GENERIC IN-USE TEST PROTOCOL FOR NONROAD EQUIPMENT

Prepared for

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ABSTRACT

Although new technologies have facilitated the development of improved portable emissions monitoring systems (PEMS), widely-accepted procedures for using PEMS to determine in-use nonroad equipment emissions performance are lacking. Variability in duty cycle, ambient conditions, site-specific operations, and other factors make comparisons between isolated test campaigns difficult. New control strategies (such as aftermarket devices, engine operating algorithms, inspection and maintenance programs, etc.) are coming to market, but vendors, regulators, equipment fleet operators, and other stakeholders recognize a pressing need for repeatable and comparable approaches to evaluating their effectiveness. Implementation of this generic protocol and the associated site-specific protocols provide the required consistent approach. It specifies test organization, instruments, and procedures which will yield quantified performance results of known accuracy.

KEY WORDS

PEMS
ISS
in-use
nonroad
on-highway
emissions control strategy
emissions control device
duty cycle
fleet
engine control module
mechanically-controlled engine

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LIST OF ACRONYMS AND ABBREVIATIONS

A-h	Ampere-hour
CAR	corrective action report
CFR	Code of Federal Regulations
CH_3	methyl radical
CH_4	methane
C_3H_8	propane
CLD	chemilumenescence detector
CO	carbon monoxide
CO_2	carbon dioxide
CVS	constant volume sampling
DPF	diesel particulate filter
DQO	data quality objective
ECM	engine control module
EGR	exhaust gas recirculation
FID	flame ionization detector
FS	full scale
g/bhp-h	grams per brake horsepower hour
g/dscm	grams per dry standard cubic meter
g/gal	grams per gallon
g/h	grams per hour
g/run	grams per run
gal/bhp-h	gallons per brake horsepower hour
gal/run	gallons per run
gph	gallons per hour
hp	horsepower
ISS	integrated filter or bag sampling system
LFE	laminar flow element
NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
NIST	National Institute of Standards and Technology
NMHC	non-methane hydrocarbons
NO_X	nitrogen oxides
NTE	not to exceed
NYSERDA	New York State Energy Research and Development Authority
O_2	oxygen
PAM	portable activity monitor
PEMS	portable emissions monitoring system
ppm	parts per million
ppmv	parts per million by volume
QCM	quartz crystal microbalance
RH	relative humidity
RPM	revolutions per minute
TEOM	tapered element oscillating microbalance
THC	total hydrocarbons
TPM	total particulate matter
ULSD	ultra-low sulfur diesel
VDC	volts direct current
σ_{n-1}	sample standard deviation

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SUMMARY

The New York State Energy Research and Development Authority (NYSERDA) sponsored this project to assess the performance of air pollutant emission control strategies which can be applied to existing nonroad equipment fleets.

The internal combustion engines that power nonroad equipment are significant sources of air pollution in the U.S. Such equipment is coming under more stringent emissions regulations as the population and environmental impacts increase. Their in-use emissions and fuel consumption are not generally known, however, because laboratory dynamometer tests of the engines alone have been the basis for regulatory certification. Laboratory dynamometer tests generally employ a limited series of steady-state or transient modes which may not accurately reflect the duty cycles actually seen by a particular piece of equipment in the field [1, 2]. Consequently, the U.S. Environmental Protection Agency has modified the Title 40 Code of Federal Regulations (CFR) 86 on-highway vehicle emissions regulations to incorporate in-use testing [3]. The agency also has promulgated Title 40 CFR 1065 in-use testing regulations for new nonroad equipment and engines [4], which form the basis for the test methods outlined in this protocol.

In-use testing is also valuable for existing fleets because test results can:

- show the relationship between the laboratory certification and actual field performance
- determine the emissions and fuel consumption performance differences between vehicles of different ages and duty cycles
- facilitate the development and quantify the performance of retrofit control devices or emissions control strategies
- assist in emissions inventory development through more representative emission factors

In-use emissions, fuel consumption, and nonroad equipment performance evaluations are now possible because of the advent of portable emissions monitoring systems (PEMS) and portable integrated bag- or filter-sampling systems (ISS). PEMS include constant-volume sampling equipment for gaseous emissions or partial flow proportional dilution sampling systems for gaseous and particulate emissions. Both types of PEMS withdraw a partial flow sample from the exhaust gas stream and provide real-time data. Most portable ISS incorporate a partial flow proportional dilution sampling system which collects diluted bagged samples for gaseous emissions or a gravimetric filter sample for TPM emissions. ISS produce emissions results which are integrated over an entire test run and cannot provide real-time data.

Protocols which drive consistent use of these new techniques are few and treat only isolated aspects of in-use testing. For example, some protocols have not discussed the procedural and analytical differences between PEMS (real-time) and ISS (integrated) test results.

This NYSERDA project addresses the lack of in-use testing consistency through the development of this generic protocol. The protocol provides overall test campaign designs, procedures for developing simple, synthesized, and in-use duty cycles, instrument specifications, step-by-step test procedures, and analytical techniques. The associated site-specific protocols will provide information about individual test sites, nonroad equipment, control strategies, and other details unique to a particular test campaign. Proper implementation of the protocol and associated site-specific protocols will allow the assessment of control strategy performance, in-use emissions, extended interval performance trends, and comparisons between different types of emissions measurement equipment.

1.0 INTRODUCTION

Nonroad equipment emissions under real field conditions may vary considerably from those seen during laboratory testing [1, 2]. Regulators, engine manufacturers, and control strategy developers have expressed an increasing need for in-use emissions testing data which would facilitate new designs, estimate impacts from fleet aging and retrofit options, enhance regulatory compliance activities, or to meet other needs. This protocol is intended to provide a consistent in-use testing approach while nonroad equipment is performing actual work under simple, synthesized, or in-use duty cycles.

Portable emissions monitoring systems represent a significant evolution in testing technology because of their ability to measure emissions on a real-time basis. This allows correlation of emissions performance with instantaneous engine or equipment operating parameters under actual field conditions. In contrast, ISS acquire integrated emissions samples for later analysis while the equipment is working in the field over a complete test run. Both systems may be used in conjunction with simple or synthesized duty cycles, while in-use duty cycles generally require PEMS.

A test campaign should be governed by two documents: this *generic protocol* which describes overall testing concepts, and a *site-specific protocol* which addresses individual test details. The generic protocol provides:

- scope of nonroad equipment, control strategies, fuels, measurement parameters, testing equipment, and test types
- procedures for developing simple, synthesized, and in-use duty cycles for use in the field
- PEMS, ISS, and other instrument specifications
- step-by-step procedures for control strategy performance tests, in-use emissions tests, extended interval performance tests, and measurement method comparison tests
- analytical techniques
- reporting requirements

The generic protocol meets stakeholder requirements for flexibility because it allows selection and implementation of various techniques in response to individual test objectives. For example, one test series may seek to quantify control strategy effects as compared to baseline performance while a second may intend only to measure emissions. Each would implement the appropriate sections of the protocol. Although the two campaigns would require different resources, their results would be comparable because of the generic protocol's unified structure.

The testing concepts discussed here could be extended to other transportation sectors such as marine, locomotive, stationary, or on-highway vehicles with suitable modifications. For example, the in-use duty cycle and test procedures could be used to acquire emissions data which meets EPA “not to exceed” (NTE) testing requirements for on-highway vehicles.

2.0 APPLICABILITY

This protocol is applicable to any diesel-fueled nonroad equipment powered by mechanically-controlled engines or electronically-controlled engines equipped with engine control modules (ECM). Engines may be naturally aspirated, turbocharged, or equipped with exhaust gas recirculation-equipped (EGR). All tested equipment should be representative of the fleet of interest.

Nonroad equipment may include, but is not limited to, mobile vehicles, such as:

- excavators
- rubber-tired loaders
- crawler tractors or dozers

or stationary equipment, such as:

- generators
- compressors
- air-conditioning refrigeration units

and can include construction, agricultural, commercial / industrial, logging, or similar applications.

Certain procedures contained in this protocol may be adaptable for evaluations of other equipment categories such as airport ground support, lawn and garden maintenance, recreational vehicles, marine, locomotive, pleasure craft, or other fuel types such as propane, gasoline / methanol blends, and natural gas. Assessment of this generic protocol's applicability beyond the categories specified above will require additional research.

Horsepower (hp) ranges between approximately 5 and 2000 are reasonable, but practical limitations apply because of PEMS, ISS, or other test equipment features and capacities. For example, exhaust gas volumetric flow rates, fuel consumption, torque, ECM outputs, logged engine parameters, or ambient conditions must be within the PEMS, ISS, or auxiliary sensor capacities.

Site-specific protocols may require special considerations depending on engine size. For example, engines larger than approximately 1500 hp may require custom-engineered exhaust gas volumetric flow rate measurements. Smaller single- or two-cylinder engines may require temporarily-installed plenums to attenuate exhaust gas pulsations.

Allowable fuels are those intended for spark- or compression-ignition engines, including:

- nonroad diesel fuel (approximately 2500 to 3000 parts per million [ppm] sulfur by weight)
- current specification on-highway diesel fuel (capped under EPA regulation at 500 ppm sulfur)
- ultra-low sulfur diesel (capped under EPA regulation at 15 ppm sulfur in October, 2006; ULSD)
- biodiesel blends (typically B5 or B20 with 5 percent and 20 percent biodiesel, respectively)
- gasoline
- hydrogen
- diesel fuel / water emulsions
- diesel fuels which incorporate additives such as fuel-borne catalysts, lubricity, or cetane enhancers

This protocol excludes other fuels because of the limitations of current PEMS technology. Compressed natural gas, liquified natural gas, and propane contain significant amounts of methane. Methane is an important greenhouse gas, but which current PEMS can quantify it only as total hydrocarbons. Fuel with added ethanol or oxygenates, such as gasahol or E-diesel, can produce aldehyde emissions. Test personnel must recalibrate currently-available PEMS to measure such emissions, and this is generally impractical in a field setting.

The nonroad equipment design must allow PEMS or ISS installation, along with the required support equipment such as gas cylinders, exhaust pipe adaptors, and storage battery or generator power supply. The installation should not constrain the nonroad equipment during its normal operation or while performing simple cycles or synthesized duty cycles. This means that the site-specific protocol must specify the appropriate mounting adaptors, brackets, shrouds, or other physical modifications as needed. For example, equipment which undergoes extensive motion during typical operations, such as excavators or loaders, represent significant PEMS or ISS installation challenges.

3.0 SCOPE

This section outlines the scope of the various types of test campaigns (Table 3-1) and summarizes the measurement systems, methods, and test parameters required for each test type (Table 3-2). Any or all test types could be performed during a given test campaign, and the tables should serve as planning tools. For example, a TPM emissions control strategy performance test will require baseline and candidate tests (see Table 3-1). A PEMS TPM accessory, integrated filter samples from an ISS, or a suitable standalone analyzer will be required to determine the TPM emissions (see Table 3-2). Note that while ISS are more readily available than PEMS for measuring TPM emissions at present, the test results are integrated over an entire test run. This generally limits ISS to simple cycles or synthesized duty cycles because in-use duty cycles are uncontrolled. The integrated results would not be repeatable which would prevent meaningful analysis.

The tables include multiple options for some determinations or measurement systems, such as fuel consumption. Test personnel should select the option(s) which are appropriate to the project and specify them in the site-specific protocol.

<table>
<tr><th colspan="3">Table 3-1. Test Types</th></tr>
<tr><th>Type</th><th>Description</th><th>Units</th></tr>
<tr><td>Control strategy emissions and fuel consumption performance</td><td>-- Difference between baseline and candidate emissions and fuel consumption
-- PEMS real-time data for gaseous emissions
-- ISS integrated filter data, PEMS accessory, or other standalone instrumentation for TPM
-- Simple, synthesized, or in-use duty cycles (PEMS)
-- Simple or synthesized duty cycles (ISS)</td><td rowspan="4">lb/run
gal/run
lb/hr
gal/hr
gal/bhp-h[a];
Statistical significance, % change, and confidence interval[b]</td></tr>
<tr><td>In-use evaluations</td><td>-- PEMS real-time emissions and fuel consumption data acquired under in-use duty cycles</td></tr>
<tr><td>Extended interval emissions and fuel consumption performance</td><td>-- Emissions and fuel consumption trends based on initial and final sets of real-time PEMS test runs separated by an extended interval (usually 6 months). Performance trend consists of the difference between the initial and final test series. Simplified qualitative tests are also possible.
-- Simple, synthesized, or in-use duty cycles
-- Initial and final test run duty cycles must be the same type</td></tr>
<tr><td>Emissions method comparisons</td><td>Difference between two emissions measurement systems integrated over the same test run series</td></tr>
<tr><td colspan="3">[a]Brake-specific data (g/bhp-h) data will be available for ECM-equipped engines. Surrogates, such as RPM multiplied by exhaust gas volumetric flow, may be appropriate for baseline / candidate comparisons on mechanically-controlled engines (see §8.2).
[b]Test personnel will conduct at least three test runs for each condition.</td></tr>
</table>

Table 3-2. Measurement Systems and Test Parameters

Parameter		Measurement System	Units
Gaseous Emissions	CO CO_2 NO_X THC	-- PEMS real-time data from simple, synthesized, or in-use duty cycles -- ISS bag sample integrated over entire simple, synthesized, or in-use duty cycle test run and analyzed at portable bench	ppmv g/run g/h g/gal g/bhp-h[a]
Particulate Emissions	TPM	-- PEMS real-time data from TPM accessory such as tapered element oscillating microbalance, quartz crystal microbalance, light scattering devices, laser-induced incandescence, etc.[b] -- ISS particulate filter integrated over test run and analyzed gravimetrically -- Standalone TPM analyzer	g/run g/dscf g/dscm g/gal g/bhp-h[a]
Unregulated Emissions	Speciated TPM (Examples)	-- ISS samples analyzed for PAH by SW-846, Method 8270c, methylene chloride and acetone extract [5] -- ISS samples analyzed for organic carbon / elemental carbon by NIOSH Method 5040 [6] -- ISS samples partitioned by cascade impactor, cyclone, etc. for $PM_{2.5}$ or other size fractions and analyzed gravimetrically -- PEMS real-time data from TPM accessories for size distribution, number[b,c] -- ISS samples analyzed for speciated metallic particulate from fuel additives -- vanadium emissions from vanadium / titanium catalysts	g/run g/dscf g/dscm g/gal g/bhp-h[a]
	Gaseous emissions (Examples)	PEMS and ISS accessories or modifications for quantification of: -- nitrogen dioxide emissions such as those from indoor vehicles -- ammonia (CH_3) slip or cyanuric acid (HNCO) emissions from urea selective catalytic NO_X reduction systems	ppmv g/run g/h g/gal g/bhp-h[a]
Fuel Consumption	Gravimetric	-- Weight change quantification in a removable day tank. Data are integrated over an entire test run.	lb/run gal/run lb/hr gal/hr gal/bhp-h[a]
	Differential mass flow	-- Real-time differential mass flow measurements taken from two coriolis-type flow meters. Fuel consumption is the difference between engine supply and return mass flow.	
	Volumetric	-- Real-time positive displacement, temperature-compensated volumetric flow meter which measures makeup flow into the engine fuel supply and return loop.	
	Carbon balance	-- Real-time exhaust gas carbon concentration correlated with exhaust gas (or inlet air) flow rate and fuel carbon content. See Title 40 CFR §1065.15 (c) (3) (ii), Title 40 CFR §86.1342 (g) for more information.	
Control Strategy First Cost		-- Site-specific data collection on the following: • Capital equipment • Support equipment • Inventoried spares • Inventoried reagents and supplies • Purchased tooling, brackets, options, nonroad equipment modifications	$

Table 3-2. Measurement Systems and Test Parameters		
Parameter	**Measurement System**	**Units**
	• In-house fabricated tooling, brackets, options, nonroad equipment modifications • Installation and implementation labor • Nonroad equipment downtime for control strategy installation and implementation • Training expenses for technicians, operators	
Control Strategy Operating Cost	-- Site-specific data collection on the following: • Routine maintenance labor, parts • Major maintenance labor, parts • Daily reagents, supplies, fuel or electric surcharges, etc. • Daily downtime for refilling reagents, regeneration, etc. • Overhaul labor, parts, core replacement, disposal	$
Control Strategy Operating Impacts[d]	-- Site-specific data collection on the following: • Nonroad equipment performance changes as horsepower, brake-specific fuel consumption and net fuel consumption differences between baseline and candidate • Scheduling or dispatch impacts as the time required for routine maintenance, major maintenance, training, control strategy regeneration, reagent refreshment, modified fueling practices, oil change intervals, potential problems caused by cold or hot weather, etc.	$ or hours
[a]Brake-specific data (g/bhp-h) data will be available for ECM-equipped engines. Surrogates, such as RPM multiplied by exhaust gas volumetric flow, may be appropriate for baseline / candidate comparisons on mechanically-controlled engines (see §8.2). [b]Real-time TPM methods are under development. Comparability with laboratory results is problematic at this writing [7] but test personnel may evaluate the available methods while developing site-specific protocols. [c]Real-time number methods may be questionable because of widely varying dilution [8], nonroad vehicle vibration, and other effects. [d]Data are likely to consist of management and dispatcher business data, anecdotal discussions, etc.		

Assessments of control strategy impacts on engine life or durability is beyond the scope of this protocol. Such assessments are possible, however, and should be developed in close collaboration with the control strategy and engine manufacturer. For example, a durability assessment could include dimensional or surface inspection of critical engine components on a fleet of vehicles after extended operating intervals. Comparison of the inspection results with those expected from an untreated engine fleet, based on the manufacturer's specifications and experience, could yield an assessment of durability impacts.

3.1. TEST CAMPAIGN OUTLINE

A given test campaign may include any or all of the determinations listed in §3.1. Test personnel should complete tasks in a logical order to yield consistent results. Figure 3-1 shows a generalized work flow diagram which outlines a control strategy performance evaluation. All flow diagram tasks appear in this generic protocol; the site-specific protocols will treat certain items (such as individual duty cycle specifications, the design for PEMS mounting brackets, etc.) in more detail.

