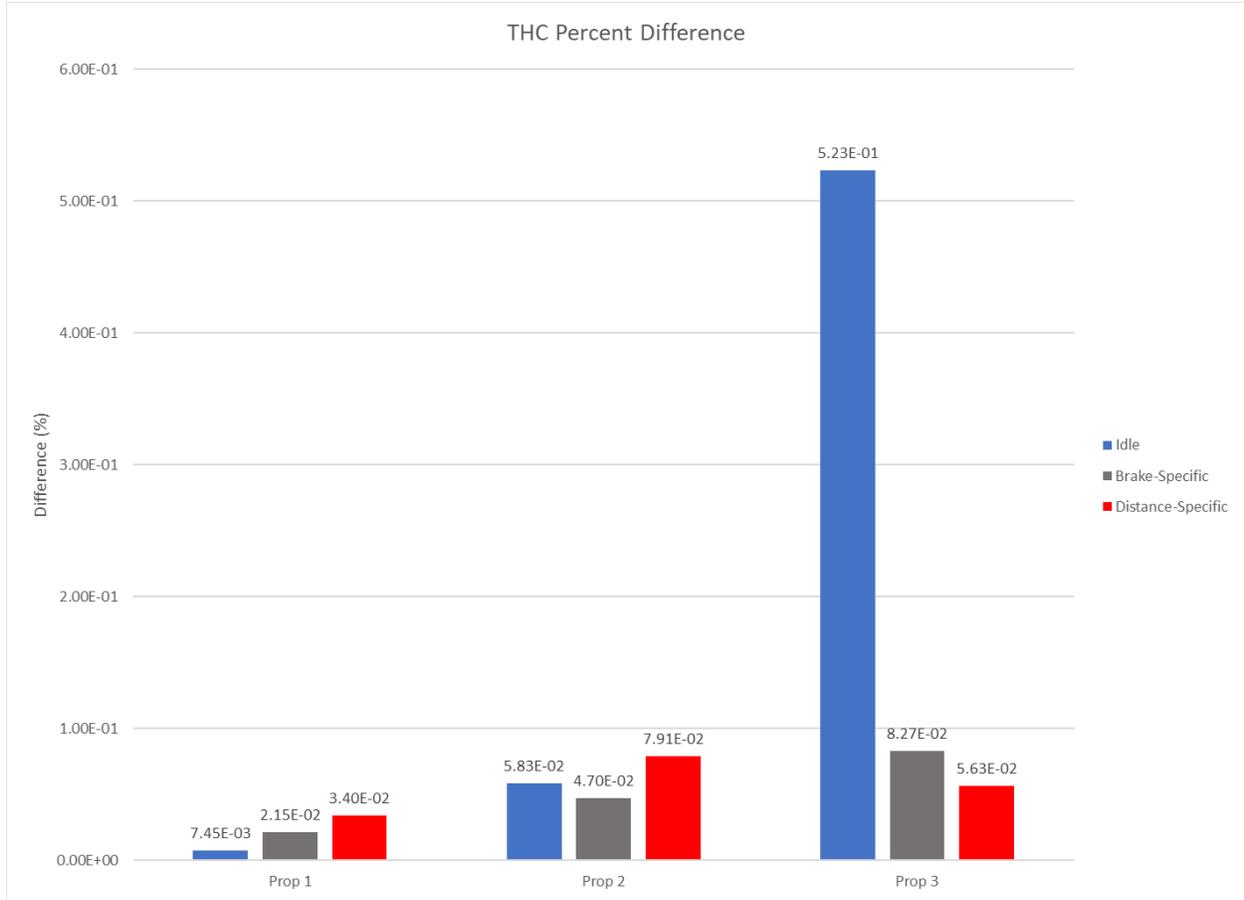


Figure 9.8 Percent Differences in Simulated Data and Original Data for THC Emissions

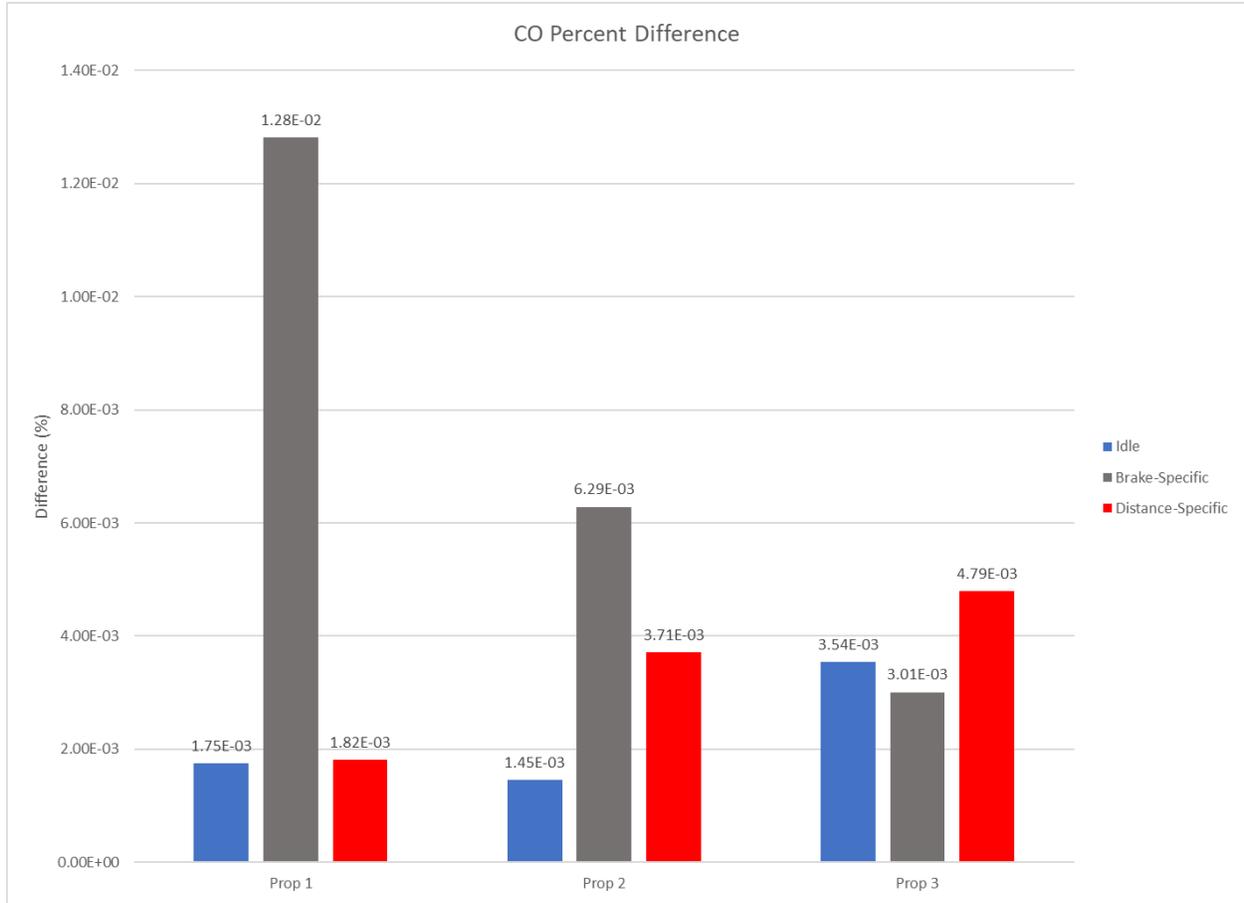


Figure 9.9 Percent Differences in Simulated Data and Original Data for CO Emissions

9.4 Final Results

9.4.1 Activity Data

Distribution of activity for the various test sequences are presented in Figure 9.10. As indicated, the propane-fueled tractor spent more time at idle conditions than the diesel-fueled tractor, with test sequence “Propane 2” including nearly 63% of the test time at idle conditions.

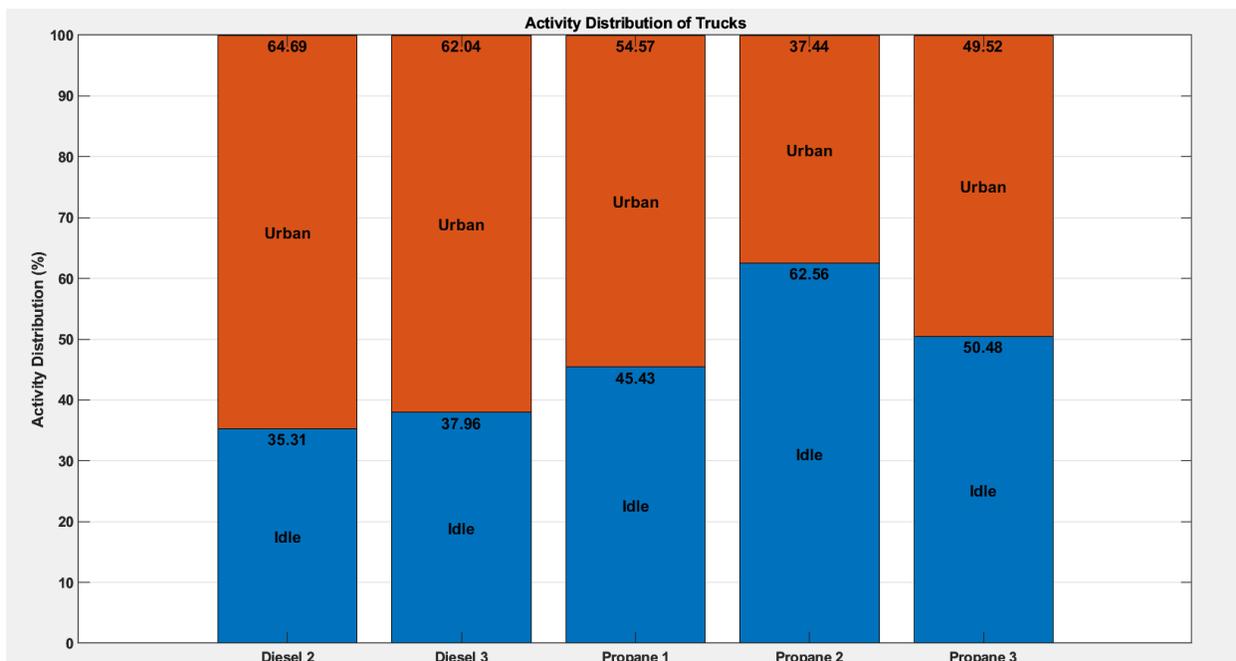


Figure 9.10 Activity Distribution of the Yard Tractors

Total distance traveled for each of the test sequences are compared in Figure 9.11. As indicated, data recorded from the “Diesel 3” test sequence comprised the longest route, with a total of 10.6 miles. The shortest test sequence was “Propane 2,” with a total of 3.02 miles. This corroborates well with the activity distribution of Figure 9.10, as “Propane 2” included the shortest distance traveled and the highest percentage of time spent at idle conditions.

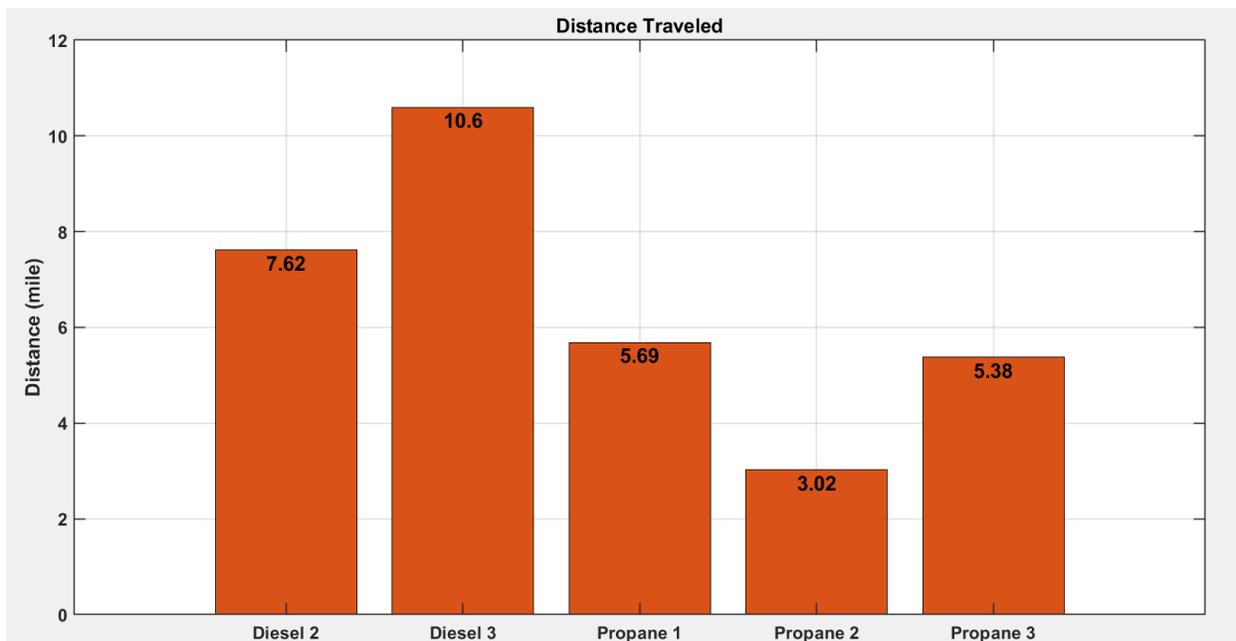


Figure 9.11 Distance Traveled for the Recorded Test Sequences

Recorded work for each of the test sequences is illustrated in Figure 9.12. Again, the trend for work corroborated well with the reported distribution of activity and the vehicle distance traveled for each of the test sequences. In summary, with regards to the activity information presented herein, it shall be noted that activity data are predominantly dictated by driver schedule and total container daily transport schedule. Hence, good repeatability on a test-to-test or day-to-day basis should not be expected.

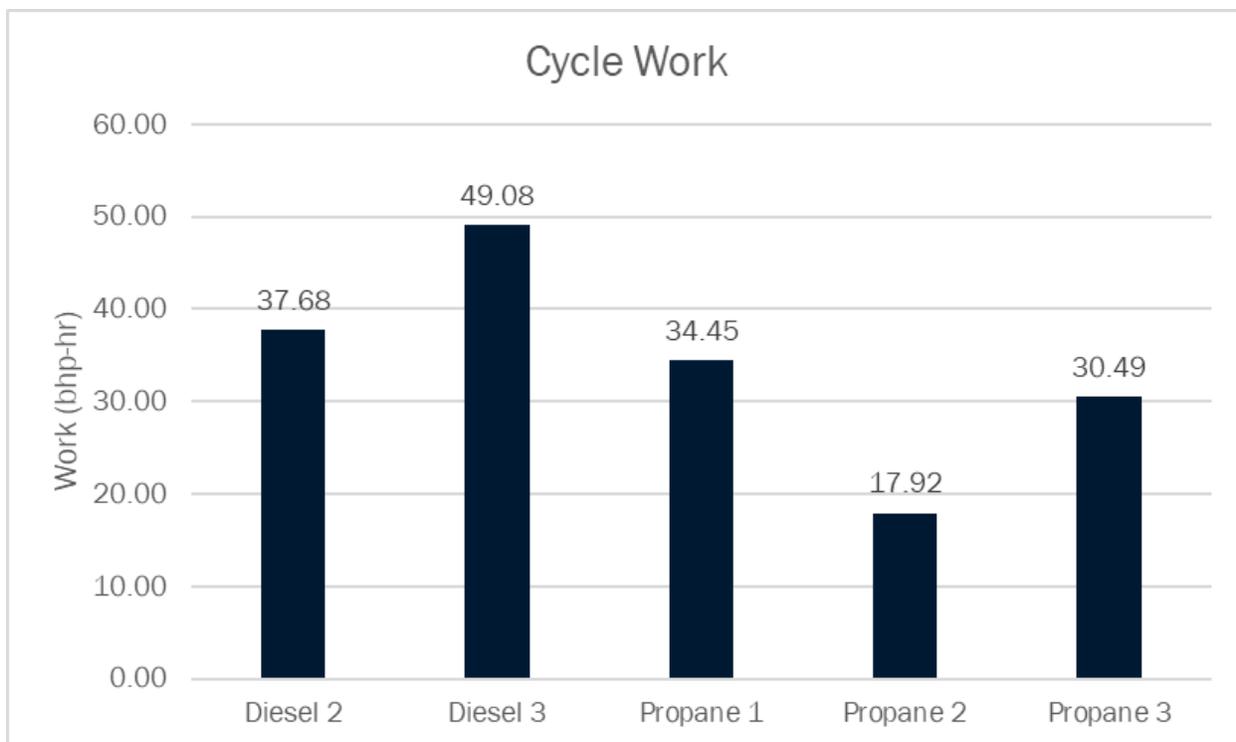


Figure 9.12 Cycle Work for Each Test Sequence

9.4.1.1 Engine Speed

Measured engine speed for each test cycle is illustrated in Figure 9.13. The Propane-fueled tractors ran at a higher average idle of 749 RPM compared to the average idle of the Diesel-fueled tractors of 704 RPM. This trend continued through the urban activity resulting in propane average urban cycle of 1440 RPM exceeding diesel’s average urban cycle of 1375 RPM. A drop in engine speed toward the end of the “Propane 2” resulted from the engine being turned off and back on again.