The control strategy evaluation outlined in the figure requires the following:

- select the nonroad equipment and control strategy in conjunction with its feasibility and the availability of a suitable host site (see §4.0)
- develop the duty cycle for the site-specific protocol (see §5.0)
- prepare for testing, including site coordination, test equipment installation, and operator duty cycle training (see §6.1), specify, select, and install sampling equipment
- perform baseline tests (see §6.2)
- implement the control strategy; break in, or degreen if necessary
- perform candidate tests
- analyze and report the data (see §7.0 and §8.0)

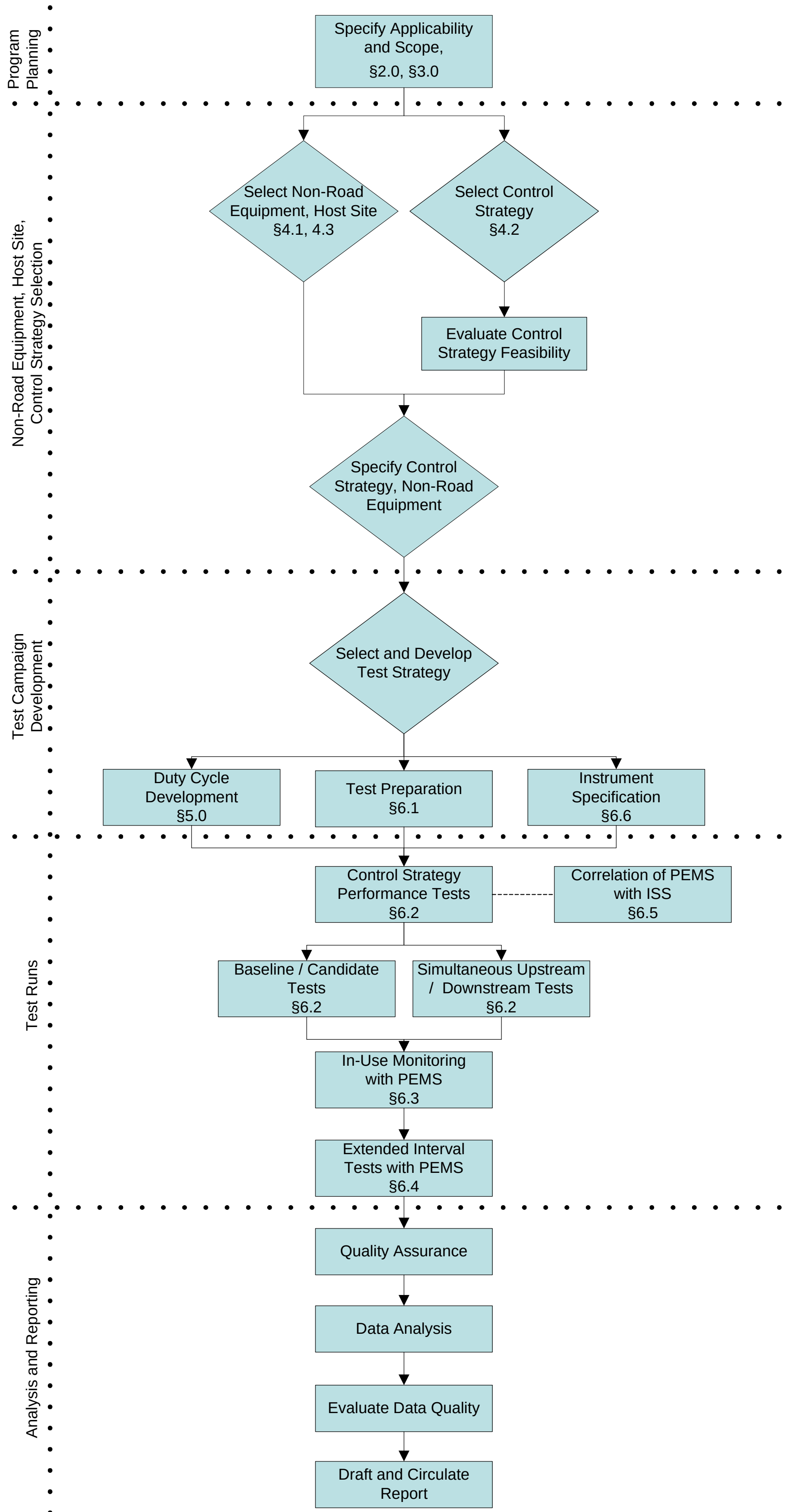

Figure 3-1. Test Campaign Flow Diagram

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4.0 NONROAD EQUIPMENT, CONTROL STRATEGY, AND HOST SITE SELECTION

In-use tests require significant stakeholder participation. These include nonroad equipment operators or fleets, field testing facilities, control technology venders, installers, and others. Other required resources include the individual nonroad equipment or control strategies to test. Appropriate selection of these major stakeholders and test components will profoundly affect the success of any test campaign. This section discusses guidelines for selecting nonroad equipment, control strategies, and host sites.

The steps in the nonroad equipment, control strategy, and host site selection process interact with each other. Every test campaign should select the nonroad equipment, the control strategy (if applicable), and host site early in the site-specific protocol development. For example, the selected host site must be able and willing to participate with the appropriate operators, facilities, and other resources. Each site-specific protocol should explicitly list the resources required. The host site should review it and provide comments prior to testing. Appendix B provides sample field data forms for nonroad equipment, host site, and control strategy selection.

4.1. NONROAD EQUIPMENT SELECTION

The nonroad equipment selected for testing must be "representative" of the population of interest to each test campaign. The site-specific protocol should discuss the features and criteria which determine if the selected equipment is representative. Equipment age, fleet purchasing practice, time since the last major overhaul, state of repair, or other considerations may all affect the population of interest and the resulting selection. The site-specific protocol should therefore provide detailed data about the selected piece such as manufacturer, model, year, engine type, displacement, rated power (or engine / ECM calibration), drive train (torque converter, hydrostatic, manual transmission), accessories, implements, etc.

Some example selection criteria are (depending on the test campaign objectives):

- a qualified technician should certify that the selected machine and any modifications or repairs to the engine, exhaust, drive train, hydraulic, electrical, or other systems conform to the manufacturer's specifications and are in good working order
- outlier machines, either under- or over-performing or with significant aftermarket modifications to the engine, exhaust, drivetrain, hydraulic, electrical, or other systems (unless the modifications are part of an acceptable retrofit design) should not be selected as representative of a fleet of vehicles

- all attachments, implements, or accessory equipment must meet the manufacturer's specifications except for minor repairs, adjustments, or modifications which do not affect performance unless the evaluation of such modifications is a test campaign objective
- site representatives should install a new air filter immediately prior to testing
- the ECM, if equipped, must have no trouble codes flagged which reflect improper engine operations, emissions, or fuel consumption
- mechanically-controlled engine configurations should allow for the installation of the proper sensors and equipment (such as engine speed, exhaust gas flow, and exhaust gas temperature sensors)
- test personnel should review and report the machine's dispatch and maintenance records for routine and unscheduled work
- torque converters should meet manufacturer's specifications during a full torque stall engine revolutions per minute (RPM) check, if applicable

Interviews with site personnel, equipment operators, or pretest screening of groups of nonroad equipment will contribute to the selection of representative machines.

4.2. CONTROL STRATEGY SELECTION

This section discusses control strategy selection criteria. Selected control strategies should typically be those with some degree of market penetration and maturity, although prototypes and development models may be tested under special circumstances.

Control strategy implementation must be feasible for the selected piece of nonroad equipment. Test personnel should plan to coordinate feasibility determinations early in the site-specific protocol development in conjunction with the control strategy provider. Installation of some control strategies will not be feasible on some types of equipment or at certain host sites due to exhaust temperature profiles, flow rates, physical configuration, or other factors. Some feasibility analysis considerations include:

- specification of limitations on the overall changes in exhaust backpressure, exhaust temperature, and other engine parameters to prevent negative impacts on equipment
- acquisition of real-time exhaust temperature profiles during normal in-use operations to ensure that the selected control strategy will operate properly
- review of physical, ambient and exhaust temperature, fuel specification, or other requirements for control strategy installation and operation
- determination of installation or implementation requirements such as brackets, electrical services, etc.

- review of site-specific ambient temperature or other environmental constraints (such as fugitive dust) and their potential impacts on control strategy performance
- development of a break-in or degreening procedure
- documentation of the control strategy's potential ancillary effects, such as power loss, operator visibility impairment, etc.
- documentation of proper engine, nonroad equipment, and control strategy operations after installation

Once test personnel select the nonroad equipment and associated control strategy, the site-specific protocol should summarize:

- selected control strategy manufacturer, model, and operating principles
- step-by-step implementation, installation, operating, and maintenance instructions
- recommended duty cycles, idling period restrictions, or other limitations
- refueling, recharging, regeneration, or other specialized procedures
- limitations on engine crankcase pressure, exhaust back pressure, and exhaust temperatures
- general requirements for break-in or degreening, often specified as 25 to 125 hours of normal operations [18], and step-by-step procedures where necessary
- anticipated performance impacts on the selected nonroad equipment

All control strategy evaluations should include validation by a qualified technician or manufacturer's representative that it is operating correctly prior to testing.

4.3. HOST SITE SELECTION

Host site selection is crucial to the success of any test campaign executed under this protocol. This subsection discusses host site resource requirements and selection criteria. Resources may be provided by different parties as specified in the site specific protocol.

Test personnel are responsible for ensuring that all parties are aware of their roles, responsibilities, and resource requirements as part of the site-specific protocol development.

4.3.1. Nonroad Equipment Fleet, Fuel, and Support Services

The host site should plan to make the selected nonroad equipment available for testing, either from their fleet or from rental or leasing agents. The host site (or equipment lessor) should have a written equipment maintenance program and evidence showing compliance with that plan. Test personnel should work with the host site to ensure that facilities, personnel, and resources are provided for equipment maintenance and control strategy implementation. For example, data collection for control strategy feasibility studies should occur during normal in-use service.

Performance testing may require that the equipment be withdrawn from normal in-use service for:

- installation and removal measurement instruments, sensors, and dataloggers
- installation and removal of control strategy parts and accessories
- duty cycle development test runs and operator training
- baseline and candidate testing for control strategy evaluations under simple and synthesized duty cycles (see §6.2)
- data downloads and measurement instrument maintenance during in-use evaluations (see §6.3)
- initial and final extended interval tests with PEMS (see §6.4)
- emissions measurement equipment comparisons (see §6.5)

Fuel should meet the minimum specifications listed in Title 40 CFR §86.113 unless the site-specific protocol requires other formulations such as bio-diesel or water / fuel emulsions. Site-specific protocols may require ULSD or other fuels in response to individual test campaign requirements or local regulations. This protocol recommends that the fuel holding tank be emptied and cleaned prior to filling with the test fuel lot to ensure consistent fuel properties. The fuel supplier should plan to provide a certified fuel analysis or the site-specific protocol may require an independent analysis. All fuel for baseline / candidate control strategy evaluations, if applicable, should come from a common lot.

4.3.2. Host Site Operations and Other Resource Requirements

Testing will involve three types of operations, depending on the objectives:

- simple cycles
- synthesized duty cycles
- in-use duty cycles (during normal service)

Sufficient normal in-use operating hours should be available for control strategy feasibility data collection, break-in or degreening, simple or synthesized duty cycle development, and test runs as specified in the site-specific protocol.

It is likely that simple or synthesized duty cycle tests will require a designated area, pit, working face, or pile which will allow close control of nonroad equipment performance, material properties, or other considerations. For example, a rubber-tired loader test may specify that a given gravel or sand pile be manipulated as part of a duty cycle. Test personnel will collaborate with host site representatives to develop the unique details for each test campaign which will be presented in the site-specific protocols.

The host site should have a sufficient number of duty cycles available for a given test campaign. See §5.0 for a discussion of how long a typical duty cycle may last.

A single nonroad equipment operator should be made available for duty cycle training and all simple or synthesized duty cycle test runs. Ideally, the same operator should plan to conduct all baseline and candidate control strategy test runs.

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5.0 DUTY CYCLES

This generic protocol is intended for use with "simple cycles," "synthesized duty cycles," or "in-use duty cycles" during normal service. Duty cycles are detailed descriptions of the nonroad equipment maneuvers during testing.

Nonroad equipment maneuvers may be described as individual "events" such as backing, travel forward, bucket extension, digging, etc. Composite events consist of a combination of individual events over varying time periods. A rubber-tired loader, for example, may combine simple forward travel, reverse travel, bucket extension, tilting, and lifting events over a repeatable time period into a single "load bucket" composite event. *A simple duty cycle is an arbitrary arrangement of simple or composite events of specified duration performed in sequence under controlled conditions (such as at an artificial gravel pile, designated working face, etc.).*

A complete simple cycle could include a series of composite events or short simple cycles. The simple cycle definition for a loader could be described as "load truck", and include several "load bucket" events. This would be appropriate when the duration for the individual events is too short for adequate testing or sampling.

A synthesized duty cycle is a specified series of events, performed under controlled conditions, which are based on in-use equipment maneuvers as logged at the host site. The synthesized duty cycle is intended to reproduce the in-use events found at the host site but in a quantifiable and repeatable manner over a controlled time frame.

An in-use duty cycle consists of the nonroad equipment's normal duties performed at its usual work location according to its normal schedule and process capacity. In-use duty cycles are uncontrolled except to allow for routine emissions testing equipment calibrations, QA / QC checks, or data downloads.

This section:

- provides procedures for researching and logging in-use duty cycles at the host site
- presents simple, synthesized, and in-use duty cycle development and validation principles
- describes cycle criteria development
- specifies duty cycle documentation

Duty cycle development, cycle criteria definition, duty cycle validation, in-use evaluations, and test runs will require monitoring and logging the following engine parameters at 1 Hz [see Table 1 of §1065.915]:

- engine speed, RPM
- intake air or exhaust gas flow rate or surrogate (optional if engine torque, bhp, or fuel consumption are available)
- exhaust temperature at the turbocharger or exhaust manifold outlet (T_{turb}), degrees Fahrenheit (^oF) or degrees Celsius (^oC)
- exhaust temperature at the muffler or silencer outlet (T_{out}), ^oF or ^oC (optional)
- measured engine torque, percent maximum torque (derived from ECM), or bhp (derived from ECM), if available
- fuel consumption by direct measurement or carbon balance

A suitable dedicated datalogger or ruggedized laptop computer with the required signal conditioners, software, and interface can directly acquire and record the necessary data from most ECM-equipped engines. Mechanically-controlled engines will need temporarily-installed sensors. All sensors should meet the specifications listed in §6.6.

Once duty cycles are developed based on host site operations, test personnel will define cycle criteria which, if met during testing, will help minimize run-to-run variability.

The following subsections discuss host site operations evaluation, duty cycle development procedures, cycle criteria, and documentation.

5.1. HOST SITE OPERATIONS EVALUATION

Host site operations will drive the choice between simple, synthesized, or in-use duty cycles and the subsequent duty cycle development process. Some of the duty cycle issues that host site managers, dispatchers, operators, and test personnel should discuss are:

- reason for the selected nonroad equipment's purchase and its primary mission or function
- primary, secondary, and tertiary duties and average number of hours per day for each
- materials handled or processes implemented
- special considerations, such as:
    - material condition (sizing, moisture content)
    - sources of variability and how to minimize them during testing

- existing in-use maneuvers and events which could be specified under a simple or synthesized duty cycle

Some ECM-equipped machines may accommodate the temporary installation of a portable activity monitor (PAM). The PAM could be used to develop simple cycles or synthesized duty cycles.

Once consensus is reached regarding the selected equipment's most-used functions and maneuvers, test personnel will, with site assistance, define typical events, including idling and shutdowns. Event definitions may consist of a single action (simple event) or multiple actions in series (composite event). For example, short and long duration backing maneuvers will likely require separate simple event definitions. Similarly, "raise and dump load" could be a composite event description for a rubber-tired loader. These events, when pieced together and performed in sequence, should fully describe any observed duty cycle. They will also serve as the components for simple and synthesized duty cycles. Appendix B7 provides a log form.

5.2. SIMPLE CYCLE DEVELOPMENT

A simple cycle consists of an arbitrary series of simple or composite events performed in sequence. Duty cycle developers should use the events defined in §5.1 to develop the simple cycle in consultation with host site personnel. The simple cycle should:

- be representative of a typical work activity, such as several load and dump repetitions for a loader
- last between 1/4 and 1 hour to allow a reasonable number of test runs during a typical day
- be repeatable as determined by the appropriate cycle criteria

Test personnel should dispatch the nonroad equipment to perform the simple cycle while logging the engine parameters listed in §5.0. The operator should perform several simple cycles as a warmup exercise. Then, the simple cycle should be performed until at least three repetitions of each event have been logged. This will ensure that the proposed duty cycle is actually feasible. Also, analysts will use each event's maximum, minimum, mean, and sample standard deviation (σ_{n-1}) for each parameter to develop cycle criteria described in §5.4.

5.3. SYNTHESIZED DUTY CYCLE DEVELOPMENT

Development efforts for synthesized duty cycles have ranged from simple observation, video-taping, and interviewing techniques [9, 10, 11] to complex statistical analysis of data logged during normal revenue service [12, 13, 14]. The techniques strive to digest real-world operations into representative duty cycles for use either in the field or the laboratory. This protocol specifies methods that are reasonably simple for field applications and help ensure that the synthesized duty cycles:

- represent actual operations at the host site or typical nonroad equipment usage
- are repeatable, with as little variation from run to run as is possible, as documented by appropriate cycle criteria

Test personnel will implement the following procedure to develop the synthetic duty cycles for use under this protocol. Appendix B provides field data forms while Figure 5-1 provides a conceptual schematic.