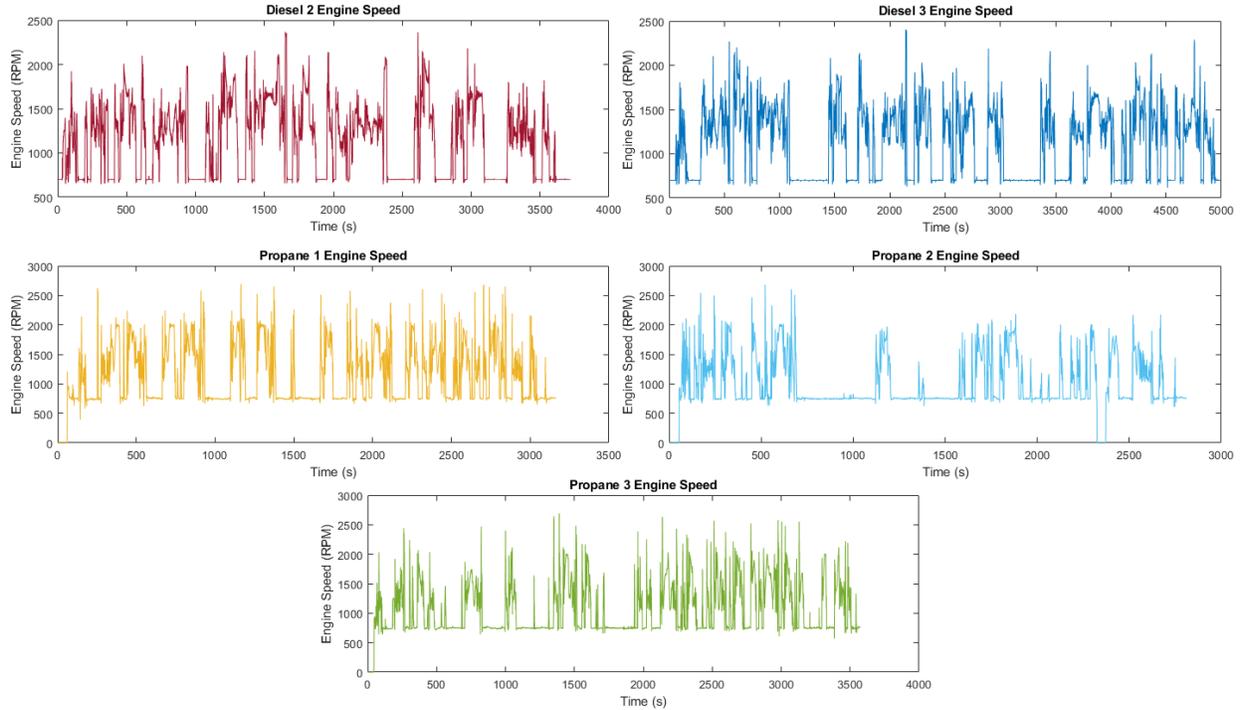


Figure 9.13 Engine Speed Data for Each of the Recorded Test Sequences

9.4.1.2 Vehicle Speed

Recorded vehicle speed for the whole test cycle is illustrated in Figure 9.14. The average urban vehicle speed for the Diesel-fueled tractor was slightly higher than the average urban vehicle speed of the Propane-fueled tractor. With diesel averaging urban vehicle speeds of 19.56 km/hr to that of propane averaging 18.71 km/hr.

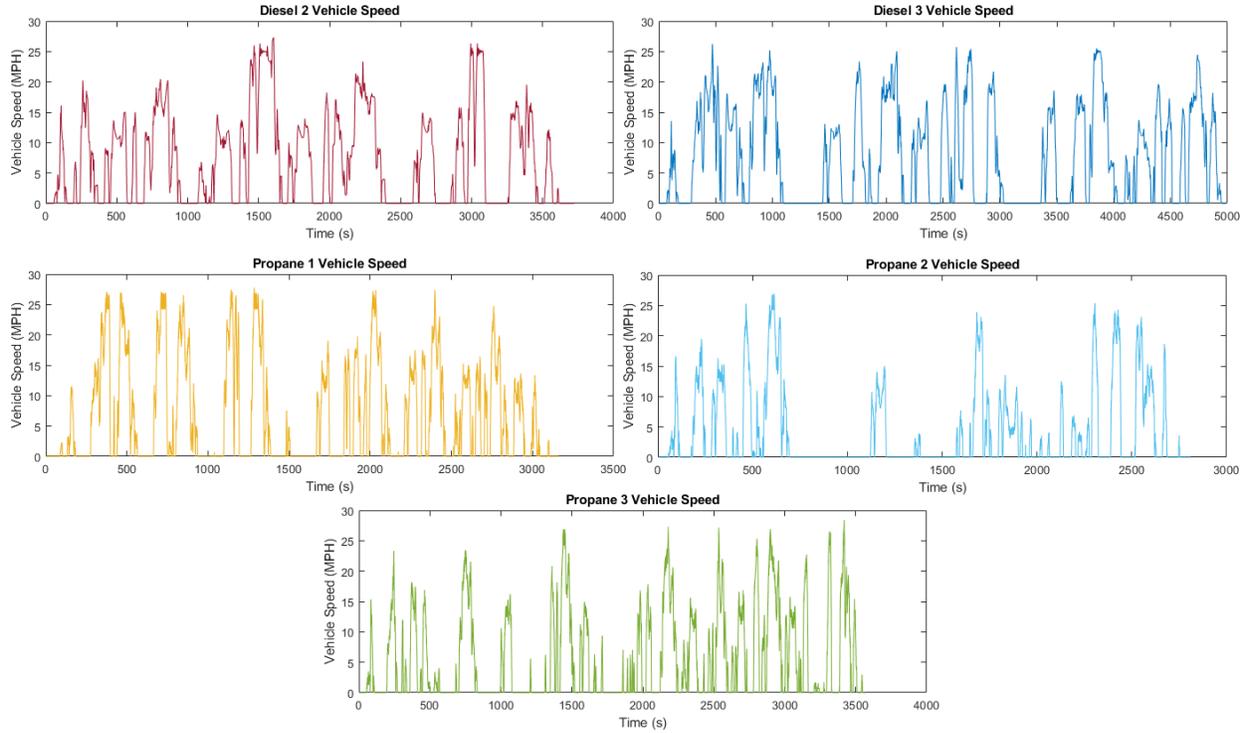


Figure 9.14 Vehicle Speed Data for Each of the Recorded Test Sequences

9.4.1.3 Relative Positive Acceleration (RPA)

RPA is a speed-related average acceleration metric frequently used for the analysis of driving patterns and in the development of chassis dynamometer test schedules, particularly those aimed at representing real-world driving patterns. RPA is directly related to average power and is often used to characterize cycle or route power demand when engine loading information is not readily available. RPA for a time interval is the integral of the product of vehicle speed and positive acceleration for each instance in time, divided by the total distance traveled over that time interval, as given by Equation 1. For this study, the interval over which RPAs were calculated (micro trip) was defined as any continuous portion of the test route where the vehicle speed was larger than 2 km/h for a duration of at least 5 seconds. Instantaneous vehicle acceleration was calculated according to Equation 2, by differentiating vehicle speed data collected from the vehicle CAN bus, and subsequently forcing negatives values to zero.

$$RPA = \frac{\int_0^{t_j} (v_i \cdot a_i) dt}{x_j}$$

Equation 1

- Where:
- t_j duration of micro trip j
 - x_j distance of micro trip j
 - v_i speed during each time increment i
 - a_i instantaneous positive acceleration during each time increment i contained in the micro trip j

$$a_i = \begin{cases} \frac{(v_2 - v_1)}{(t_2 - t_1)} & \text{if } i = 1 \\ \frac{(v_{i+1} - v_{i-1})}{(t_{i+1} - t_{i-1})} & \text{if } 2 \leq i \leq n - 1 \\ \frac{(v_n - v_{n-1})}{(t_n - t_{n-1})} & \text{if } i = n \end{cases}$$

Equation 2

Figure 9.15 depicts the relative positive acceleration calculated from the micro trips from test sequences Diesel 2, Diesel 3, Propane 1, Propane 2 and Propane 3. Considering the modest range of the vertical axis, the RPA of all test sequences appear to be in relatively good agreement, indicating that the vehicles were operated over similarly aggressive speed/load series. Diesel 2 and Diesel 3 are associated with lower RPA, indicating that lower accelerations were measured throughout the micro trip speed domains. Without knowing the combined vehicle load information for each trip driven by the test vehicles, the differences in RPA are attributed to the lower power rating of the diesel engine and the delayed acceleration that can occur due to turbo response time.

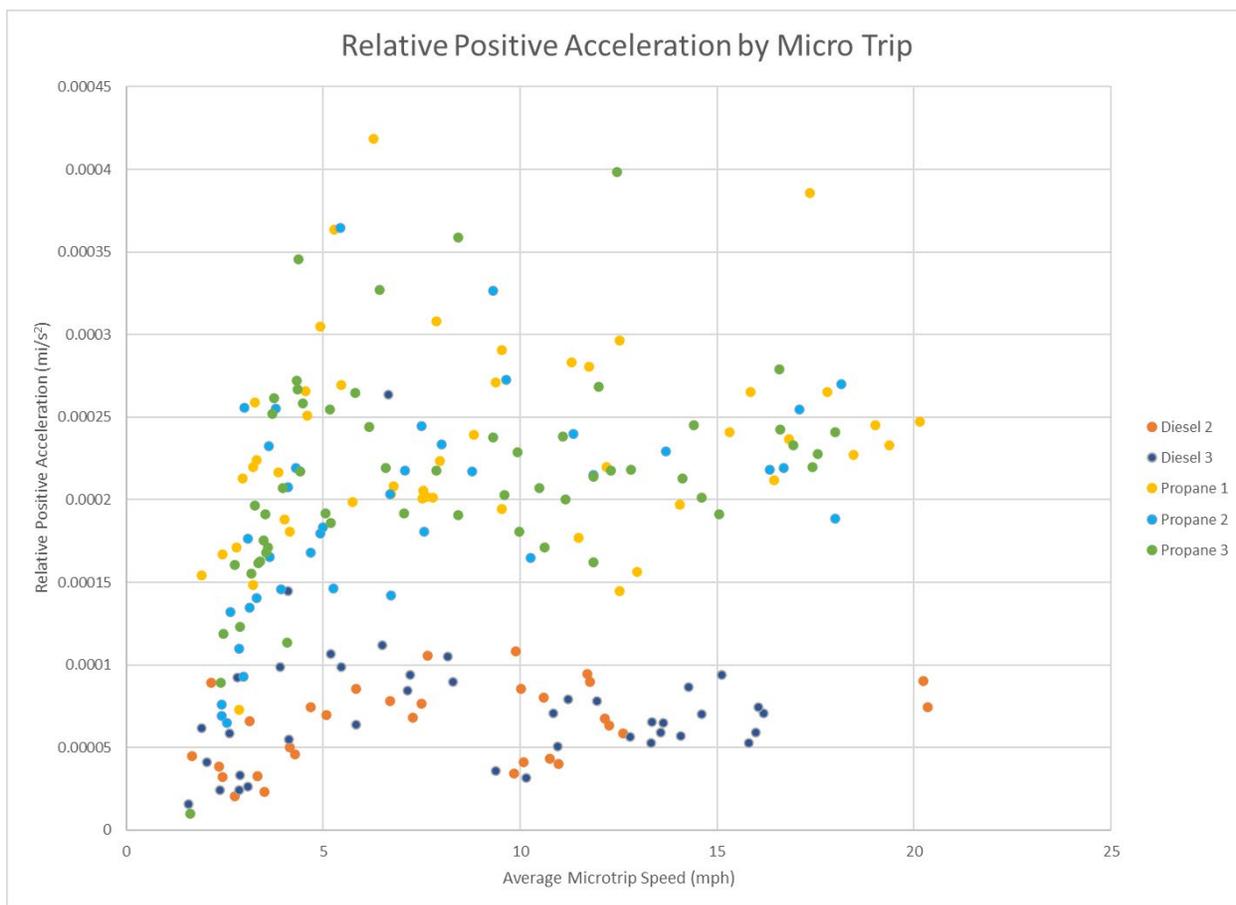


Figure 9.15 Relative Positive Acceleration of Microtrips for Each Test Sequence

9.4.2 Mass Emission Results

Each gaseous mass emissions rate has been summarized on a time-specific basis for idle activity and on both brake- and distance-specific bases for urban activity. Total particulate matter was reported as a

test sequence-integrated result in a brake-specific format. Idle emission results consist of 3 propane tests, 2 diesel tests, and values recorded for the first 2 mins from cold start for diesel test 1.

9.4.2.1 Carbon Dioxide (CO₂) Emissions

CO₂ emission results are presented in Figure 9.16 and Figure 9.17. Idle CO₂ emissions for the propane-fueled tractor were approximately two times greater than those produced by the diesel-fueled tractor, with the highest average occurring over test sequence “Propane 3” with a value of 10518 g/hr.

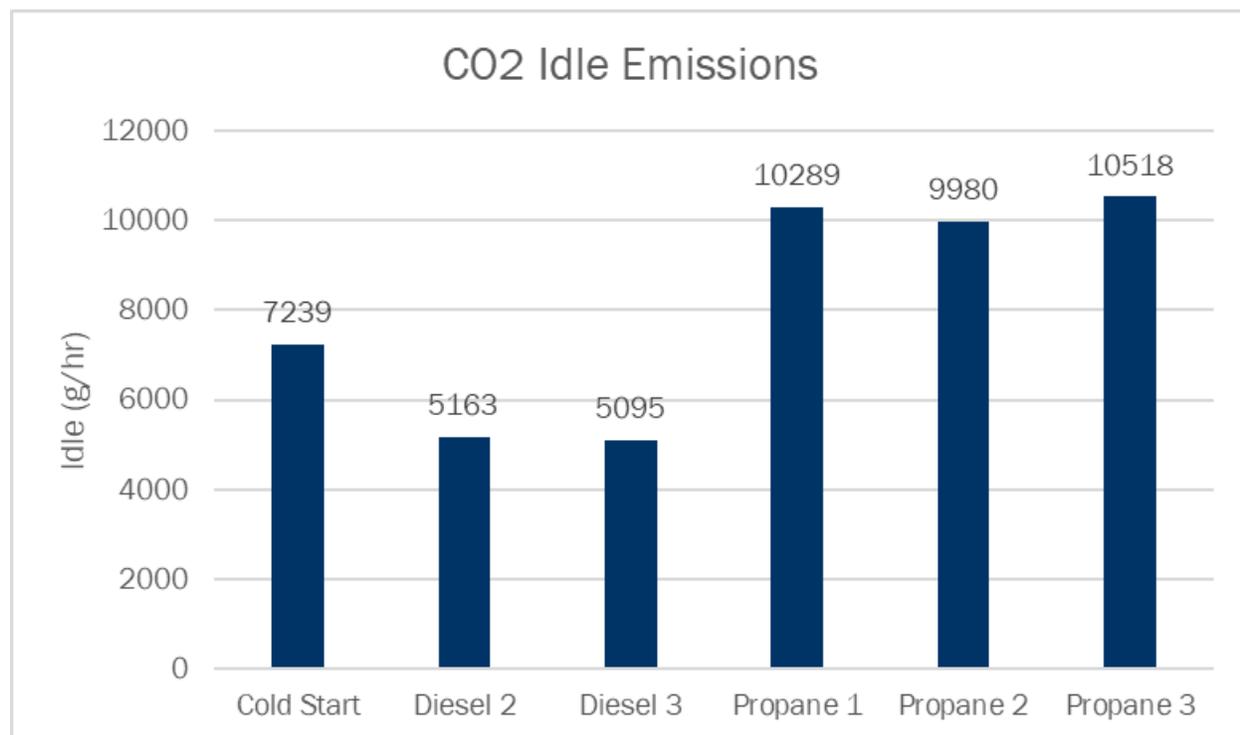


Figure 9.16 Comparison of Time-Specific CO₂ Emissions for Idle Activity

Brake-specific CO₂ emissions (Figure 9.17) from the Diesel-fueled tractor were higher than those collected from the Propane-fueled tractor across all test sequences. The average brake-specific CO₂ for the Diesel-powered tractor across all test sequences was 587.2 g/ bhp-hr, whereas the Propane-fueled tractor produced 505.9g/bhp-hr. The elevated CO₂ emissions associated with the Diesel-fueled tractor when compared to the Propane-fueled tractor may be attributed to the increased fuel consumptions cause by increased EGR rates. These rates were the primary means of NO_x control and the removal of idle data for that urban operation. Mitigating the inherent advantage of reduced pumping losses associated with non-throttled compression ignition.