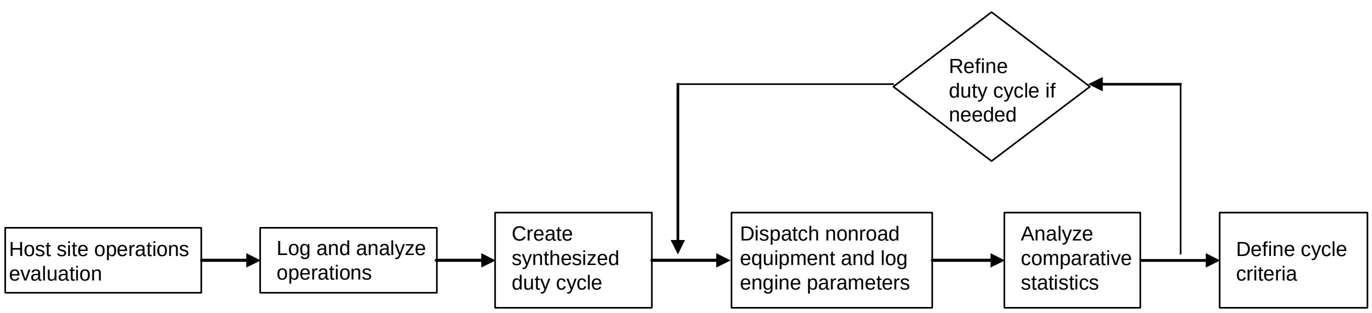

Figure 5-1. Synthesized Duty Cycle Development Path

5.3.1. <u>In-Use Operations Logging</u>

Test personnel will log the nonroad equipment engine parameters listed in §5.0 during at least three normal in-use operations periods. Operations logging period duration may vary, but should generally be longer than one hour in order to fully characterize the equipment functions.

Test personnel will observe and document normal operations events or record the test vehicle during at least one full normal operations period with a video camera. These observations should be synchronized with the nonroad equipment datalogger timestamp for later analysis.

5.3.2. Operations Analysis

Analysts will first compare the visual observations with the event list developed prior to the operations logging (see §5.1), confirm the list definitions, or revise them as needed. The analysis will then proceed as follows (see Appendix B for the appropriate log forms):

1. Identify each event and its type as it occurs in sequence.
2. Determine the elapsed time for each event "i" as: $t_{elapsed,i} = t_{end,i} - t_{start,i}$
3. Record RPM, exhaust gas flow, T_{turb}, T_{out}, percent power (ECM-equipped engines), torque (ECM-equipped engines), or any other logged parameter for each event as maximum, minimum, mean, and σ_{n-1}.
4. Calculate the descriptive statistics for each logged operations period:
   - frequency as the number of times event "i" occurs
   - number proportion as the frequency for event "i" divided by the total number of events
   - mean and σ_{n-1} for $t_{elapsed,i}$ for those events which occur more than three times each
   - time proportion as the sum of $t_{elapsed,i}$ for each event divided by the duration of the operations period

5.3.3. Design Synthesized Duty Cycle

Duty cycle developers will develop a synthesized duty cycle consisting of a series of events associated with specified elapsed times for each event. Duty cycle developers should use the analysis developed in §5.3.2 as source material. The synthesized duty cycle should represent all the logged and analyzed events, but over a shorter time frame. It should include the most important events logged in similar frequency and elapsed time proportions.

Duty cycle developers may, however, wish to select certain types of events, such as the highest-emitting or most frequent, for some test campaigns, such as control strategy developmental work. The site-specific protocol must clearly explain the rationale for such special duty cycles.

Most synthesized duty cycles should last from one half to one hour (similar to simple cycles). This will facilitate the efficient performance of numerous test runs and aid the statistical analysis. Longer duty cycles may be necessary, however, to fairly represent host site operations or to collect sufficient TPM loading on ISS sample filters.

Duty cycle developers should consult with host site personnel to establish:

- feasible duty cycle development and test locations
- availability of suitable materials and methods to control their properties
- a reasonable event sequence
- required support activities, specialized facilities and scheduling

For example, rubber-tired loader duty cycles may require establishment of a working face or pile from which to operate. If the duty cycle involves frequent lifting and dumping with the bucket high, as with truck loading, a pair of support trucks and a stacker may be required to receive the material and place it back on the pile. Also, simple hand compaction tests, ambient condition monitoring, moisture controls, or mixing practices may be necessary to ensure that sand or aggregate pile properties do not vary excessively. Site-specific protocols should discuss the appropriate procedures.

5.3.4. Validate Synthesized Duty Cycle

Once developed, test personnel will dispatch the nonroad equipment to perform the synthesized duty cycle while logging the parameters described in §5.0. Analysts should compare the resulting synthesized duty cycle data with that from the three operations periods logged according to §5.3.1 and will refine the duty cycle if necessary. The comparison tools are:

Descriptive Statistics
The mean and σ_{n-1} for elapsed time, RPM, intake air flow, exhaust gas flow, T_{turb}, T_{out}, or other appropriate logged parameters for each event should be within ± 5.0 percent of the mean σ_{n-1} seen during the three normal operations logging periods for that event.

Wilcoxon Rank-Sum Test
The Wilcoxon Rank-Sum test [15] provides a non-parametric statistical assessment of whether the data logged during normal operations and that logged during the synthesized duty cycle come from the same population. This reasonably simple test indicates whether, for example, the exhaust gas flow rate observed during a synthesized duty cycle run truly represents that observed during normal operations. Appendix C provides the procedures, and analysts should apply the test to each of the logged parameters.

5.4. CYCLE CRITERIA

Test campaigns which use simple or synthesized duty cycles must incorporate methods which show that each test run accurately reproduced the specified duty cycle. This will reduce run-to-run variability and minimize confidence intervals, such as during baseline / candidate control device evaluations. This protocol therefore specifies the development of cycle criteria which test personnel will apply to each event after each test run. If all test run events meet their respective cycle criteria, the run may be deemed valid.

General cycle criteria apply to all test campaigns, locations, and nonroad equipment types. Site-specific cycle criteria use data logged during the duty cycle development process as a basis.

5.4.1. General Cycle Criteria

General duty cycle criteria are as follows:

- §86.1330 (e) suggests ambient air pressure should not vary more than 1 "Hg for all test runs. Site-specific protocols may require tighter limits, especially when control strategy or fuel consumption effects are expected to be small. This is because a 1" Hg air pressure change can cause an approximately 0.3 % change in engine efficiency [19].
- test run ambient air temperatures must be within ± 10 ^{o}F of the mean for all test runs if the mean is < 80 ^{o}F, or within ± 5 ^{o}F if the mean is ≥ 80 ^{o}F
- elapsed time for each event must be within ± 5.0 % of the mean observed during simple cycle development (see §5.2) or that specified in the synthesized duty cycle (see §5.3). Test personnel should strive for tighter elapsed time tolerances, if possible.
- mean exhaust temperature over the test run must be within ± 5.0 % of the mean observed during simple cycle development (see §5.2) or that specified in the synthesized duty cycle (see §5.3). Exhaust temperature criteria must be set for each test vehicle model, as different vehicles will have different exhaust temperature characteristics.

Test personnel should schedule control strategy evaluations, which involve baseline / candidate test runs, during seasons that can reasonably be expected to fulfill these criteria. This will minimize the impact of ambient condition changes. If, for example, a control strategy requires a 3-month break-in period, late spring and early fall may be the best times to schedule testing. Site-specific protocols should address these issues.

5.4.2. Site-Specific Cycle Criteria

Site-specific cycle criteria consist of definitions and numerical targets for each event as observed during testing.

A valid test run will meet the elapsed time cycle criteria and each of the site-specific cycle criteria. Appendix B9 provides a log form. The elapsed time cycle criteria is that each event observed during testing should be within ± 5 percent of the mean elapsed time for that event recorded during duty cycle development. Time cycle criteria will be largely influenced by the driver of the test vehicle and the test vehicle itself. Time cycle criteria should therefore be set for each driver / test vehicle combination during the test campaign.

Site-specific cycle criteria definitions may consist of individual parameters or combinations. Definitions will vary depending on the test campaign and the nonroad equipment. For example, RPM multiplied by fuel consumption (obtained from direct measurements or ECM data) produces a signal that is reasonably proportional to torque. This could serve as a cycle criteria definition. If fuel consumption is not available, RPM multiplied by T_{out} or RPM multiplied by an exhaust gas surrogate ($\sqrt{\Delta P}$) could serve as cycle criteria.

Sections 5.2 and 5.3.2 specified logging of each parameter over at least three repetitions of each event for both simple and synthesized duty cycles. The cycle criteria target value for each event observed during testing should be:

$$\left(X_{development,i} - 1.7\left(\sigma_{n-1,development,i}\right)\right) \leq X_{run,i} \leq \left(X_{development,i} + 1.7\left(\sigma_{n-1,development,i}\right)\right) \qquad \text{Eqn. 5-1}$$

where:

$X_{development,i}$ = cycle criteria mean value for event i observed during duty cycle development

$\sigma_{n-1,development,i}$ = cycle criteria σ_{n-1} for event i observed during duty cycle development

$X_{run,i}$ = cycle criteria mean value for event i observed during the test run

This σ_{n-1} range implies that the mean cycle criteria value for each event, as observed during testing, must be within approximately ± 10 percent of the mean value observed during duty cycle development.

5.4.3. Documentation

The site-specific protocol duty cycle documentation will include:

- working face, pile, or other detailed test location description
- material properties or process loading monitoring and control procedures

- event descriptions and nonroad equipment settings (such as gear selection, throttle position, etc.)
- event sequence, including elapsed times
- general procedures and instructions, such as:
    - strive to perform each event as consistently as possible
    - do not attempt to "catch up" or "slow down" to meet a particular elapsed timestamp

Appendix B provides a sample documentation form.

5.5. IN-USE DUTY CYCLES

In-use duty cycles should incorporate the normal revenue service expected of the nonroad equipment at the host site. Test personnel should first evaluate the host site operations as described in §5.1. Participants will then develop a consensus description of the in-use duty cycle. The description should accurately reflect normal in-use service.

5.5.1. <u>Nonroad Equipment Dispatching Procedures</u>

Although tests which incorporate in-use duty cycles should be conducted during regular day-to-day operations, some modifications may be necessary to accommodate testing. All in-use evaluations, unless the site-specific protocol states otherwise, should:

- have similar overall time durations, exclusive of zero / span checks and battery changes (at least six hours is recommended)
- incorporate battery changes and PEMS warmup procedures if necessary
- allow for an initial, final, and interim PEMS analyzer zero and span checks during the evaluation period

The nonroad equipment under test may be conditioned either of two ways prior to testing:

- "cold start"
    - shut down the equipment and let the engine lubricant, coolant, and control strategy components cool to between 20 ^{o}C and 30 ^{o}C [§1065.530 (a) (1) (i)]. Do not start the engine or move the equipment under power until the test run commences.
- "hot start"
    - dispatch the equipment for a minimum warmup period of in-use service, then shut it down for a 20-minute "soak" period [§1065.530 (a) (1) (ii)]

Test personnel should plan how the PEMS operator will rendezvous with the equipment to conduct zero and span checks and data downloads. Battery capacity and PEMS power requirements will also require consideration. Dispatchers, the equipment operator, and test personnel should develop the appropriate procedures for inclusion in the site-specific protocol.

6.0 TEST PROCEDURES

Projects may incorporate, but are not limited to, the following types of performance tests:

- control strategy performance tests (with PEMS or ISS)
- in-use duty cycle emissions monitoring with PEMS (or ISS as noted in Table 6-1)
- extended interval emissions tests with PEMS
- emissions measurement method comparisons (between PEMS, ISS, or other systems)

Control strategy performance tests are also intended to collect nonroad equipment operational performance, performance impacts, control strategy cost, and maintenance data.

This section discusses preparation and step-by-step procedures for each type of test. The concluding subsection provides the required instrument and analyzer specifications. A test campaign may require consideration of any or all of the concepts. Table 6-1 shows how each major test parameter (see Section 3.0) applies to the performance test types.

Table 6-1. Test Phase Summary

Parameter		*Test Type*			
		Preparation	Control Strategy Performance Tests	In-Use Evaluations	Extended Interval Tests
Duty Cycle Type	Simple or Synthesized		✓		✓
	In-Use			✓	✓
Measurement Instrument	PEMS		✓	✓	✓
	ISS		✓	(✓[a])	
Gaseous Emissions	CO		✓	✓	✓
	CO_2		✓	✓	✓
	NO_X		✓	✓	✓
	THC		✓	✓	✓
Particulate Emissions	TPM		✓	◆[b]	◆
	Speciated TPM		◆		◆
Fuel Consumption	Carbon balance		✓	✓	✓
Control strategy emissions performance			✓	◆	◆
Control Strategy Capital Cost		✓			
Control Strategy Operating & Maintenance Costs			✓		◆[c]
Control Strategy Operating and Maintenance Impacts			✓		◆[c]
Long term emissions and fuel consumption performance			◆[d]		✓

Table 6-1. Test Phase Summary	
	Test Type
✓ = Standard Test ◆ = Optional Test	
[a]Two ISS operating simultaneously upstream and downstream of a control strategy may be used during in-use evaluations [b]In-use evaluations may include real-time PM emission monitoring, depending upon available instrumentation. [c]Test personnel will acquire operational and maintenance cost data over the entire period between initial and final extended interval testing for control strategy extended interval tests. [d]An extended interval test consists of an initial test run series followed by a final test run series after an extended interval (usually 6 months). The candidate test runs for a control strategy performance test could serve as the initial test runs for an extended interval test. Comparison with the final test runs would allow an assessment of control strategy performance changes over the extended interval.	

All test campaigns require development of a site-specific protocol. Site-specific protocols will note considerations which are unique to a particular campaign, control strategy feasibility findings, duty cycle descriptions, site coordination issues, personnel, lines of responsibility, and other essential items.

All test campaigns should nominate a field team leader. This individual should be responsible for:

- initial and ongoing site relations
- coordinating daily activities
- declaring the start and end for each test run
- reviewing analyses and quality assurance checks during testing
- scheduling additional test runs as needed

The field team leader should maintain a signed daily test log which will supplement field log forms and electronically-gathered data.

All Appendix B log forms should be signed and dated before submittal to the field team leader. Electronic data should be copied at the end of each test run and stored in different locations, with at least one copy to be retained by the field team leader.

Test personnel should archive all data for at least two years or in accordance with their organization's standard operating procedures.

6.1. PREPARATION

This section discusses preparation for a control strategy performance test. This type of test is the most complicated because they require feasibility evaluations, integration with the selected nonroad equipment, baseline verses candidate test runs, cost collection, and other activities. They also require installation of ISS or PEMS onto the nonroad equipment and they may require duty cycle development. In general, test personnel should plan to:

- closely coordinate with the host site
- choose the appropriate nonroad equipment and control strategy for the test
- develop PEMS (and ISS, if necessary) handling, logistical, and operating procedures as needed
- develop and document simple, synthesized, or in-use duty cycles with the appropriate datalogger, ECM data, and auxiliary sensors
- install, setup, synchronize, calibrate, and operate the PEMS (and ISS) for baseline tests
- integrate the control strategy onto the nonroad equipment
- install, setup, synchronize, calibrate, and operate the PEMS (and ISS) for candidate tests

Test personnel should first perform the nonroad equipment, control strategy, and site selection processes discussed in §4.0. Prior to testing, maintenance personnel should ensure that the selected nonroad equipment is operating properly. The equipment configuration should be as consistent as is possible for all test runs, especially for baseline / candidate control strategy evaluations. Record the inlet air restriction, exhaust gas restriction, and the control setting (on, off, or automatic) for the major parasitic loads (lights, air-conditioning, heater, fan clutch) in Appendix B15. The selected nonroad equipment may have additional parasitic loads, such as a continuously-operating hydraulic pump / motor combination, which should be set to operate consistently during all test runs.

Test personnel should then develop the appropriate duty cycles (see §5.0) and acquire test instruments, sensors, and equipment (see §6.6).

Test participants should perform as many control strategy implementation and cost collection (see §3.3) steps as possible prior to baseline testing. They should not, however, install equipment that may impact the nonroad equipment's baseline performance until baseline tests are complete.

6.1.1. PEMS Integration

PEMS will generally require location and temporary installation of:

- PEMS, mounting brackets, hold-downs
- external sensors (usually magnetic ambient temperature / RH unit)

- external global positioning system antenna
- exhaust pipe adaptor
- heated sample line and hangers
- computer control system
- ECM communications cable and connectors (if used)
- gas cylinder caddy
- 24 volts direct current (VDC) deep-cycle battery power supply

Integration requirements will vary, depending on the particular PEMS and the selected nonroad equipment. The site-specific protocol should include estimates for labor, materials, and equipment downtime. Figure 6-1 provides a photograph of an example PEMS installation for reference.

Figure 6-1. Example PEMS Installation

Test personnel should install the unit in the operator's cab or under a protective shelter. The location must allow proper clearances for machine operations and minimize exposure to damage. If installed in the operator's cab, proper venting is required for the PEMS exhaust gases.

<u>Exhaust pipe adaptor</u>

Many PEMS use an exhaust pipe adaptor to acquire exhaust flow rate data and gas samples. All engine exhaust should therefore be routed through a single exhaust pipe. The site-specific protocol will denote the required PEMS exhaust pipe adaptor size. Some nonroad equipment may be too large for the available exhaust pipe adaptors or have multiple exhaust pipes. In this case, the site-specific protocol will develop other strategies for acquiring real-time exhaust flow data and gas samples such as temporarily installing a pitot tube. ΔP pressure sensors, and suitable datalogger.

If possible, test personnel should install the adaptor at the end of a pipe section which is at least ten diameters downstream of the closest disturbance (elbow, flange, etc.) as shown in Figure 6-2. Entries in Appendix B-15 should document the upstream and downstream disturbances, especially for TPM tests. The adaptors weigh approximately two to five pounds, depending on size. Additional bracing may be required for support and to reduce vibration.