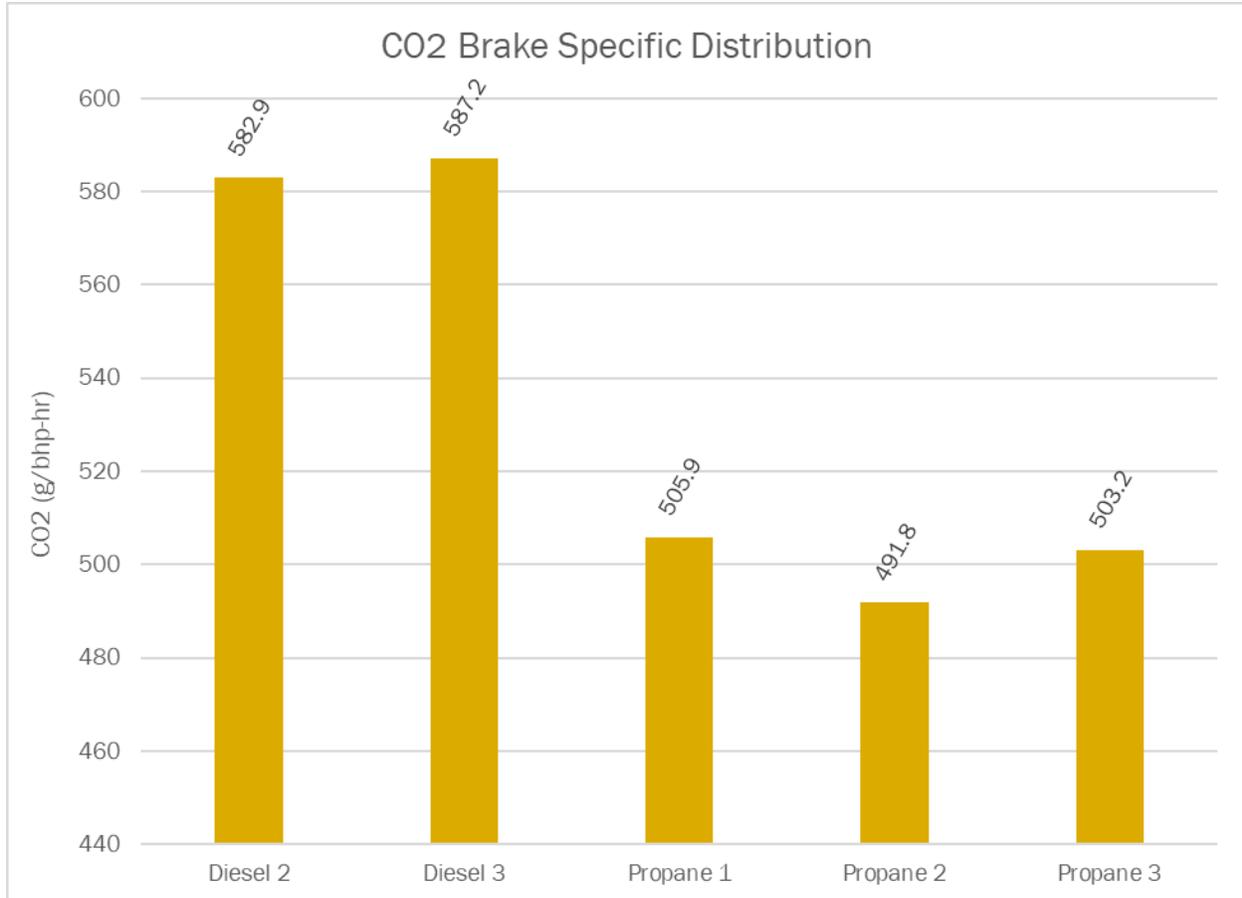


Figure 9.17 Comparison of Brake-Specific CO₂ Emissions for Urban Activity

9.4.2.2 Total Oxides of Nitrogen (NO_x) Emissions

NO_x emission results are presented in Figure 9.18 and Figure 9.19. Consistent with the certification values reported to the US EPA, the propane-fueled tractor produced near-zero NO_x emissions. While the cycle-averaged brake-specific NO_x emissions for the diesel-fueled tractor were significantly higher – nearly three orders of magnitude. Results averaged across all test sequences were 93.5 g/hr during idle operation for the Diesel-fueled tractor and 3.838 g/bhp-hr for this vehicle during urban operation. In stark contrast, the propane-fueled tractor produced 0.053 g/hr during idle operation and 0.005 g/bhp-hr for urban operation.