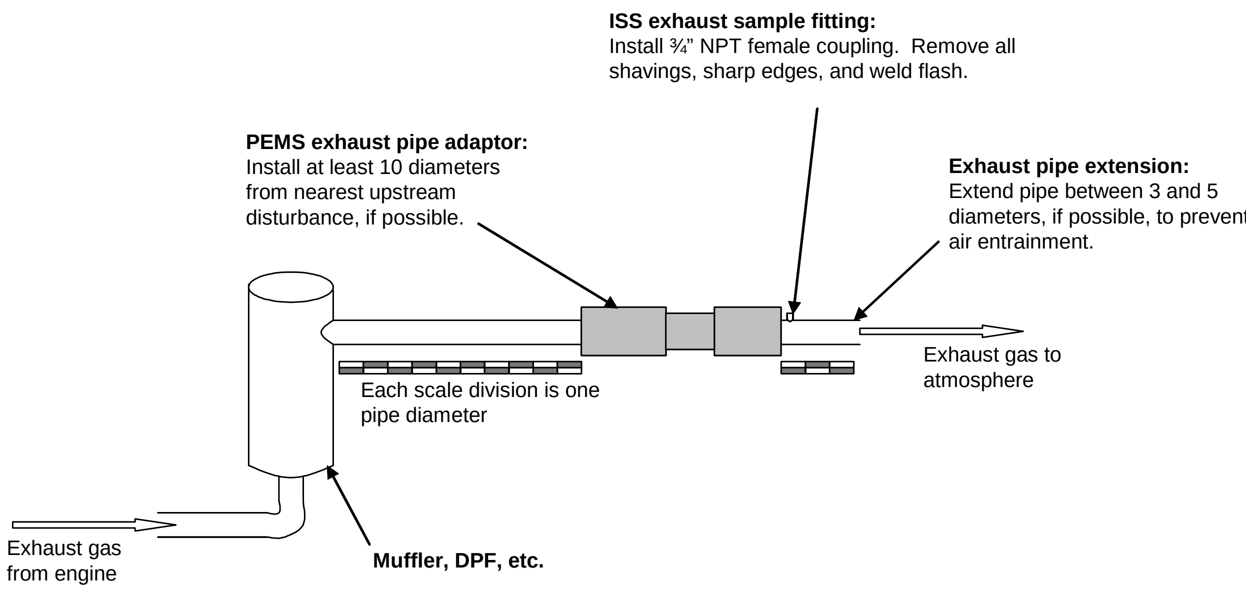

Figure 6-2. PEMS Exhaust Pipe Adaptor and ISS Sample Fitting Locations

PEMS power supply

Most PEMS require significant amounts of operating power. The nonroad equipment under test may be able to provide a portion of that power, but this should not exceed 1.0 percent of its equivalent engine bhp [§1065.910 (d) (1) (iii)]. Separate power supplies are preferred. Many PEMS will require a separate 24 VDC battery power supply. Hold-down, support bracket, and handling equipment designs must account for battery size and heavy weights. Test personnel should select battery capacity which will limit battery discharge to 50 percent of the nameplate ampere-hour (A-h) rating to avoid short battery lifespans.

6.1.2. ISS Integration

Major ISS system components may include:

- ISS dilution tunnel, probe, heated umbilical
- pump box for sampling and dilution air pumps
- sample bag container
- sample filter body
- heated sample line
- 110 VAC generator power supply
- laminar flow element (LFE) for intake air flow measurements
- exhaust pipe sample fitting

Figure 6-3 shows an example ISS and pump box installed and ready for testing. The 110 VAC generator is out of view at the rear of the test vehicle. Test personnel usually suspend the sample bag container (not shown) from any convenient point.

Figure 6-3. Example ISS and Pump Box Installation on a Sweeper (photo courtesy of Environment Canada)

<u>Intake air flow measurement</u>

ISS testing must include methods to measure either intake air or exhaust gas flow rates. A PEMS exhaust pipe adaptor may function with a ISS. Some tests, however, may incorporate both PEMS and ISS. In this case, the PEMS exhaust pipe adaptor will occupy that position on the nonroad equipment. This means that the ISS instruments must acquire intake air flow rates with a LFE and air filter assembly installed at engine intake air plenum. LFE size will depend on the nonroad equipment selected for testing. Test personnel should plan to specify the appropriate flanges, adaptors, and sensor line routing in the site-specific protocol.

Note that the existing air filter or any replacement must meet or exceed all manufacturer's specifications. If the LFE incorporates its own intake air filter, test personnel should review the filter specifications or conduct an inlet air filter restriction test. The inlet air restriction should be less than halfway between the value seen with a new air filter alone and the maximum value specified by the engine manufacturer [§86.1330 (f) (1) (i)], generally less than 15 "H_2O.

Test personnel should plan to leave the LFE air filter assembly and elements, if used, in place throughout any baseline / candidate control strategy evaluation.

6.2. CONTROL STRATEGY PERFORMANCE TESTS

Control strategy performance tests will consist of at least three baseline and three candidate test runs performed under simple or synthesized duty cycles. Test personnel may perform more test runs in order to:

- show a statistically significant difference between the baseline and candidate conditions
- refine the confidence interval on the difference

The number of baseline test runs is a function of sampling variability (or σ_{n-1} of the test results), and the control strategy performance. Duty cycles, operators, and significant ambient condition changes can all affect sampling variability. The number of candidate test runs should at least equal the number of baseline test runs.

Control strategy tests may incorporate either ISS or PEMS, depending on individual test campaign requirements. ISS results are integrated over the entire test run while PEMS data is real-time. Note that control strategy tests may also incorporate ISS / PEMS comparisons.

In general, control strategies intended to reduce TPM require testing with ISS. Site-specific protocols may employ PEMS, however, as real-time TPM instruments become available. The PEMS data should be correlated with simultaneous ISS results, collected over the same simple cycle or synthesized duty cycle, as outlined in §6.5.

Control strategies such as diesel particulate filters (DPF) incorporate regeneration cycles which will affect duty cycles and testing schedules. The site-specific protocol should include procedures for determining the DPF operating state and whether to test just before, just after, at other times, or how to capture all events with respect to regeneration. For example, one duty cycle may produce mean exhaust temperatures which are too low for DPF regeneration while those seen during a second duty cycle might be sufficiently high for long enough periods. In this case, it may be necessary for test runs to incorporate both duty cycles into a longer integrated duty cycle.

Site-specific protocols may specify that testing occur in the following order:

- baseline test runs prior to installation of the control strategy
- control strategy installation, break-in, or degreening
- candidate test runs

Suitable sampling location choices can represent baseline and candidate conditions, respectively, on nonroad equipment with existing control strategies. Figure 6-4 shows an example. Upstream ("baseline") and downstream ("candidate") tests can utilize a single PEMS or ISS over simple cycles or in-use duty cycles. Test personnel would switch the sampling probe between the two locations depending on the desired test condition. Two PEMS or ISS, with their sampling probes installed on the upstream and downstream locations simultaneously, could provide performance data during the same test runs. Also, this is the only configuration that would provide meaningful results for ISS used under in-use duty cycles.

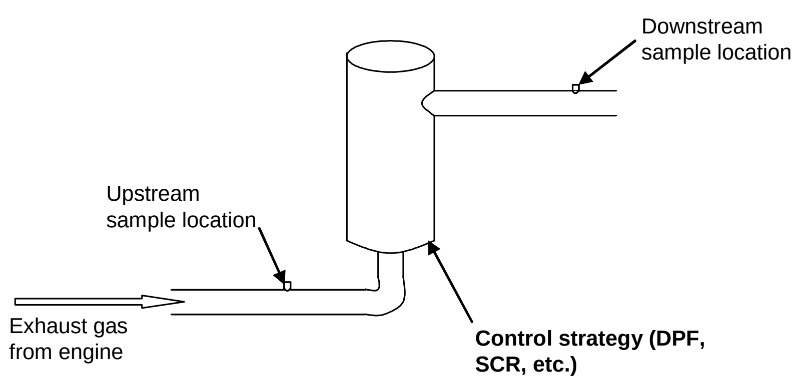

Figure 6-4. Upstream and Downstream Sample Locations

6.2.1. PEMS Control Strategy Tests

Baseline Test Runs

1. Ensure that all applicable preparations (see §6.1) are complete, that all required instruments and sensors are installed and functioning properly.
2. Synchronize all clocks to the PEMS datalogger timestamp or to GPS time, if available.
3. Start the nonroad equipment and dispatch it to perform one complete simple or synthesized duty cycle for warmup. Immediately begin a 20-minute "soak" period, either at low idle or with the

machine shut down, as specified in the site-specific protocol. Follow the manufacturer's recommendations regarding turbocharger cooling if the engine is shut down.

4. Energize the PEMS for its specified warmup period. Use power mains for PEMS warmup to avoid depleting the batteries. Conduct PEMS initial zero and span checks. Perform at least one NMHC contamination check per test day. Collect ambient air samples for background CO, CO_2, NO_X, TPM, or THC correction.
5. Switch PEMS to battery power supply without interruption.
6. Start PEMS sampling.
7. Start the nonroad equipment and operate the engine at midrange idle for 30 seconds. Reduce engine speed to low idle for 10 seconds. Accelerate the engine to full speed (rpm) for 2 seconds to create a spike in the logged data file. Reduce the engine speed to low idle for 5 seconds and immediately start the test run. This operating profile will provide readily recognizable data patterns which will help later analysis.
8. Immediately dispatch the nonroad equipment to perform one complete simple or synthesized duty cycle.
9. Immediately begin a 20-minute soak period (at low idle if the PEMS is connected to the vehicle battery or shut down) during data download and post-run checks. Follow the manufacturer's recommendations regarding turbocharger cooling if the engine is shut down.
10. Inspect the PEMS sample line, in-line filter housings, and other components upstream of the analyzers for condensed moisture. Invalidate the test run if moisture is present. Conduct PEMS final zero and span checks.
11. Review cycle criteria (3 complete cycles needed to develop cycle criteria; see §5.4) to establish the run's validity. This step may be completed later, depending on cycle duration and workloads.
12. Repeat steps 5 through 11 until 3 valid test runs are complete.
13. Calculate the mean and confidence interval on the results for each parameter (see §7.1). Conduct additional test runs if the confidence interval is a significant fraction of the expected performance.
14. Note: connect the PEMS to the power mains and exchange the PEMS batteries as needed without interruption to avoid having to repeat its warmup period. The site-specific protocol should specify the appropriate interval.

<u>Candidate Test Runs</u>

15. Implement, degreen, or break in the control strategy according to procedures in the site-specific protocol (typically 25 to 125 hours [18]).
16. Certify proper operation of the control strategy and nonroad equipment as specified in the site-specific protocol.
17. Conduct candidate test runs according to the baseline test run procedures (steps 1 through 12) except that the number of candidate test runs should at least equal the number of baseline runs.

18. Calculate and report the mean and confidence interval on the difference between the baseline and candidate results according to procedures in §7.1. Conduct additional candidate test runs (up to 6) if necessary.
19. Collect control strategy cost, performance, and user's information (see Appendix B3, B4).

6.2.2. <u>ISS Control Strategy Tests</u>

ISS and PEMS control strategy evaluations are generally equivalent.

<u>Baseline Test Runs</u>

1. Ensure that all applicable preparations (see §6.1) are complete, that all required instruments and sensors are installed and functioning properly.
2. Synchronize all clocks to the ISS datalogger timestamp or GPS time, if available.
3. Energize the ISS analyzer bench for at least ½ hour warmup period.
4. Collect and analyze an integrated ISS bag sample of the ambient air. It will serve as the background sample for ambient pollution concentration corrections.
5. Start the nonroad equipment and dispatch it to perform one complete simple synthesized duty cycle for warmup. Immediately begin a 20-minute "soak" period, either at low idle or with the machine shut down, as specified in the site-specific protocol. Follow the manufacturer's recommendations regarding turbocharger cooling if the engine is shut down.
6. Perform ISS tunnel leak check, collect NMHC and TPM (as needed) tunnel blank and background samples at least once per day. Analyze ISS gaseous samples immediately or during the following test run.
7. Start ISS sampling and immediately dispatch the nonroad equipment to perform one complete simple or synthesized duty cycle.
8. Stop ISS sampling and inspect sample train, sample bag, and filter housings for condensed moisture. Invalidate the test run if moisture is present.
9. Recover and inspect TPM filters (if used) for condensed moisture. Invalidate the test run if moisture is present. Store TPM filters under refrigeration or in a cooler until analyzed.
10. Immediately begin a 20-minute soak period (at low idle if the ISS is connected to the vehicle battery, or shut down) during data download and post-run checks. Follow the manufacturer's recommendations regarding turbocharger cooling if the engine is shut down.
11. Analyze ISS gaseous samples immediately. Perform all applicable zero, span, and drift checks.
12. Review the TPM filter face temperature log (if used; see Table 6-4) and cycle criteria (3 complete cycles needed to develop cycle criteria; see §5.4) and to establish the run's validity. Cycle criteria review may be completed later, depending on cycle duration and daily workloads.
13. Forward the TPM filters for gravimetric or additional analysis (see Table 3-2.)

14. Repeat steps 8 through 13 until 3 valid test runs are complete.
15. Calculate the mean and confidence interval on the results for each parameter (see §7.1). Conduct additional test runs if the confidence interval is a significant fraction of the expected control strategy performance.

<u>Candidate Test Runs</u>

16. Implement, degreen, or break in the control strategy according to procedures in the site-specific protocol (typically 25 to 125 hours [18]).
17. Control strategy vendor, technician, or authorized personnel to certify proper operation of the control strategy and nonroad equipment.
18. Conduct candidate test runs according to the baseline test run procedures (steps 1 through 13) except that the number of candidate test runs should at least equal the number of baseline runs.
19. Calculate the mean and confidence interval on the difference between the baseline and candidate results according to procedures in §7.1 Conduct additional test runs (up to 6) if necessary.
20. Collect control strategy cost, performance, and user's information (see Appendix B3, B4).

6.3. IN-USE EVALUATIONS

In-use evaluations will consist of PEMS monitoring under in-use duty cycles and will allow emissions assessments under real world conditions.

In-use evaluations could also be configured to yield a different type of control strategy performance evaluation than that described in §6.2. The following test schedule would yield two independent control strategy performance assessments:

- conduct baseline test runs under a synthesized duty cycle
- conduct baseline in-use evaluation
- conduct candidate test runs under a synthesized duty cycle
- conduct candidate in-use evaluation

Step-by-step in-use test procedures are as follows:

1. Ensure that all applicable preparations (see §6.1) are complete, that all required instruments and sensors are installed and functioning properly.
2. Synchronize all clocks to the PEMS datalogger timestamp or GPS clock.

3. Energize the PEMS for its warmup period, if necessary. Use power mains for PEMS warmup to avoid depleting the batteries.
4. Switch PEMS to battery power supply without interruption. Conduct PEMS initial zero and span checks. Perform at least one NMHC contamination check per test day.
5. Start PEMS sampling.
6. Check the site-specific test plan and §5.5.1 regarding "cold start" or "hot start" procedures. Start the nonroad equipment and dispatch it to normal in-use service with the appropriate cold or hot start procedure.
7. Conduct zero and span checks as needed. The frequency of these interim checks depends on PEMS performance and stability characteristics. Test operators should begin with hourly checks, but this period may be modified as needed.
8. Exchange batteries at the time(s) noted in the site-specific protocol. Note that if power mains are unavailable or if the battery exchange cannot be made without interruption, conduct another warmup period, zero, and span check prior to continuing the test run.
9. Continue testing until the planned in-use period has elapsed, not including zero and span checks or PEMS warmup periods (6 hours is recommended).
10. Collect control strategy cost, performance, and user's information (see Appendix B3, B4).

6.4. EXTENDED INTERVAL TESTS

Extended interval tests are intended to assess nonroad equipment or control strategy performance trends. They consist of a series of initial PEMS test runs followed by an extended interval of normal in-use service, typically at least 6 months. Tests conclude with a series of final PEMS test runs.

Extended interval tests may employ simple cycles, synthesized duty cycles, or in-use duty cycles as long as the initial test techniques and duty cycles match those used for the final test series. For example, a control strategy candidate series could serve as the initial test series for an extended interval test. Comparison of the final and initial test series results would show how the control strategy performs over time. Test personnel may opt to remove the control strategy to return the nonroad equipment to its baseline configuration and conduct additional test runs, or conduct additional test runs upstream of the control device. This may be particularly valuable if the extended interval tests show significant positive or negative changes from the initial test series.

Some control strategies may be amenable to simplified extended interval performance assessments. For example, a blackened tailpipe or black spots on the outlet face of a DPF indicate a failure while a clean outlet face is a strong indication that the control efficiency remains high. Although such assessments are qualitative rather than quantitative, site-specific protocols may incorporate them in conjunction with the control strategy performance tests described in §6.2.

Ambient temperatures should be as close as possible between the initial and final test series. Judicious choice of season, based on local weather conditions, may dictate the test schedule. The site-specific protocol should address this issue.

The nonroad equipment operator should be the same for the initial and final test series.

Step-by-step procedures are as follows:

1. Perform at least three initial test runs with PEMS according to §6.2.1. Use steps 1 through 14 for nonroad equipment without control strategies. Use steps 15 through 17 for control strategy extended interval tests.
2. Calculate the mean and confidence interval on the results. Perform additional test runs (up to 6) to refine the confidence interval if necessary. This especially applies if the confidence interval is a significant fraction of expected control strategy performance.
3. Dispatch the nonroad equipment to normal in-use service for the specified extended interval.
4. Collect the operations data specified in the site-specific protocol at least monthly.
5. At the end of the extended interval, perform final test runs. The number of final test runs should at least match the number of initial test runs. Use the same duty cycle and PEMS. The nonroad equipment operator should also be the same for synthesized duty cycle tests.
6. Calculate and report the mean and confidence interval on the difference between the initial and final test run series according to procedures in §7.1.Conduct additional final test runs (up to 6) if necessary.
7. Collect control strategy cost, performance, and user's information (see Appendix B3, B4).

6.5. EMISSIONS METHOD COMPARISONS

Emissions measurement method comparisons consist of at least three test runs which incorporate each method operating simultaneously under a simple or synthesized duty cycle. Test personnel may conduct up to six test runs in conjunction with control technology evaluations if desired. This section uses the comparison between a ISS and a PEMS as an example.

1. Ensure that all applicable preparations (see §6.1) are complete, that all required instruments and sensors are installed and functioning properly.
2. Synchronize all clocks to the PEMS datalogger timestamp or GPS clock.

3. Energize the ISS analyzer bench for at least ½ hour warmup period.
4. Start the nonroad equipment and dispatch it to perform one complete simple or synthesized duty cycle for warmup. Immediately begin a 20-minute "soak" period, either at low idle (if the PEMS or ISS is connected to the vehicle battery) or with the machine shut down, as specified in the site-specific protocol. Follow the manufacturer's recommendations regarding turbocharger cooling if the engine is shut down.
5. Perform ISS tunnel leak check, collect NMHC and TPM (as needed) tunnel blank and background samples at least once per day. Analyze ISS gaseous samples immediately or during the following test run.
6. Energize the PEMS for the warmup period, if necessary. Use power mains for PEMS warmup to avoid depleting the batteries. Perform initial zero, span checks.
7. Switch PEMS to battery power without interruption. Start PEMS sampling
8. Start the nonroad equipment and operate the engine at midrange idle for 30 seconds. Reduce engine speed to low idle for 10 seconds. Accelerate the engine to full speed (rpm) for 2 seconds to create a spike in the logged data file. Reduce the engine speed to low idle for 5 seconds and immediately start the test run. This operating profile will provide readily recognizable data patterns which will help later analysis.
9. Start ISS sampling and immediately dispatch the nonroad equipment to perform one complete simple or synthesized duty cycle.
10. Stop ISS sampling and inspect ISS sample train, sample bag, and filter housings for condensed moisture. Invalidate the test run if moisture is present.
11. Immediately begin a 20-minute soak period (at low idle or shut down, as above) during data download and post-run checks. Follow the manufacturer's recommendations regarding turbocharger cooling if the engine is shut down.
12. Perform PEMS final zero, span, and drift checks.
13. Analyze ISS gaseous samples immediately. Perform all applicable zero, span, and drift checks.
14. Review cycle criteria (3 complete cycles needed to develop cycle criteria; see §5.4) to establish the run's validity.
15. Repeat steps 8 through 13 until 3 valid test runs are complete.
16. Calculate the mean and confidence interval on the difference between ISS and PEMS results for each parameter according to the procedures in §7.4.
17.

6.6. INSTRUMENT SPECIFICATIONS, CALIBRATIONS, AND PERFORMANCE CHECKS

The emissions and performance determinations described in this protocol require numerous contributing measurements, sensors, instruments, analytical procedures, and dataloggers. This section provides general specifications which, if met, will help ensure repeatability within a test campaign and comparability with other programs.

Instrumentation and sensor selection depends on whether test personnel are determining control strategy feasibility, developing duty cycles, or conducting test runs. If the engine is ECM-equipped, test personnel should plan to confirm the communications protocol (SAE J1939, J1708 / J1587, or proprietary) and datalogging feasibility prior to testing. Engines without feasible ECM communications will require temporary installation of auxiliary sensors for the parameters suggested in Table 6-2 and a suitable datalogger. The appropriate brackets, fittings, equipment supports, and enclosures should also be considered during test planning.

Table 6-2. Test Measurements

Parameter or Sensor	ECM-Equipped			Mechanically-Controlled	
	Control Strategy Feasibility and Duty Cycle Development	PEMS and ISS Emissions Testing	SAE J1939, J1708 / J1587 SPN ID # (reference)	Control Strategy Feasibility and Duty Cycle Development	PEMS and ISS Emissions Testing
Percent load	+	*	92		
Net brake torque	+	*	93		
Turbocharger boost pressure[a]	+	*	102	√	√
Exhaust gas temperature (T_{out})	+	*	173	√	*
Speed (RPM)	+	*	190	√	*
Air inlet pressure	+	*	106	❖	❖
Exhaust gas backpressure	+	*	131	√	√
Barometric pressure (P_{bar})	+	*	171	√	*
Ambient temperature (T_{amb})	+	*		√	*
Turbocharger exit temperature (T_{turb})				√	√
Pollutants (CO, CO_2, NO_X, THC, TPM if used)		*			*
Exhaust gas flow rate		*			*
Exhaust gas flow rate surrogate: high range ΔP				√	√
Exhaust gas flow rate surrogate: low range ΔP				√	√
Supply fuel flow[a]				√	√
Return fuel flow[a]				√	√

+ ECM output to standalone datalogger
* Recorded by PEMS datalogger
√ Dedicated sensor output to standalone datalogger

Table 6-2. Test Measurements					
Parameter or Sensor	**ECM-Equipped**			**Mechanically-Controlled**	
	Control Strategy Feasibility and Duty Cycle Development	**PEMS and ISS Emissions Testing**	**SAE J1939, J1708 / J1587 SPN ID # (reference)**	**Control Strategy Feasibility and Duty Cycle Development**	**PEMS and ISS Emissions Testing**
❖ Manually recorded from temporarily-installed gauge prior to testing [a] If used					

6.6.1. Instrument Specifications

Analytical instruments, such as those used for emissions, fuel consumption, and other determinations should employ the detection principles listed in Title 40 CFR 1065 [4], §1065.201 through §1065.295. Table 6-3 lists the accuracy specifications recommended for use with this protocol. The specifications generally conform to Table 1 of §1065.915. The ISS anticipated to be used for in-use testing has many similarities to laboratory-based constant volume sampling (CVS) systems. This protocol, therefore, adopts several of the CVS system specifications listed in Table 1 of §1065.205 and applies them to the ISS. Instrument specifications and detection principles may differ from those listed here if the test report explicitly identifies the differences and the reasons for them.

Table 6-3. PEMS and ISS Specifications			
Parameter	**Logging Frequency**	**Accuracy**	**Repeatability**
Engine speed	1 Hz	5.0 % of point or 1.0 % of max[a]	2.0 % of point or 1.0 % of max
Torque estimator, BSFC	1 Hz	8.0 % of point or 5.0 % of max	2.0 % of point or 1.0 % of max[b]
Pressure transducers	1 Hz	5.0 % of point or 5.0 % of max	2.0 % of point or 0.5 % of max
Ambient barometric pressure	6 second	0.07 “Hg (250 Pa)	0.06 “Hg (200 Pa)
Temperature transducers (T_{turb}, T_{out}, T_{amb})	1 Hz	1.0 % of point or 5.0 °C	0.5 % of point or 2.0 °C
Dewpoint / RH[c] (if used)	6 second	5.0 °F	2.0 °F
Exhaust flow	1 Hz	5.0 % of point or 3.0 % of max	2.0 % of point
Instrumental analyzer concentration	1 Hz	4.0 % of point	2.0 % of point
Fuel flow (if used)[d]	1 Hz	2.0 % of point or 1.5 % of max	1.0 % of point or 0.75 % of max
ISS only			
Instrumental analyzer conc.	1 Hz	2.0 % of point	1.0 % of point
Gravimetric TPM balance	n/a[e]	0.1 % (see §1065.790)	0.5 µg

Table 6-3. PEMS and ISS Specifications			
Parameter	**Logging Frequency**	**Accuracy**	**Repeatability**
Main flow rate	2 Hz	1.0 % FS[f]	n/a
Dilution air flow rate			
Sample flow rate			
Differential pressure (if used)			

[a]"max" refers to the maximum value expected during testing.
[b]Quantification of ECM torque estimator accuracy may be difficult because §1065.915(b)(5)(i) regulations requiring this on nonroad engines are not effective until 2010.
[c]relative humidity (RH)
[d]This specification refers to fuel consumption by: 1) net gravimetric determinations from removable day tanks, 2) net of diesel engine fuel supply and return mass flows, 3) volumetric makeup flow into a closed diesel engine fuel circulation loop, or 4) other methods of direct fuel consumption measurement. Note that the supply and return flow meters must be extremely accurate (generally better than ± 0.2 %) to achieve this specification for differential flow at low fuel consumption rates.
[e]Not applicable (n/a)
[f]Full scale (FS)

Data acquisition systems must be capable of logging all parameters at the intervals specified in Table 6-3 or more frequently. Analog to digital conversion resolution must be sufficient to show less than ± 0.05 percent change in any logged value (11-bit or better). The logged values (after analog to digital conversion) should form the basis for all instrument calibration analysis.

6.6.2. Calibrations and Performance Checks

Table 6-4 lists recommended calibration intervals and performance checks as discussed in 40 CFR 1065 [4]. Note that test personnel should perform some performance checks, such as leak checks, analyzer zero and spans, etc. before and after each test run while others may be performed either in the field or laboratory. The 40 CFR 1065 references provide step-by-step procedures.

Table 6-4. Recommended Calibrations and Performance Checks			
System or Parameter	**Description / Procedure**	**Frequency**	**Reference**
Engine speed	11-point linearity check	At purchase / installation	§1065.307 (d); (e) (1)
Pressure transducers	NIST-traceable[a] calibration	Within 12 months	§1065.315
Temperature transducers (T_{turb}, T_{out}, T_{amb})			
Dewpoint / RH			
Exhaust flow			§1065.330
All instrumental analyzers	11-point linearity check	Within 12 months	§1065.307 (d); (e) (6)
CO_2 (NDIR detectors)[b]	H_2O interference	Within 12 months	§1065.350

Table 6-4. Recommended Calibrations and Performance Checks

System or Parameter	Description / Procedure	Frequency	Reference
CO (NDIR detectors)	CO_2, H_2O interference		
Hydrocarbons (FID)[c]	Propane (C_3H_8) calibration		§1065.360 (b)
	FID response optimization		§1065.360 (c)
	C_3H_8 / methyl radical (CH_3) response factor determination		§1065.360 (d)
	C_3H_8 / CH_3 response factor check		§1065.360 (e)
	Oxygen (O_2) interference check		ISO 8178-1, §8.8.3 (see Table 2 of §1065.1010)
NO_X	CO_2 and H_2O quench (CLD)[d]		§1065.370
	Non-methane hydrocarbons (NMHC) and H_2O interference (NDUV detectors)[e]		§1065.372
NO_X	Ammonia interference and NO_2 response (zirconium dioxide detectors)	Within 12 months	§1065.374
	Chiller NO_2 penetration (PEMS with chillers for sample moisture removal)		§1065.376
	NO_2 to NO converter efficiency	Within 6 months or immediately prior to departure for field tests	§1065.378
PEMS	Comparison against laboratory CVS system	At purchase / installation; after major modifications	§1065.920
	Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of cal gas concentration)[f]	Before and after each test run or as needed during in-use evaluations	§1065.925, §1065.935
	Perform analyzer drift check (≤ ± 4.0 %)[g]	After each test run	§1065.657
	NMHC contamination check (≤ 2.0 % of expected concentration or ≤ 2 ppmv)	Once per test day	§1069.925 (h)
Exhaust gas or intake air flow measurement device	Differential pressure line leak check (ΔP stable for 15 seconds at 3 "H_2O)	Once per test day	40 CFR 60 Appendix A, Method 2, "Determination of Stack Gas Velocity And Volumetric Flow Rate", §8.1
ISS	Comparison against laboratory CVS system	At purchase / installation; after major modifications	§1065.920
	Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of cal gas concentration)[f]	Before and after each test run	§1065.925, §1065.935
	Inspect sample lines, filter housings, and sample bags	After each test run	n/a

Table 6-4. Recommended Calibrations and Performance Checks			
System or Parameter	**Description / Procedure**	**Frequency**	**Reference**
	for visible moisture (none is allowed)		
	Perform analyzer drift check (≤ ± 4.0 %)[g]		§1065.657
	NMHC background check and dilution tunnel blank	Once per test day	§1065.667 or ISS standard operating procedure
	TPM background check and dilution tunnel blank		
	Dilution tunnel leak check		
	Sample bag leak check (< 0.5 % of normal system flow rate)		§1065.345
	TPM filter face temperature (not to exceed 47 °C or 117 °F)	continuously during sampling	§86.1310-2007 (b) (6) (E) (v)
Fuel flow	11-point linearity check	At purchase (coriolis meters only); within 6 months or immediately prior to departure for field tests (turbine or gear meters)	§1065.307 (d); (e) (3)
TPM gravimetric balance	NIST-traceable calibration	Within 12 months	n/a
	Reference sample weights	Within 12 hours of filter weighings	§1065.390
ISS main, dilution, and sample flow rates	11-point linearity check	Within 12 months	§1065.307 (d); (e) (4)

[a]National Institutes of Standards and Technology (NIST)
[b]non-dispersive infrared (NDIR)
[c]flame ionization detector (FID)
[d]chemilumenescence detector (CLD)
[e]non-dispersive ultra violet (NDUV)
[f]Table 1 of §1065.915 zero accuracy specifications are unclear. Most Title 40 CFR 60 Appendix A reference methods specify a zero response within ± 2.0 % of the analyzer span. This protocol adopts that value.
[g]§1065.550(b)(1) allows up to ± 4.0 % difference between the raw and drift-corrected brake-specific emissions. In general, field tests will achieve this criterion if analyzer drift is ≤ 4.0 % of the span gas concentration.

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7.0 DATA QUALITY AND ANALYSIS

This section outlines general data analysis procedures for each type of test and data quality requirements for all tests. Appendix C supplements the discussion with statistical concepts and equations.

7.1. CONTROL STRATEGY PERFORMANCE TESTS

Section 6.2 specifies a minimum of three baseline test runs followed by the same number or more (typically up to six) candidate test runs. Site-specific protocols may require simple cycles, synthesized duty cycles, or in-use duty cycles. Note that ISS will generally provide TPM results (if required) while PEMS will provide gaseous emissions results.

7.1.1. Emissions Reductions and Fuel Consumption Changes for Synthesized Duty Cycles

Analysts should first examine the data set for outliers (such as mean emission rates or other parameters) for each test run. They should consider removing those that meet criteria described in ASTM E178-02 [21] prior to further analysis. More than three test runs are generally necessary for this. Analysts should then, for each parameter (CO, CO_2, NO_X, THC, TPM, fuel consumption):

- calculate the mass emissions (g/run) mean and σ_{n-1} for all baseline and candidate test runs
- calculate the fuel-specific emission rate (g/gal) mean and σ_{n-1} for all baseline and candidate test runs
- calculate the brake-specific emission rate mean (g/bhp-h) and σ_{n-1} for all baseline and candidate test runs, if torque or horsepower data are available from an ECM
- calculate the difference between the baseline and candidate mean results
- evaluate the statistical significance of the difference
- calculate the 95-percent confidence interval on the difference

Appendix C provides the statistical analysis equations and procedures. These include Student's T test for statistical significance, the F test for evaluating similarity of variance, and the error value calculation for the 95 percent confidence interval.

Brake-specific results require engine brake horsepower, but ECM power data is often in terms of percent maximum torque at a given engine speed. In this case, analysts must:

- obtain the maximum torque / RPM specifications from the engine manufacturer
- multiply the ECM percent torque by the manufacturer's specified maximum torque at the reported ECM engine speed for each data entry
- calculate bhp as [17]:

$$bhp = \frac{2\pi Frn}{33000} \qquad \text{Eqn. 7-1}$$

where:

bhp = brake horsepower

Fr = brake torque (force multiplied by radius), lb-ft

n = engine speed, RPM

Note that some parameters and their products, such as RPM times exhaust standard volumetric flow, can serve as a surrogate for engine power in brake-specific emission calculations. Site-specific protocols may develop and implement such surrogates during analysis as needed.

7.1.2. Emissions Reductions and Fuel Consumption Changes for In-use Duty Cycles

Analysts should use the data reduction and statistical procedures described in §7.1 and Appendix C for baseline and candidate tests. Assume, for example, that in-use data analysis identifies an operating event, such as loaded reverse travel for a rubber-tired loader, as being a significant contributor to overall emissions. The control strategy performance, then, is the difference between the mean baseline and candidate results for that event. Analysts should:

- identify at least three separate operating events with similar parameters (mean duration, RPM, exhaust temperature, exhaust gas flow, ECM outputs, etc.) that occur during both baseline and candidate testing
- calculate the baseline and candidate mean emission rate and σ_{n-1}
- calculate the difference between the baseline and candidate results
- evaluate the statistical significance of the difference
- calculate the 95-percent confidence interval on the difference

7.1.3. Control Strategy Cost Analysis

Analysis of control strategy costs consists primarily of summing and reporting the data collected in Appendix B3. Costs should be separated into the following general categories:

- capital purchases
- shop-made modifications, specialty items
- downtime (or demurrage), installation, and training labor
- operating materials, supplies, and reagents
- operating labor

7.1.4. Control Strategy Engine and Operational Performance Impact Analysis

Some test campaigns may acquire credible brake horsepower data, either from an ECM or through direct measurements. If so, analysts may calculate the difference between the baseline and candidate horsepower and fuel consumption, normalized to brake horsepower. This approach requires caution, however, when using ECM data if ECM accuracy is not well-established.

If ECM data are suspect or not available, performance impacts may be calculated and reported as the difference in mean fuel consumption between baseline and candidate conditions as observed during simple or synthesized duty cycles. For in-use duty cycles, performance impacts reported as the fuel consumption difference between baseline and candidate conditions over a consistent time period (per shift, per day, etc.) may be meaningful. Performance impacts may also include operator or dispatcher anecdotal information.

Performance impacts should also include an assessment of potential problems from extremely cold or hot ambient conditions, scheduling changes, labor, or downtime required for:

- routine and major maintenance
- training and operator certification
- regeneration or reagent refreshment
- modified fueling, engine oil change, filter change, or other intervals

Some control strategies, such as shore-powered active DPFs, may have off-line emissions during regeneration or other impacts which also should be quantified as described in the site-specific protocols.

7.2. IN-USE EMISSIONS TESTS

This section discusses application of basic descriptive statistics, but analysts should be open to other possibilities depending on the circumstances of a particular test campaign. Appendix C provides additional analytical concepts such as methods for identifying in-use events. For example, repeatable in-use events could be used as the basis for control strategy performance evaluations.

In-use emissions and fuel consumption data analysis should be adaptable to the transient conditions seen during field testing. For example, fuel consumption time series plots will differ considerably between an air compressor and a backhoe / loader. This is because an air compressor usually cycles between periods of full power and low idle while a backhoe operates at all possible engine speeds and torques.

Once in-use data are gathered, many types of post-processing algorithms are available. For example, meaningful analysis may be possible on data which occur within restricted engine speed and torque envelopes. This is analogous to the 40 CFR 86 "not to exceed" (NTE) emissions testing requirements [16]. Identifiable and repeatable events may occur during baseline and candidate control technology tests which would allow direct performance comparisons.

The following descriptive statistics should be generally useful to describe the events which occur within an in-use emission test or to describe the test as a whole. Exclude the following data from this event description analysis:

- PEMS zero and span checks
- battery exchange and warmup periods

<u>In-use mean, σ_{n-1}, and maximum values</u>

The mean is one measure of the central location of a data set. It consists of the sum of all values in the set divided by the number of items. σ_{n-1} is the square root of a data set's variance, which is a measure of dispersion. The variance is the sum of the squared deviations of the data values about the mean divided by the number of data points minus 1 [15]. σ_{n-1} of RPM times exhaust gas temperature, exhaust gas flow, or ECM torque could be especially useful in tracking in-use duty cycle variability because they are analogous to σ_{n-1} of velocity in on-highway vehicle testing. Some researchers have found this statistic to be valuable in comparing one duty cycle to another [2, 20].