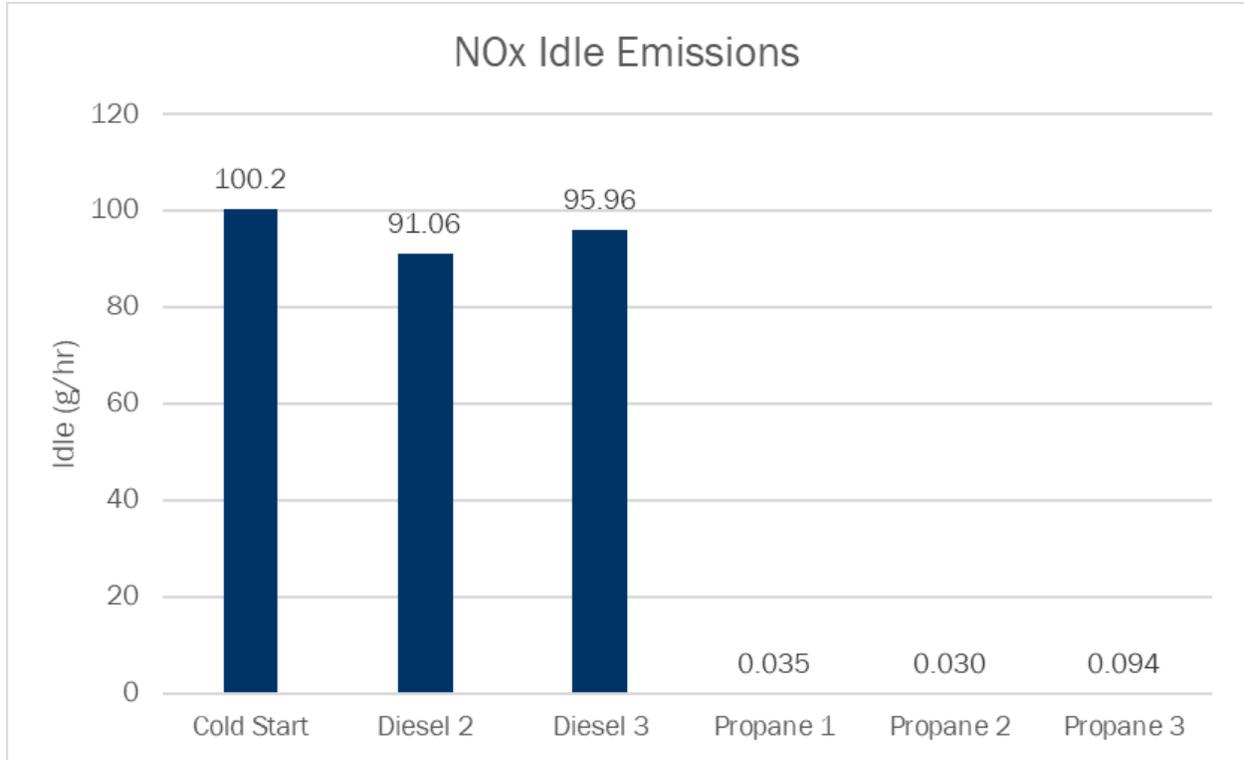


Figure 9.18 Comparison of Time-Specific NOx Emissions for Idle Activity

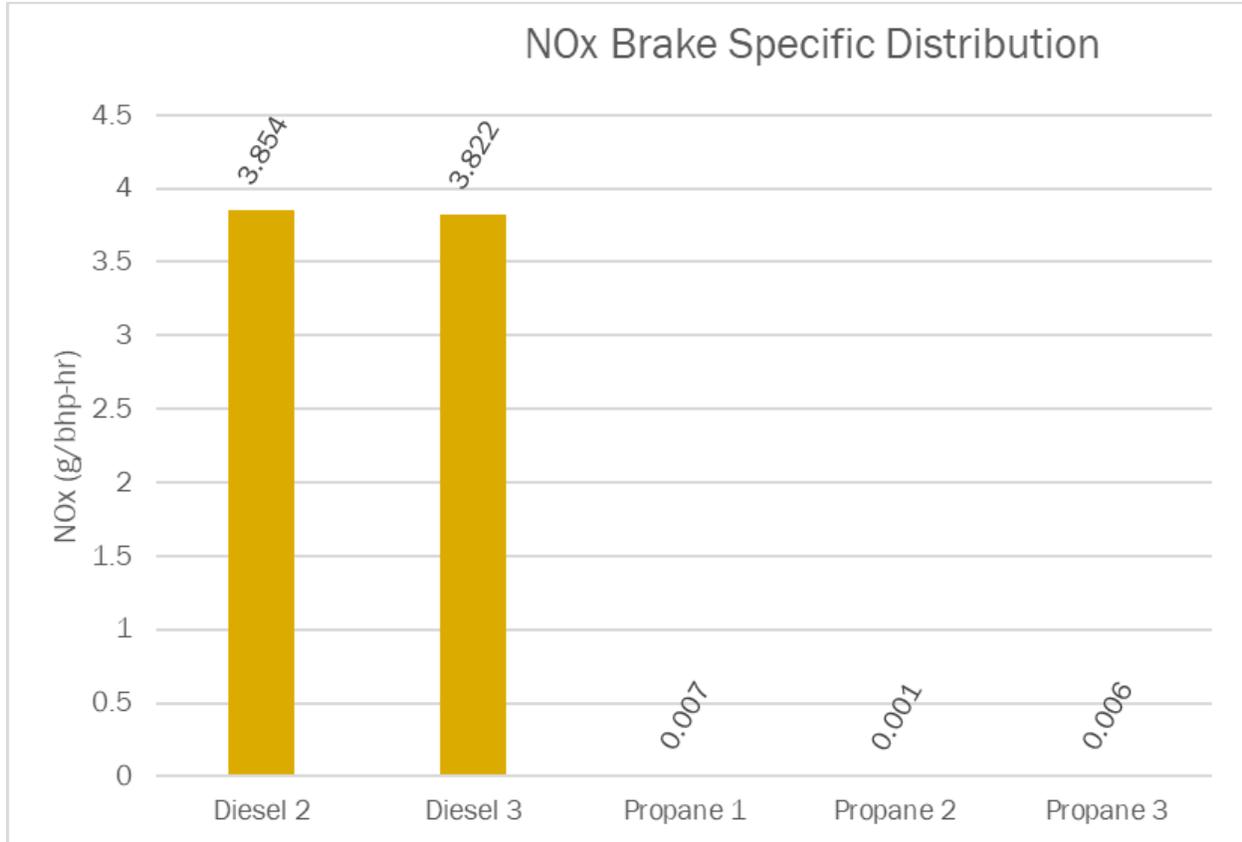


Figure 9.19 Comparison of Brake-Specific NOx Emissions for Urban Activity

9.4.2.3 Total Particulate Matter (TPM)

TPM is presented in Figure 9.20 as a batch-measurement result, integrated over the entire test sequence and normalized by total cycle work. PM emissions from the Propane-fueled tractor were substantially lower than those measured from the Diesel-powered tractor. For urban operation, the Diesel-powered tractor emitted approximately 0.0088 g/bhp-hr, whereas the Propane-fueled tractor produced approximately 0.0023 g/bhp-hr.

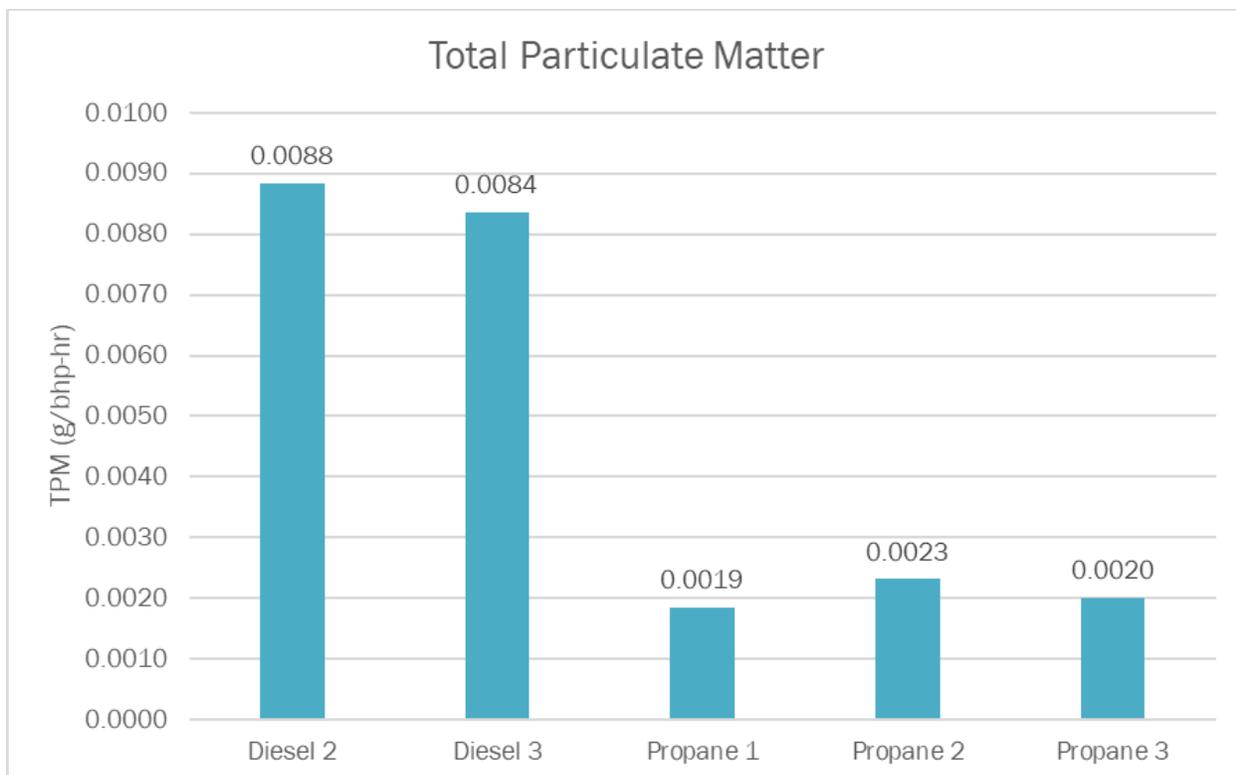


Figure 9.20 Integrated PM Results for the Recorded Test Sequences

9.4.2.4 Total Hydrocarbon (THC) Emissions

THC emission results are presented in Figure 9.21 and Figure 9.22. The cold-start operation for the Diesel-powered tractor produced approximately 2.871 g/hr. In contrast to CO emissions results, the Diesel-powered tractor produced significantly more THC emissions for both idle and urban operation, on both brake- and distance-specific bases, when compared with the propane-powered tractor. Test sequence “Diesel 2” and “Diesel 3” resulted in approximately five times those values recorded for test sequences “Propane 2” and “Propane 3.” Excluding cold start, the highest value was recorded during “Diesel 2,” approximately 1.225 g/hr.