Report the mean and σ_{n-1} values for a selection of identifiable in-use events if each event occurs at least three times. Also report the mean and σ_{n-1} for the in-use test as a whole. Suggested parameters are:

- RPM
- RPM times exhaust gas temperature (T_{out}) or turbocharger outlet temperature (T_{turb})
- exhaust gas flow
- ECM-derived torque or bhp

Also examine the data set for outliers (such as mean values for identifiable events) and consider removing those that meet criteria described in ASTM E178-02 [21]. Report the maximum value for each parameter for the entire in-use testing period, the mean, and σ_{n-1} of the highest 6 values.

Median

The median is another measure of the central location of a data set. It is the value which splits the data set into two equal groups. A median RPM which is larger than the mean RPM can imply, for example, that the in-use test run may have many more high RPM events as opposed to mid-level RPM events.

Report the median as follows:

1. Rank the data for each parameter in ascending order.
2. Report the middle-ranked value (odd number of data points) or
3. Report the average of the two middle ranked values (even number of data points).

Frequency distributions

Frequency distributions can yield useful information about how often different conditions occur within a data set. It may be possible, for example, to state that the nonroad equipment operates between a mid-level and maximum RPM for a known percentage of the in-use test.

Report the relative and cumulative frequency distribution as follows:

1. Divide the range between the maximum and minimum values for each parameter into 10 to 15 intervals.
2. Sort the data into the appropriate intervals.
3. Count the number of data occurrences in each interval.
4. Calculate and report the relative frequency as:

$$p_i = \frac{n_i}{n_{tot}} \qquad \text{Eqn. 7-2}$$

where:

p_i = relative frequency of interval i (proportion or percent)

n_i = number of occurrences in interval i

n_{tot} = total number of data points collected

5. Calculate and report the cumulative frequency for each interval as:

$$p_{cum,i} = \frac{\sum_{1}^{i} n_i}{n_{tot}} \qquad \text{Eqn. 7-3}$$

where:

$p_{cum,i}$ = cumulative frequency up to interval i (proportion or percent)

Note that the frequency distribution methods assume that all datalogging time periods are equal (ideally, 1 Hz). Graphic plots (such as histograms for relative or ogive curves for cumulative frequency distributions) with the parameter value on the x-axis and frequency on the y-axis can aid the data interpretation.

7.3. EXTENDED INTERVAL TESTS

Extended interval tests begin with a series of initial test runs followed by a duplicate final test series conducted at a later time (usually at least 6 months). Analysts can consider extended interval tests as a baseline / candidate test series, similar to a control strategy evaluation. The difference between the mean final and initial test runs will serve as the performance metric. Analysts should calculate and report the difference according to the procedures in §7.1 and Appendix C.

Analysts can also consider the final test series in isolation to verify whether the selected nonroad equipment (or control strategy) is still performing nominally.

7.4. EMISSIONS MEASUREMENT METHOD COMPARISONS

7.4.1. Gaseous Emissions

Section 6.5 specifies three test runs while two emissions measurements methods operate simultaneously. Analysts should, for each parameter (CO, CO_2, NO_X, THC, fuel consumption):

- report the ISS mass emissions (g/run) for each test run
- calculate the mass emissions mean and σ_{n-1} for all test runs
- calculate the PEMS mass emissions as

$$m_{run} = \sum_{1}^{n} m_{\sec} \qquad \text{Eqn. 7-4}$$

Where:

m_{run} = emission mass for the test run, g

m_{sec} = PEMS mass emission rate per second, g/s

n = number of seconds in the test run

- calculate the mass emissions mean and σ_{n-1} for all PEMS test runs
- calculate the difference of the ISS and PEMS mean results
- evaluate the statistical significance of the difference
- calculate the 95-percent confidence interval on the difference.

Please see Appendix C for the appropriate statistical analysis procedures.

7.4.2. TPM Emissions

Some test campaigns may specify use of a real-time TPM accessory to the PEMS. In this case, analysts should process the TPM data and compare it to the integrated ISS mass emissions as described in §8.1.1.

7.5. DATA QUALITY

All test campaigns should meet the following qualitative data quality objective (DQO):

Sensors, measurements, step-by-step test methods, and the resulting determinations will meet or exceed this protocol's and reference method specifications as outlined in §5.0 through §6.6.

Evidence of the calibrations and performance checks summarized in Table 6-4, data and signatures from Appendix B field data forms, field notes, and corrective action reports (CAR) will document achievement of this DQO.

Explicit quantitative DQOs are not appropriate for this generic protocol because of its applicability to a wide variety of possible test campaigns. Also, test personnel cannot adopt explicit goals such as confidence intervals about a mean because relevant data will not be available prior to testing. Site-specific protocols, however, may adopt implicit DQOs based on the individual test campaign.

For example, assume that test personnel expect the control technology will improve emissions performance by 5.0 percent. Implicit DQOs could be:

- the difference between mean baseline and candidate performance will be statistically significant
- test personnel may refine the 95 percent confidence interval on the result as much as possible up to 6 runs

8.0 REPORTS

Original electronic and written field data, including the field team leader's daily test log, will form the basis for all analyses, conclusions, and reports.

Reported results, data summaries, and statistical analyses depend on the individual test campaign. Table 8-1 provides a general list of items to be included in each type of report. See Table 3-1 for individual parameters and units; see §8.0 for analysis procedures.

Table 8-1. Reported Results List

Test Type / **Description**	Control strategy performance evaluation	In-use emissions tests	Extended interval tests	Emissions measurement method comparisons
Emission rates	√	√	√	√
Fuel consumption	√	√	√	√
Difference between baseline and candidate emissions and fuel consumption	√	+	+	
Control strategy costs	√	+	+	
Control strategy performance impacts	√	+	+	
Simple or synthesized duty cycle specifications	√		√	
In-use duty cycle descriptive statistics		√		
√ Included in report + Included in reports for control strategy evaluations only				

All reports should include tabular or narrative descriptions of:

- selected nonroad equipment data:
    - manufacturer, model, serial number, year
    - drivetrain configuration
    - engine size, type, manufacturer, model, engine family
    - modifications performed since purchase and the effect on the original configuration
    - modifications performed to allow testing
    - state of repair during testing, including hourmeter readings
    - dispatch information such as vehicle mission, daily duties
- host site data:
    - location, including elevation
    - overall fleet description
    - maintenance program description
- test equipment specifications, calibration, and performance check results
- field activity narrative:

    - dates, times
    - ambient conditions
- departures from the generic and site-specific protocols, as documented in CARs
- data quality assessments

Control strategy evaluations should include descriptions of:

- delivered condition, readiness for installation
- modifications needed to allow installation

A signed statement which certifies that the results represent the actual test conditions should accompany each report.

9.0 REFERENCES

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[2] *Analysis and Experimental Refinement of Real-World Driving Cycles*, N. Dembski, Y. Guezennec, A. Soliman, SAE International # 2002-01-0069, Warrendale, PA 2002

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[7] *Particulate Mass Measurements of Heavy-Duty Diesel Engine Exhaust Using 2007 CVS PM Sampling Parallel to QCM and TEOM—Final Report*, I. A. Khalek, U.S. Environmental Protection Agency, Ann Arbor, MI 2003

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[13] *Development of Refuse Vehicle Driving and Duty Cycles*, N. Dembski, G. Rizzoni, A. Soliman, SAE International # 2005-01-1165, Warrendale, PA 2005

[14] *Analysis and Experimental Refinement of Real-World Driving Cycles*, N. Dembski, Y. Guezennec, A. Soliman, SAE International # 2002-01-0069, Warrendale, PA 2002

[15] *Statistics Concepts and Applications*, D. Anderson, D. Sweeney, T. Williams, West Publishing Company, St. Paul, MN 1986

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[17] *Mechanical Engineering reference Manual -- Eighth Edition*, M. Lindeburg, Professional Publications, Inc., Belmont, CA 1990

[18] *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*, U.S. EPA Air Pollution Control Technology Verification Center, Research Triangle Park, NC 2002

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[20] *Development of a Heavy-Duty Chassis Dynamometer Driving Route*, R. Nine, N. Clark, J. Daley, C. Atkinson, Proceedings of the Institute of Mechanical Engineers, Vol 213, Part 2, London 1999

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APPENDIX A
SITE-SPECIFIC PROTOCOL OUTLINE

1.0 INTRODUCTION

This site-specific protocol addresses individual test details not discussed in the *Generic In-use Test Protocol for Nonroad Equipment* (generic protocol).

Note: Section numbering below follows the generic protocol system. This allows easy cross-referencing. If a test campaign will not employ a particular subsection (such as §6.4, "Extended Interval Tests"), retain the subsection heading but replace the explanatory text with "not applicable". This will ensure that section numbering is consistent with other site-specific protocols.

Project name: ____

Description of test: ____

____

Test goals: ____

2.0 APPLICABILITY

This protocol is applicable to any diesel-fueled nonroad equipment powered by mechanically-controlled engines or electronically-controlled engines equipped with engine control modules (ECM). Engines may be naturally aspirated, turbocharged, or equipped with exhaust gas recirculation (EGR). All tested equipment should be representative of the fleet of interest. This protocol also details any required special considerations depending on engine size.

Equipment powered by: mechanically-controlled engine ☐ engine control module (ECM) ☐
Engine is: naturally aspirated ☐ turbocharged ☐ exhaust gas recirculation-equipped ☐

Special considerations: ____

____

____

The nonroad equipment design must allow portable emissions monitoring system (PEMS) or integrated sampling system (ISS) installation, along with the required support equipment such as gas cylinders, exhaust pipe adaptors, and storage battery or generator power supply. Specify the appropriate mounting adaptors, brackets, shrouds, or other physical modifications as needed in §6.1.1 or §6.1.2 for PEMS or ISS, respectively

3.0 SCOPE

This section outlines the scope of the test campaign (Table 3-1) and summarizes the test parameters required for each test type (Table 3-2). Any or all test types could be performed during a given test campaign. In each table, check the boxes applicable to this test. See Tables 3-1 and 3-2 in the generic protocol for further descriptions.

Table 3-1. Test Types	
Control strategy emissions and fuel consumption performance	☐
In-use evaluations	☐
Extended interval emissions and fuel consumption performance	☐
Emissions method comparisons	☐

Table 3-2. Measurement Systems and Test Parameters		
Gaseous Emissions	CO	☐
	CO_2	☐
	NO_X	☐
	THC	☐
Particulate Emissions	TPM	☐
Unregulated Emissions	Speciated TPM	☐
	Gaseous emissions	☐
Fuel Consumption	Gravimetric	☐
	Differential mass flow	☐
	Volumetric	☐
	Carbon balance	☐
Control Strategy Cost (generic protocol Appendix B3)		☐
Control Strategy Operating Impacts[a] (generic protocol Appendix B4)		☐
[a]Data are likely to consist of management and dispatcher business data, anecdotal discussions, etc.		

Specify the unregulated emissions, test methods, and analytical techniques, if applicable. See Table 3-2 of the generic protocol for more information about methods. Table 3-3 below summarizes several important methods.

Table 3-3. Additional Test Methods				
✓ if Req'd	Control Strategy Type	Analyte	Sampling System / Location	Method
	SCR	NH_3	ISS / downstream of SCR	Citric acid-treated filter; ion chromatography analysis
		NH_4 in TPM	ISS / downstream of SCR	extraction of TPM filter; ion chromatography analysis
	PDPF	NO_2	PEMS	Simultaneous NO_X and NO_2 output signals
			PEMS	3 test runs with NO_2 converter enabled alternated with 3 test runs with NO_2 converter disabled
	All	Elemental carbon to organic carbon (EC / OC) ratio in exhaust	ISS / upstream of ECT	Quartz TPM filter analyzed by "improved" NIOSH Method 5040

4.0 NONROAD EQUIPMENT, CONTROL STRATEGY, AND HOST SITE SELECTION

This section discusses the selected nonroad equipment, control strategies, and host sites. Table 4-1 provides an example.

Table 4-1. PEMS and ISS Test Matrix								
Equip. Type	Make	Model	MY	Engine Model	bhp	Control Strategy Type	Make	Notes (including special considerations, additional test methods, etc.)

Every test campaign should select the nonroad equipment, the control strategy (if applicable), and host site early in the site-specific protocol development because the steps interact with each other. This site-specific protocol should explicitly list the personnel, administrative support, operations, and other resources required.

Special Considerations:

- Control strategy and fuel consumption performance tests usually require baseline and candidate comparisons. The same operator(s) must be assigned to run the nonroad equipment (and support equipment, if needed) during simple cycle development, synthesized duty cycle development, baseline, and candidate tests for such comparisons. See §5.2 and §5.3 for further discussion.

4.1. NONROAD EQUIPMENT SELECTION

The nonroad equipment selected for testing should be "representative" of the population of interest to each test campaign. This site-specific protocol should discuss the features and criteria which determine if the selected equipment is representative. Equipment age, fleet purchasing practice, time since the last major overhaul, state of repair, or other considerations may all affect the population of interest and the resulting selection. This protocol should therefore provide detailed data about the selected piece.

Describe how the selected nonroad equipment is representative of the population of interest: ___________

____

____

Test personnel will use the generic protocol, Appendix B1, "Nonroad Equipment Information" to acquire nonroad equipment information prior to testing. This will ensure that the selected machines truly represent the host site fleet. Information to be gathered includes:

- time since the last major overhaul
- state of repair
- maintenance history
- major modifications

4.2. CONTROL STRATEGY SELECTION

This section discusses the control strategy selection process, with reference to Table 4-1 above. Control strategy implementation must be feasible for the selected piece of nonroad equipment. Installation of some control strategies will not be feasible on some types of equipment or at certain host sites due to exhaust temperature profiles, flow rates, physical configuration, or other factors. Fill out and attach Appendices B2, "Control Strategy Information" and B3, "Control Strategy Cost Information" from the generic protocol. At the conclusion of testing, fill out and attach the generic protocol Appendix B4, "Control Strategy User's Interview".

4.3. HOST SITE SELECTION

This section discusses host site selection. Host site selection is crucial to the success of any test campaign executed under this protocol. Test personnel are responsible for ensuring that all parties are aware of their roles, responsibilities, and resource requirements. Fill out and attach Appendix B5, "Host Site Information" from the generic protocol.

For planning purposes, Table 4-2 shows major test tasks, estimated personnel, equipment out-of-service, and other times, other required resources, and responsibilities. Check those that apply to this test campaign and enter the appropriate information. Responsible parties in Table 4-2 are "H" for host site, "T" for test organization, and "O" for other parties such as the control device vendor. Describe the responsible parties below and provide names and phone numbers in §9.0.

"H": ______________________________

"T": ______________________________

"O": ______________________________

Table 4-2. Test Tasks, Resources, and Responsibilities

✓ if Req'd	Description	Responsible Party(s)
	Instrument, sensor, and datalogger installation for duty cycle development, in-use observations (test organization will usually supply sensors; installation with help from host site maintenance technicians)	
	Site coordination for work / pit location, test material acquisition, handling, etc. (support equipment and operators may be needed, depending on duty cycle design)	
	Dispatch, including operator assignment	
	Simple cycle development	
	Synthesized duty cycle development	
	Nonroad equipment operator labor during duty cycle development and test runs	
	In-use operations observations	
	Control strategy acquisition and installation	
	Control strategy training	
	Control strategy certification of proper operations	
	PEMS installation and integration including storage battery or generator power supply (PEMS supplied by test organization; site maintenance technicians may be needed to help fabricate and install brackets, hold-downs, enclosures, and other accessory equipment)	
	ISS installation and integration, including generator power supply (ISS supplied by test organization; site maintenance technicians may be needed to help fabricate and install brackets, hold-downs, enclosures, and other accessory equipment)	
	Baseline control strategy test runs	
	Candidate control strategy test runs	
	In-use evaluation test runs	
	Initial extended interval test runs	
	Final extended interval test runs	
	PEMS, ISS, and other equipment / sensor removal	
	Control strategy removal and disposition	

Table 4-2. Test Tasks, Resources, and Responsibilities		
✓ if Req'd	Description	Responsible Party(s)
	Fuel storage and inventory control	
	Fuel acquisition	

Describe the "other" responsible parties for Table 4-1 tasks. Provide names and phone numbers in §9.0.

____

____

5.0 DUTY CYCLES

Table 5-1 lists parameters that may be monitored and logged during duty cycle development, cycle criteria definition, duty cycle validation, in-use evaluations, and test runs. Check all boxes applicable to this test and record sensor descriptions, manufacturers, models, ranges, and accuracy specifications in §6.6 of this site-specific protocol.

Table 5-1. Parameters to be Monitored and Logged	
ECM - Equipped Engines	**Mechanically - Controlled Engines**
☐ Percent load	☐ RPM
☐ RPM	☐ Turbocharger outlet temperature (T_{turb}) or ☐ exhaust gas (T_{exh}) outlet temperature
☐ Turbocharger boost pressure	☐ Exhaust gas flow surrogate, (sqrt ΔP) high
☐ Exhaust gas temperature (optional)	☐ Exhaust gas flow surrogate, (sqrt ΔP) low
☐ Net brake torque (optional)	☐ Fuel supply flow rate (optional)
☐ Fuel consumption (optional)	☐ Fuel return flow rate[a] (optional)
☐ Other (describe below)	☐ Other (describe below)
[a]Fuel consumption is the difference between fuel supply and return flow rates on diesel engines.	

Describe other monitored and logged parameters such as injector rack position (diesel engines), throttle position (gasoline engines), hydraulic fluid pressure and flow rates, etc.: ____________________________

____

____

5.1. HOST SITE OPERATIONS EVALUATION

Describe host site operations (functions, materials handled, process rates, etc.):______________________

____

____

Describe the selected nonroad equipment's functions, duties, typical in-use maneuvers, events, or duty cycles:

____

____

____

Duty cycles to be run in this test: Simple ☐ Synthesized ☐ In-Use ☐

5.2. SIMPLE CYCLE DEVELOPMENT (IF APPLICABLE)

Appendix B6, "Simple Cycle Development and Test Run Instructions" from the generic protocol provides instructions for developing the simple cycle and performing test runs.

IMPORTANT:
Good test results depend on minimizing operator variability. It is therefore essential that the same operator run the nonroad equipment during simple cycle development, baseline, and candidate test runs for a particular ECT / nonroad equipment combination. Some simple cycles may require support equipment, such as trucks to move material, dozers to groom piles, etc. It is essential that those operators also be the same during simple cycle development, baseline, and candidate testing.

Host site managers, dispatchers, operators, and test personnel should discuss the selected equipment's most-used functions and maneuvers, and then define typical events, including idling and shutdowns. Event definitions may consist of a single action (simple event) or multiple actions in series (composite event). These events, when pieced together and performed in sequence, should fully describe any observed duty cycle. They will also serve as the components for simple and synthesized duty cycles. Appendix B7, "Duty Cycle Event List" from the generic protocol provides a log form for the event list.

The defined events should then be arranged in a logical sequence and cycle criteria developed by dispatching the nonroad equipment to perform the complete duty cycle. Define the allowable cycle criteria values (see §5.4 below), then record the sequence and cycle criteria in Appendix B8, "Simple and Synthesized Duty Cycle Description, Elapsed Times, and Cycle Criteria" from the generic protocol.

At the end of each test run, enter event elapsed times and the mean value for each cycle criteria in Appendix B9, "Cycle Criteria Worksheet and Test Run Validation". Compare the test run cycle criteria values to those defined in Appendix B8 to validate each test run.

5.3. SYNTHESIZED DUTY CYCLE DEVELOPMENT (IF APPLICABLE)

Appendix B10, “Synthesized Duty Cycle Development and Test Run Instructions” from the generic protocol provides instructions for developing the synthesized duty cycle and performing test runs.

IMPORTANT:
Good test results depend on minimizing operator variability. It is therefore essential that the same operator run the nonroad equipment during synthesized duty cycle development, baseline, and candidate test runs for a particular ECT / nonroad equipment combination. Some duty cycles may require support equipment, such as trucks to move material, dozers to groom piles, etc. It is essential that those operators also be the same during synthesized duty cycle development, baseline, and candidate testing.

Describe any specialized material handling, work locations, etc.:________________________________
____

5.3.1. In-Use Operations Logging

Record observations and event descriptions as they occur during three normal in-use operations periods in Appendix B11, “In-Use Operations Observations” from the generic protocol. Log the engine parameters specified in Table 5-1 of this site-specific protocol once per second (1 Hz).

5.3.2. Operations Analysis

Define typical events, including idling and shutdowns. Event definitions may consist of a single action (simple event) or multiple actions in series (composite event). These events, when pieced together and performed in sequence, should fully describe any observed duty cycle. Appendix B7, “Duty Cycle Event List” from the generic protocol provides a log form for the event list.

Analyze the Appendix B7 events from each of the three observation periods on separate log forms in Appendix B12, “In-Use Operations Analysis” from the generic protocol.

Aggregate the data from all three of the B12 analysis forms into Appendices B13, “In-Use Operations Summary” and B14 “In-Use Operations Descriptive Statistics”.

5.3.3. <u>Design Synthesized Duty Cycle</u>

Use Appendices B13 and B14 to arrange the events in a logical sequence. List them in sequence in Appendix B8, "Simple and Synthesized Duty Cycle Description, Elapsed Times, and Cycle Criteria from the generic protocol.

5.3.4. <u>Validate Synthesized Duty Cycle</u>

Once developed, test personnel will dispatch the nonroad equipment to perform the synthesized duty cycle while logging the parameters described in Table 5-1. Analysts should compare the resulting synthesized duty cycle data with each of the three operations periods logged according to §5.3.1 above and will refine the duty cycle if necessary. The comparison tools are:

<u>Descriptive Statistics:</u> Calculate mean and σ_{n-1} for appropriate logged parameters and elapsed time for each event should be within ± 5.0 percent of that seen during each normal operations logging period for that event.

<u>Wilcoxon Rank-Sum Test:</u> Appendix C from the generic protocol provides the procedures, and analysts should apply the test to each of the logged parameters.

If the descriptive statistics and Wilcoxon Rank-sum test indicate that the duty cycle is a valid representation of the in-use operations, analysts will then develop the appropriate cycle criteria (see §5.4 below) and enter them in the Appendix B8 form discussed in §5.3.3 above.

At the end of each test run, enter event elapsed times and the mean value for each cycle criteria in Appendix B9, "Cycle Criteria Worksheet and Test Run Validation" from the generic protocol.

5.4. CYCLE CRITERIA

Example cycle criteria for ECM - controlled engines are:

- RPM multiplied by brake torque
- percent load

Example cycle criteria for mechanically - controlled engines are:

- RPM multiplied by a PEMS exhaust gas flow rate signal or a surrogate (such as $\sqrt{\Delta P}$ as measured by a fixed pitot tube)
- RPM multiplied by T_{turb} or T_{out}

Describe the cycle criteria or cite those from an existing duty cycle which will be used for this test:

Criteria_1: ________________________________

Criteria_2: ________________________________

Other: ____________________________________

5.5. IN-USE DUTY CYCLES (IF APPLICABLE)

Describe the in-use duty cycle (processes, rates, materials handled, typical duties etc.):

____

____

____

Shift length: ________ Start times: _______________ End times: ______________

Breaks (fueling, meals, etc; describe): ____

____

Typical number of shutdowns / startups per shift: _________ Estimated idling time per shift: _______

Will equipment be dispatched: cold start ☐ warm start ☐

Describe procedures and time intervals for PEMS operator rendezvous, periodic zero and span checks, and PEMS battery change out (if needed): ____

____

6.0 TEST PROCEDURES

This section discusses preparation and step-by-step procedures for each type of test. The concluding subsection provides the required instrument and analyzer specifications. A test campaign may require consideration of any or all of the concepts.

6.1. PREPARATION

Prior to testing, maintenance personnel will ensure that the selected nonroad equipment is operating properly. A standard preventive maintenance procedure will be utilized to evaluate and document the nonroad equipment condition prior to testing. The equipment configuration should be as consistent as is possible for all test runs. Prior to testing, test personnel will record the following parameters in the generic protocol Appendix B15, "Test Run Record":

- inlet air restriction
- exhaust gas restriction
- control setting (on, off, or automatic) for the major parasitic loads (lights, air-conditioning, heater, fan clutch)

The selected nonroad equipment may have additional parasitic loads, such as a continuously-operating hydraulic pump / motor combination, which should be set to operate consistently during all test runs. Describe such other parasitic loads and their control settings here. ________________________________

____

Example parasitic loads and their control settings for simple cycle test runs are:

- communications (radio) system -- on
- cab heater -- off
- air conditioning -- off
- headlights -- on

6.1.1. Control Strategy Preparation

The control strategy must be installed and degreened according to manufacturer specifications (typically 25 to 125 hours) prior to testing. Manufacturers must also certify proper operation of the control strategy and nonroad equipment prior to testing.

6.1.2. Test Fuel

Fuel to be used in the test: nonroad diesel ☐ current specification on-highway diesel ☐
ultra-low sulfur diesel ☐ biodiesel blends ☐ gasoline ☐
diesel fuel / water emulsions ☐ diesel fuel with additive ☐

Specify biodiesel blend, water emulsion type and concentration, additives, etc.: ______________________

____

____

The host site and fuel distributor will supply fuel for all testing from a common lot. A fuel analysis sheet for the specific lot will be provided. Contact information for the fuel supplier appears in §9.0.

6.1.3. PEMS Integration (If Applicable)

EPA guidance states that PEMS may obtain on-board power up to 1.0 percent of the machine's nominal horsepower capacity. As an example, the Horiba OBS-2200 requires approximately 800 watts, maximum, of 24-volt direct current (VDC) power. This means that any nonroad equipment larger than 110 horsepower with a 24-volt electrical system is large enough to power this PEMS. 12-volt systems or smaller machines will require temporary installation of a generator or storage batteries.

List sizes and weights of PEMS equipment and accessories. Include schematic diagrams as needed, per the following example:

Horiba OBS-2200 PEMS
Required brackets, hangers, or racks must accommodate:

- OBS-2200 enclosure, 27.5" x 36.75" x 23.5" (l x d x h), approximately 100 lb
- gas cylinder rack, 23" x 8.5" x 23" (l x d x h), approximately 85 lb
- generator (if needed), 24" x 20" x 18" (l x d x h), approximately 80 lb
- storage batteries (if needed), 13" x 7" x 10", approximately 65 lb each (2 required)

The PEMS will employ exhaust pipe adaptors to determine exhaust gas flow rates. List the sizes required for this test:

____

If exhaust pipe adaptor is unavailable, specify the strategy that will be used to acquire real-time exhaust gas or intake air flow: ☐Fixed pitot for $\sqrt{\Delta P}$ and T_{out} ☐laminar flow element (LFE), size: __________
☐ECM ☐Other (describe and justify)____

____

List estimates for the following, as required for PEMS installation:

- Labor: ____
- Materials: ____________________________________

Provide a schematic of the required sampling ports and their locations. Figure 6-1 is an example. Figure 6-2 provides details. These examples are for upstream and downstream sampling with a PEMS, an ISS, and an auxiliary "ETaPS" TPM instrument.

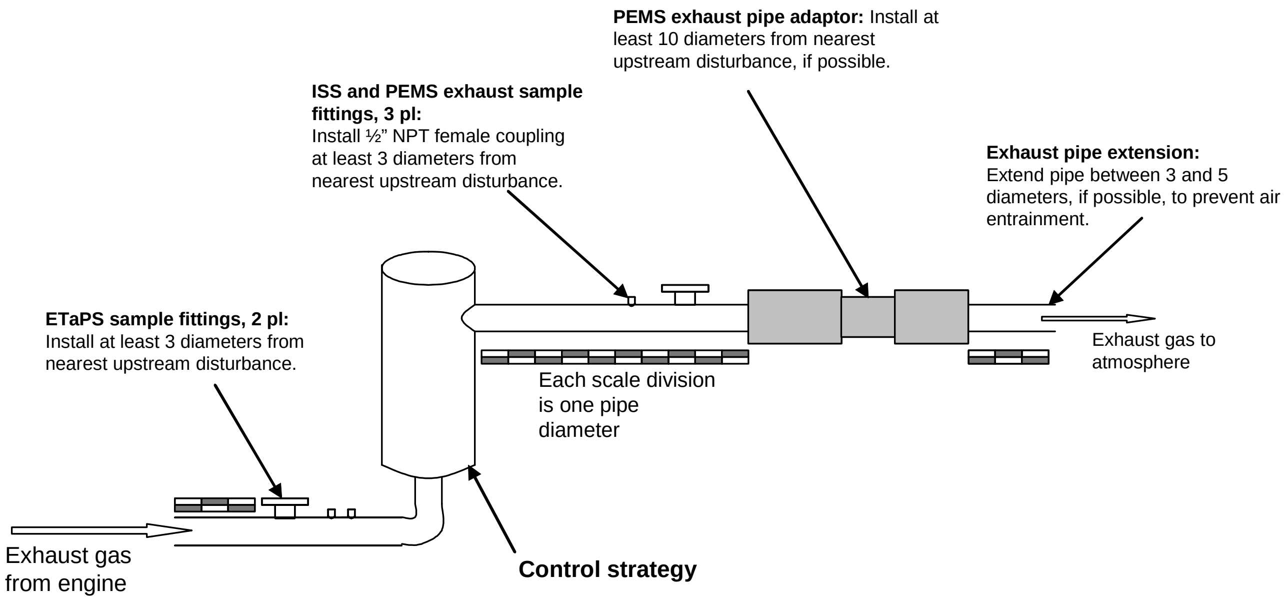

Figure 6-1. Sample Port Location Example

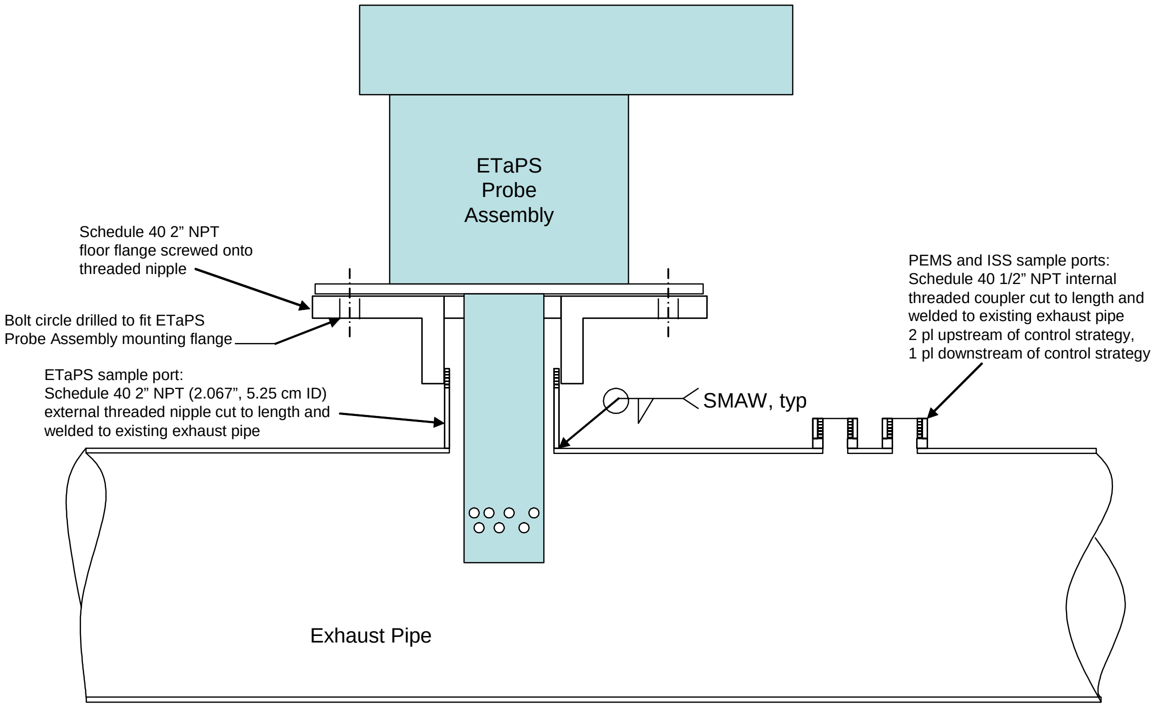

Figure 6-2. Sample Port Details Example

6.1.4. <u>ISS Integration (if applicable)</u>

List sizes and weights of PEMS equipment and accessories per the following example. Include schematic diagrams as needed. Describe any custom designs or installation requirements for the ISS:

____

____

<u>Environment Canada DOES2 ISS Example:</u>

Required brackets, hangers, or racks must accommodate:

- DOES2 enclosure, 25 x 15 x 14 (l x d x h), approximately 80 lb
- pump box, 14 x 14 x 20 (l x d x h), approximately 60 lb
- generator, 36 x 20 x 20 (l x d x h), approximately 200 lb
- laminar flow element (LFE), size varies

Test personnel will plan for the laminar flow element (LFE) installation, if used, onto the engine's intake air system with the appropriate brackets, elbows, and adaptors. Figure 6-3 shows an example installation.

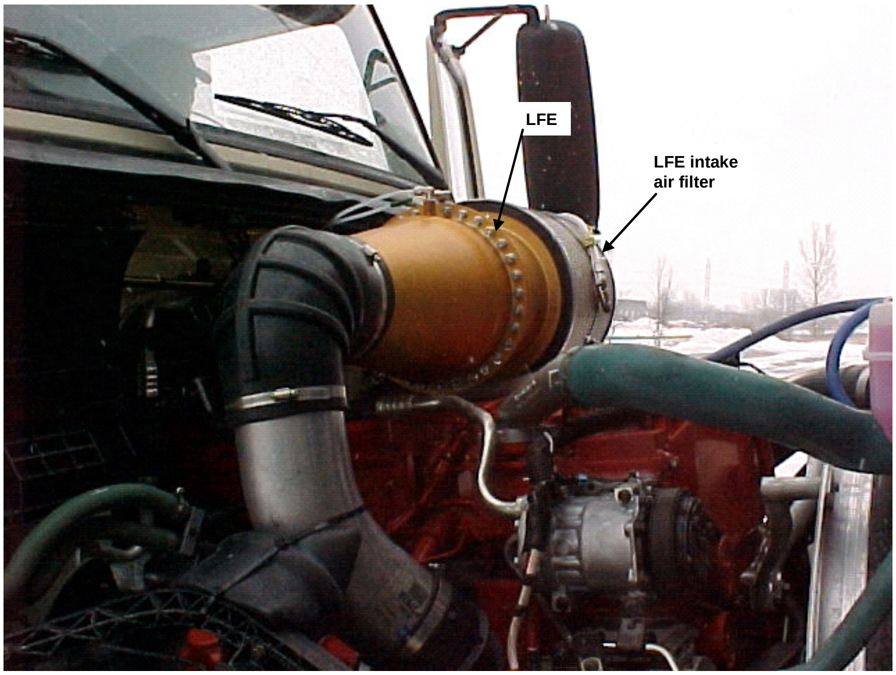

Figure 6-3. LFE Installation Example

If an LFE is not applicable, specify the strategy that will be used to acquire intake air or exhaust gas flow rate:

☐Fixed pitot for $\sqrt{\Delta P}$ and T_{intake} ☐ECM ☐Other (describe and justify): ______________________

____

____

6.2. CONTROL STRATEGY PERFORMANCE TESTS (IF APPLICABLE)

Control strategy performance tests will consist of at least three baseline and three candidate test runs performed under simple or synthesized duty cycles. Test personnel may perform more test runs up to a maximum of six each in order to:

- show a statistically significant difference between the baseline and candidate conditions
- refine the confidence interval on the difference

Copy the step-by-step test procedure(s) from §6.2.1 or §6.2.2 of the generic protocol for PEMS or ISS tests, respectively. Edit the procedure as needed to reflect the actual sequence to be used during test runs.

6.3. IN-USE EVALUATIONS (IF APPLICABLE)

In-use evaluations will consist of monitoring under in-use duty cycles and will allow emissions assessments under real world conditions.

Copy the step-by-step test procedure from §6.3 of the generic protocol. Edit the procedure as needed.

6.4. EXTENDED INTERVAL TESTS (IF APPLICABLE)

Extended interval tests are intended to assess nonroad equipment or control strategy performance trends. They consist of a series of initial PEMS test runs followed by an extended interval of normal in-use service, typically at least 6 months. Tests conclude with a series of final PEMS test runs.

Ambient temperatures should be as close as possible between the initial and final test series. Explain how this issue will be addressed, such as selection of seasons, time of day, monitoring of meteorological conditions and comparisons to previous work prior to authorizing a test run, or other procedures:

____

____

____

Copy step-by-step the procedure from §6.4 of the generic protocol. Edit the procedure as needed.