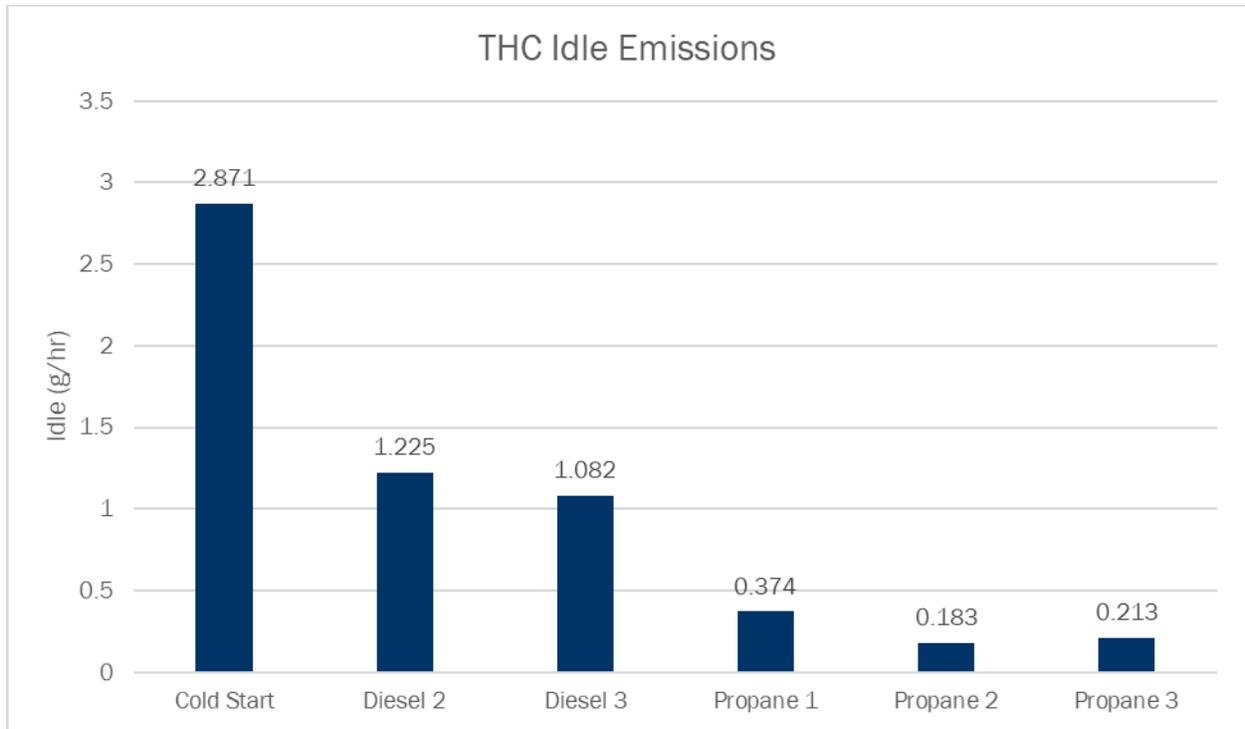


Figure 9.21 Comparison of Time-Specific THC Emissions for Idle Activity

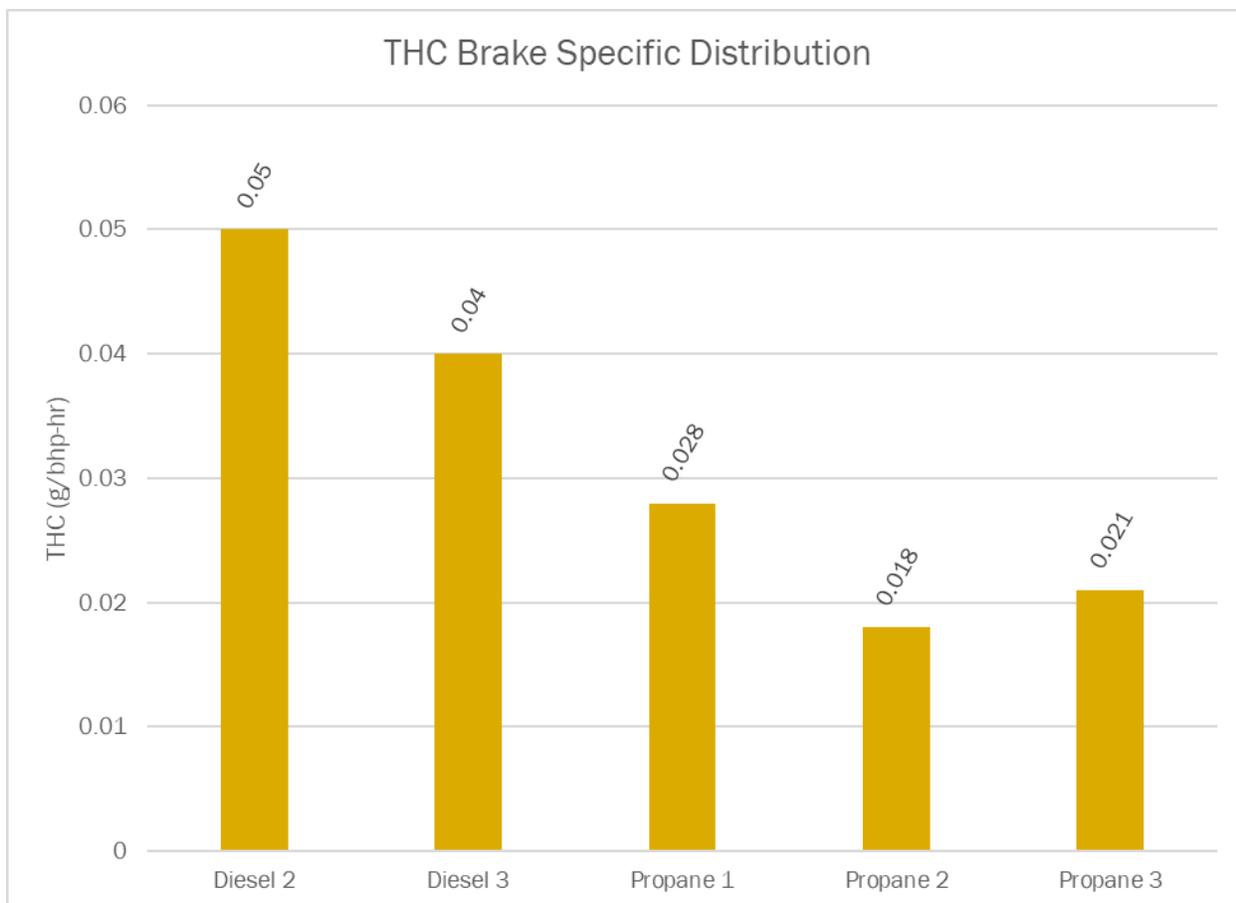


Figure 9.22 Comparison of Brake-Specific THC Emissions for Urban Activity

Carbon Monoxide (CO) Emissions

CO emission results are presented in Figure 9.23 and Figure 9.24. Elevated cold start CO emissions from the diesel-powered vehicle for test sequence “Diesel 1 – Cold Start” are consistent with published results. Similarly, CO emissions for idle activity (see Figure 9.23) are consistent with the control technology and activity of stop-and-go (creep) operation of yard tractors.

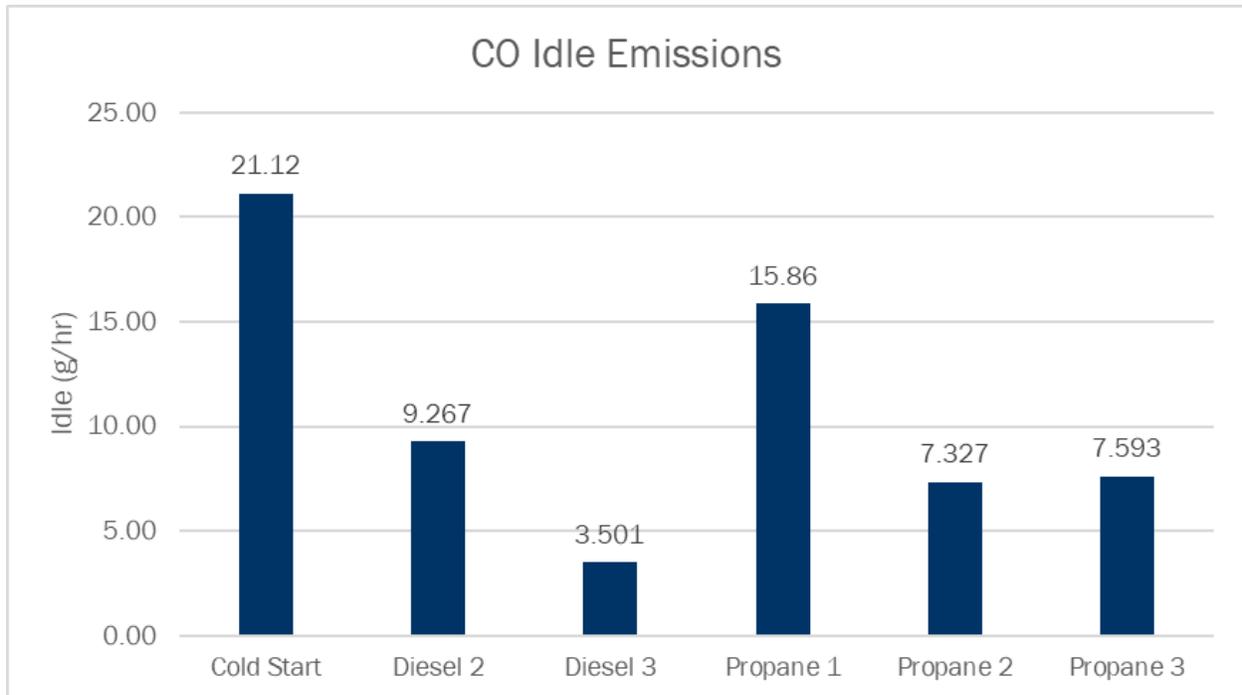


Figure 9.23 Comparison of Time-Specific CO Emissions for Idle Activity

The propane-fueled tractor produced higher brake-specific and distance-specific CO emissions for urban operation than the diesel-fueled tractor, as indicated in Figure 9.23 and Figure 9.24, respectively. This is consistent with the technology and with the challenges associated with thermal management of TWC for creep activity typical of port tractor operation.

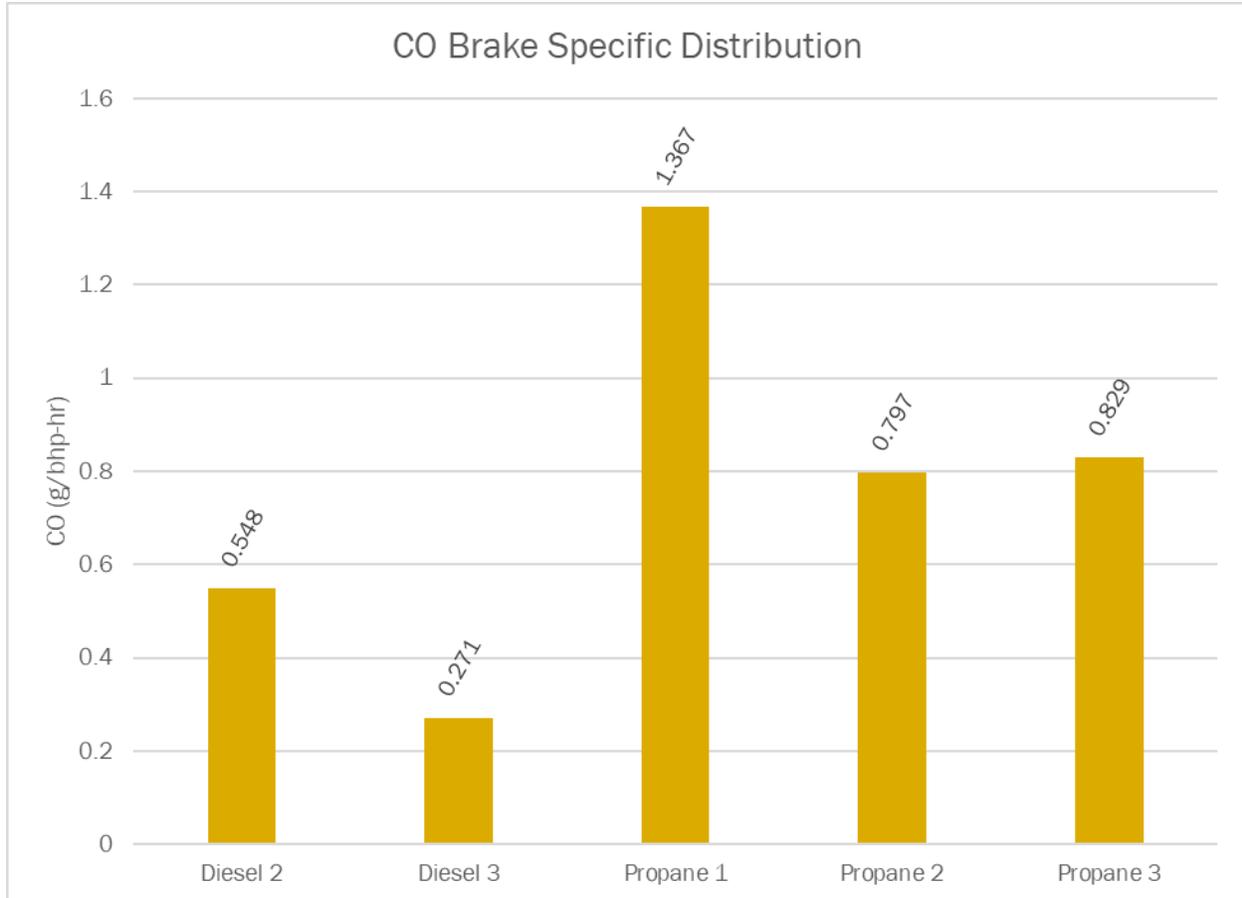


Figure 9.24 Comparison of Brake-Specific CO Emissions for Urban Activity

9.4.2.5 Brake Thermal Efficiency (BTE)

Brake thermal efficiency, averaged across the full test sequence, were calculated using fuel CAN-broadcast work and fuel consumption information and average fuel energy values provided in 40 CFR 1065. As Figure 9.25 indicates, program-averaged BTE for the diesel-fueled tractor was approximately 34.9%, while the propane-fueled vehicle data indicated an average value of nearly 24.5%.

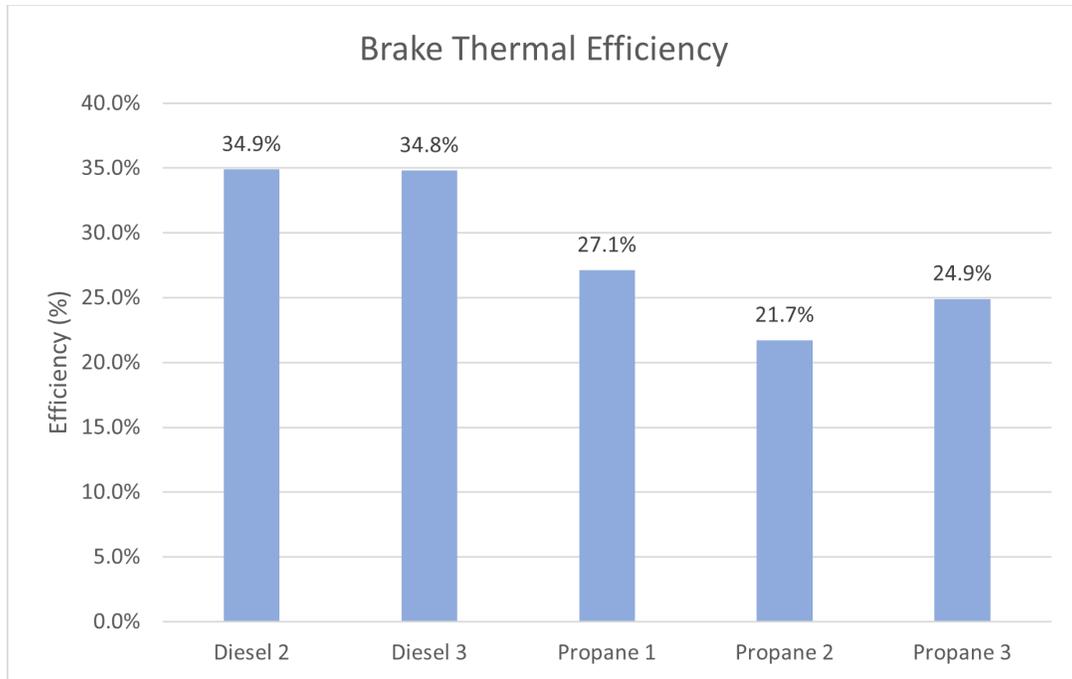


Figure 9.25 Calculated Brake Thermal Efficiency for the Recorded Test Sequences