6.5. EMISSIONS METHOD COMPARISONS (IF APPLICABLE)

Copy the step-by-step procedure from §6.5 of the generic protocol. This procedure outlines a comparison between a PEMS and ISS. Edit the procedure as needed to reflect the actual emissions methods which will be compared.

6.6. INSTRUMENT SPECIFICATIONS, CALIBRATION, AND PERFORMANCE CHECKS

The emissions and performance determinations described in this protocol require numerous contributing measurements, sensors, instruments, analytical procedures, and dataloggers. This section provides general specifications which, if met, will help ensure repeatability within a test campaign and comparability with other programs.

Table 6-1 lists the PEMS and ISS accuracy specifications recommended for use with this protocol. Enter the manufacturer and model of the measurement system or sensor and check the appropriate boxes to indicate if a measurement system will be used and if the accuracy specification was met.

Table 6-1. PEMS and ISS Specifications

Parameter	√ if used	Logging Frequency	Accuracy	Repeatability	Manufacturer	Model(s)	Meets Spec.	Date Verified
Engine speed	☐	1 Hz	5.0 % of point or 1.0 % of max[a]	2.0 % of point or 1.0 % of max			☐	
Torque estimator, BSFC	☐	1 Hz	8.0 % of point or 5.0 % of max	2.0 % of point or 1.0 % of max[b]			☐	
Pressure transducers	☐	1 Hz	5.0 % of point or 5.0 % of max	2.0 % of point or 0.5 % of max			☐	
Ambient barometric pressure	☐	6 second	0.07 "Hg (250 Pa)	0.06 "Hg (200 Pa)			☐	
Temperature transducers (T_{turb}, T_{out}, T_{amb})	☐	1 Hz	1.0 % of point or 5.0 ^oC	0.5 % of point or 2.0 ^oC			☐	
Dewpoint / RH[c] (if used)	☐	6 second	5.0 ^oF	2.0 ^oF			☐	
Exhaust flow	☐	1 Hz	5.0 % of point or 3.0 % of max	2.0 % of point			☐	
Instrumental analyzer concentration	☐	1 Hz	4.0 % of point	2.0 % of point			☐	
Fuel flow (if used)[d]	☐	1 Hz	2.0 % of point or 1.5 % of max	1.0 % of point or 0.75 % of max			☐	
ISS Only								
Instrumental analyzer concentration	☐	1 Hz	2.0 % of point	1.0 % of point			☐	

Table 6-1. PEMS and ISS Specifications								
Parameter	**√ if used**	**Logging Frequency**	**Accuracy**	**Repeatability**	**Manufacturer**	**Model(s)**	**Meets Spec.**	**Date Verified**
Gravimetric TPM balance	☐	n/a[e]	0.1 % (see §1065.790)	0.5 µg			☐	
Main flow rate	☐	2 Hz	1.0 % FS[f]	n/a			☐	
Dilution air flow rate	☐						☐	
Sample flow rate	☐						☐	
Differential pressure (if used)	☐						☐	

[a]"max" refers to the maximum value expected during testing.
[b]Quantification of ECM torque estimator accuracy may be difficult because §1065.915(b)(5)(i) regulations requiring this on nonroad engines are not effective until 2010.
[c]relative humidity (RH)
[d]This specification refers to fuel consumption by: 1) net gravimetric determinations from removable day tanks, 2) net of diesel engine fuel supply and return mass flows, 3) volumetric makeup flow into a closed diesel engine fuel circulation loop, or 4) other methods of direct fuel consumption measurement. Note that the supply and return flow meters must be extremely accurate (generally better than ± 0.2 %) to achieve this specification for differential flow at low fuel consumption rates.
[e]Not applicable (n/a)
[f]Full scale (FS)

Table 6-2 lists recommended calibration intervals and performance checks. Note that test personnel must perform some performance checks, such as leak checks, analyzer zero and spans, etc. before and after each test run while others may be performed either in the field or laboratory. Table 6-4 in the generic protocol provides specific references to step-by-step calibration procedures.

Table 6-2. Recommended Calibrations and Performance Checks				
System or Parameter	**Description / Procedure**	**Frequency**	**Meets Spec.?**	**Date Completed**
Engine speed	11-point linearity check	At purchase / installation	☐	
Pressure transducers	NIST-traceable[a] calibration	Within 12 months	☐	
Temperature transducers (T_{turb}, T_{out}, T_{amb})			☐	
Dewpoint / RH			☐	
Exhaust flow			☐	
All instrumental analyzers	11-point linearity check	Within 12 months	☐	
CO_2 (NDIR detectors)[b]	H_2O interference	Within 12 months	☐	
CO (NDIR detectors)	CO_2, H_2O interference		☐	
Hydrocarbons (FID)[c]	Propane (C_3H_8) calibration		☐	
	FID response optimization		☐	
	C_3H_8 / methyl radical (CH_3) response factor determination		☐	
	C_3H_8 / CH_3 response factor		☐	

Table 6-2. Recommended Calibrations and Performance Checks				
System or Parameter	**Description / Procedure**	**Frequency**	**Meets Spec.?**	**Date Completed**
	check			
	Oxygen (O_2) interference check		☐	
NO_X	CO_2 and H_2O quench (CLD)[d]		☐	
	Non-methane hydrocarbons (NMHC) and H_2O interference (NDUV detectors)[e]		☐	
	Ammonia interference and NO_2 response (zirconium dioxide detectors)		☐	
	Chiller NO_2 penetration (PEMS with chillers for sample moisture removal)		☐	
	NO_2 to NO converter efficiency	Within 6 months or immediately prior to departure for field tests	☐	
PEMS	Comparison against laboratory CVS system	At purchase / installation; after major modifications	☐	
	Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of point)	Before and after each test run or as needed during in-use evaluations	Refer to generic protocol Appendix B15, "Test Run Record"	
	Perform analyzer drift check (≤ ± 4.0 % of cal gas point)	After each test run		
	NMHC contamination check (≤ 2.0 % of expected conc. or ≤ 2 ppmv)	Once per test day		
Exhaust gas or intake air flow measurement device	Differential pressure line leak check (ΔP stable for 15 seconds at 3 "H_2O)	Once per test day		
ISS	Comparison against laboratory CVS system	At purchase / installation; after major modifications	☐	
	Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of point)	Before and after each test run	Refer to generic protocol Appendix B15, "Test Run Record"	
	Inspect sample lines, filter housings, and sample bags for visible moisture (none is allowed)	After each test run		
	Perform analyzer drift check (≤ ± 4.0 % of cal gas point)			
	NMHC background check and dilution tunnel blank	Once per test day		
	TPM background check and dilution tunnel blank			
	Dilution tunnel leak check			
	Sample bag leak check (< 0.5 % of normal system flow rate)			
	TPM filter face temperature (not to exceed 47 ^oC or 117 ^oF)	continuously during sampling		

Table 6-2. Recommended Calibrations and Performance Checks				
System or Parameter	**Description / Procedure**	**Frequency**	**Meets Spec.?**	**Date Completed**
Fuel flow	11-point linearity check	At purchase (coriolis meters only); within 6 months or immediately prior to departure for field tests (turbine or gear meters)	☐	
TPM gravimetric balance	NIST-traceable calibration	Within 12 months	☐	
	Reference sample weights	Within 12 hours of filter weighings	☐	
ISS main, dilution, and sample flow rates	11-point linearity check	Within 12 months	☐	
[a]National Institutes of Standards and Technology (NIST) [b]non-dispersive infrared (NDIR) [c]flame ionization detector (FID) [d]chemilumenescence detector (CLD) [e]non-dispersive ultra violet (NDUV)				

List sensors used for duty cycle development, mechanically-controlled engine parameters (such as exhaust gas flow rate surrogate sensors, which include a suitable pitot, ΔP sensors, and thermocouple) and other sensors to be used during this test campaign.

Table 6-3. Duty Cycle, Engine, and Auxiliary Sensors					
Description	**Manufacturer**	**Model**	**ID or Serial Number**	**Range**	**Accuracy**

7.0 DATA QUALITY AND ANALYSIS

This section outlines general data analysis procedures for each type of test and data quality requirements for all tests. Appendix C from the generic protocol supplements the discussion with statistical concepts and equations.

7.1. CONTROL STRATEGY PERFORMANCE TESTS

Check the boxes in the following subsections to indicate the analyses which will be performed for this test campaign.

7.1.1. Emissions Reductions and Fuel Consumption Changes for Simple and Synthesized Duty Cycles

The following calculations will be made for each parameter (CO, CO_2, NO_x, THC, TPM, and fuel consumption, as applicable). Refer to Appendix C from the generic protocol for procedures and attach documentation of calculations to the test report.

- ☐ mass emissions (g/run) mean and σ_{n-1} for all baseline and candidate test runs
- ☐ Fuel consumption rate (gal/run, gal/hr)
  - ☐ carbon balance method (from PEMS data)
  - ☐ gravimetric (day tank weight change)
  - ☐ mass-flow fuel meters
  - ☐ volumetric-flow fuel meters
- ☐ fuel-specific emission rate (g/gal) mean and σ_{n-1} for all baseline and candidate test runs
- ☐ brake-specific emission rate mean (g/bhp-h) and σ_{n-1} for all baseline and candidate test runs, if torque or horsepower data are available from an ECM
- ☐ the difference between the baseline and candidate mean results
- ☐ the statistical significance of the difference
- ☐ the 95-percent confidence interval on the difference

7.1.2. Emissions Reductions and Fuel Consumption Changes for In-use Duty Cycles

The following calculations will be made for each parameter (CO, CO_2, NO_x, THC, TPM, and fuel consumption, as applicable). Refer to Appendix C from the generic protocol for procedures and attach documentation of calculations to the test report.

- ☐ mass emissions (g/hr, g/event) mean and σ_{n-1} for each test period and individual events
- ☐ Fuel consumption rate (gal/event, gal/hr)
  - ☐ carbon balance method (from PEMS data)
  - ☐ gravimetric (day tank weight change)
  - ☐ mass-flow fuel meters
  - ☐ volumetric-flow fuel meters
- ☐ fuel-specific emission rate (g/gal) mean and σ_{n-1} for each test period and individual events
- ☐ brake-specific emission rate mean (g/bhp-h) and σ_{n-1} for all baseline and candidate test runs, if torque or horsepower data are available from an ECM
- ☐ the difference between the baseline and candidate mean results for each test period and for individual comparable events

- ☐ the statistical significance of the difference
- ☐ the 95-percent confidence interval on the difference

7.1.3. Control Strategy Cost Analysis

Analysis of control strategy costs consists primarily of summing and reporting the data collected in Appendix B3, "Control Strategy Cost Information" of the generic protocol. Costs should be separated into the following general categories:

- ☐ capital purchases
- ☐ shop-made modifications, specialty items
- ☐ downtime (or demurrage), installation, and training labor
- ☐ operating materials, supplies, and reagents
- ☐ operating labor

7.1.4. Control Strategy Engine and Operational Performance Impact Analysis

The following methods will be used to assess control strategy performance:

☐ ECM data is available: calculate the difference between the baseline and candidate horsepower and fuel consumption, normalized to brake horsepower

☐ ECM data is suspect or not available: calculate the difference in mean fuel consumption between baseline and candidate tests as observed during simple or synthesized duty cycles

☐ In-Use duty cycles: fuel consumption difference between baseline and candidate conditions over a consistent time period. Indicate time period of comparison (per shift, per day, etc.) _______________

Fuel consumption changes: ☐ brake-specific ☐ per shift ☐ per hour
☐ other (describe): duty cycle-specific

Test personnel will gather other control strategy impact information as described in Appendix B4, "Control Strategy User's Interview" from the generic protocol.

7.2. IN-USE EMISSIONS TESTS

This section discusses application of basic descriptive statistics, but analysts should be open to other possibilities depending on the circumstances of a particular test campaign. Appendix C and §7.2 from the generic protocol provides additional analytical concepts such as methods for identifying and comparing in-use events.

The following descriptive statistics should be generally useful to describe the events which occur within an in-use emission test or to describe the test as a whole. Check those applicable to this test.

☐ In-use overall mean, σ_{n-1}
☐ individual event means, σ_{n-1}
☐ Frequency distributions

7.3. EXTENDED INTERVAL TESTS

Analysts can consider extended interval tests as a baseline / candidate test series, similar to a control strategy evaluation. The difference between the mean final and initial test runs will serve as the performance metric. Analysts should calculate and report the difference according to the procedures in §7.1 above and Appendix C of the generic protocol.

7.4. EMISSIONS MEASUREMENT METHOD COMPARISONS

Analysts should, for each parameter (CO, CO_2, NO_X, THC, and fuel consumption, as applicable):

☐ report the ISS mass emissions (g/run) for each test run
☐ calculate the mass emissions mean and σ_{n-1} for all test runs
☐ calculate the PEMS mass emissions
☐ calculate the mass emissions mean and σ_{n-1} for all PEMS test runs
☐ calculate the difference of the ISS and PEMS mean results
☐ evaluate the statistical significance of the difference
☐ calculate the 95-percent confidence interval on the difference.

See Appendix C of the generic protocol for the appropriate statistical analysis procedures.

7.5. DATA QUALITY

All test campaigns should meet the following qualitative data quality objective (DQO):

Sensors, measurements, step-by-step test methods, and the resulting determinations will meet or exceed this protocol's and reference method specifications as outlined in §5.0 through §6.6.

List any site-specific DQOs here: ____

____

____

8.0 REPORTS

Reported results, data summaries, and statistical analyses depend on the individual test campaign. Table 8-1 provides a general list of items to be included in each type of report. Check all items applicable to this test.

Table 8-1. Reported Results List

Test Type / **Description**	Control strategy performance evaluation	In-use emissions tests	Extended interval tests	Emissions measurement method comparisons
Emission rates	☐	☐	☐	☐
Fuel consumption	☐	☐	☐	☐
Difference between baseline and candidate emissions and fuel consumption	☐	☐	☐	☐
Control strategy costs	☐	☐	☐	☐
Control strategy performance impacts	☐	☐	☐	☐
Simple or synthesized duty cycle specifications	☐	☐	☐	☐
In-use duty cycle descriptive statistics	☐	☐	☐	☐

Indicate where all data files related to this test will be kept.

Electronic files: ____

Hard copy files: ____

Specify the person(s) responsible for managing the data: _________________________________

Specify the person(s) responsible for performing data calculations: ___________________________

9.0 CONTACTS

<u>Site-specific protocol author</u>

Contact Name:

Company:

Phone: Fax:

<u>Field team leader for this test:</u>

Contact Name:

Company:

Phone:

<u>Fuel distributor:</u>

Contact Name:

Company:

Phone:

<u>Host Site:</u>

Contact Name:

Company:

Phone:

<u>ISS Provider</u>

Contact Name:

Company:

Phone:

<u>Control Strategy Provider(s)</u>

Contact Name:

Company:

Phone:

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APPENDIX A-1
SAMPLE SITE-SPECIFIC PROTOCOL

The preceding Site-Specific Protocol Outline (Appendix A) formed the initial template for the following sample site-specific protocol. Comparisons between the two documents show how the authors adapted the template to suit the planned tests, selected nonroad equipment, control strategies, adminstrative structures, responsibilities, and manpower.

NYSERDA CLEAN DIESEL TECHNOLOGY:
NON-ROAD FIELD DEMONSTRATION PROGRAM

Site Specific Test Plan
For
In-Use Evaluation of Diesel Emission Control Technologies at the New York City Department of Sanitation

Prepared for:

THE NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
Albany, NY

Barry Liebowitz, P.E.
Senior Project Manager

Prepared by:

SOUTHERN RESEARCH INSTITUTE
Morrisville, NC

Tim A. Hansen
Project Manager

Agreement Number 8958
22 September, 2006

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Site Specific Test Plan Number One
For
In-Use Evaluation of Diesel Emission Control Technologies at the New York City Department of Sanitation

1.0 INTRODUCTION

This site-specific protocol addresses individual test details for the evaluation of emission control technologies (ECT) on non-road diesel construction equipment operated by the New York City Department of Sanitation (DSNY). The site-specific test procedures and details are based on the *Generic In-Use Test Protocol for Nonroad Equipment* (generic protocol) developed by Southern Research Institute for New York State Energy Research and Development Authority (NYSERDA).

This site-specific protocol applies to the first three ECT evaluations to be performed under NYSERDA's Clean Diesel Technology Non-Road Field Demonstration Program. NYSERDA is funding the demonstrations, with equipment for testing and support provided by DSNY, and ECTs provided by several vendors at reduced or no cost.

The goals of this test program are to:

- demonstrate and evaluate the feasibility and performance of commercially available emission control technologies for reduction of particulate matter (PM) and oxides of nitrogen (NOx) emissions from non-road diesel equipment using in-use field testing approaches
- evaluate the performance of diesel emission control technologies (ECTs) on several pieces of non-road equipment operated by the DSNY
- evaluate ECT economic impacts, including costs, maintenance, and operations effects
- utilize integrated sampling systems (ISS) and portable emission measurement systems (PEMS) to evaluate emissions upstream and downstream of the control device
- evaluate the correlation between the two emission measurement methods

2.0 APPLICABILITY

This test plan is applicable to equipment owned and operated by the DSNY. Nonroad equipment to be tested will include of the following types of diesel engines:

Equipment powered by: mechanically-controlled engine ☒ engine control module (ECM) ☒

Engine is: naturally aspirated ☐ turbocharged ☒ exhaust gas recirculation-equipped ☐

The following equipment has been identified and provided by DSNY for installation of retrofit ECTs and in-use evaluations and testing:

- Rubber Tire Loaders, 100-600 HP

The nonroad equipment design must allow portable emissions monitoring system (PEMS) and integrated sampling system (ISS) installation, along with the required support equipment such as gas cylinders, exhaust pipe adaptors, and storage battery or generator power supply. Sections 6.1.3 and 6.1.4 specify the required mounting adaptors, brackets, shrouds, or other physical modifications.

3.0 SCOPE

This section outlines the scope of the test campaign (Table 3-1) and summarizes the test parameters required for each test type (Table 3-2). In each table, checked boxes indicate applicable tests. See Tables 3-1 and 3-2 in the generic protocol for further details.

Table 3-1. Test Types

Control strategy emissions and fuel consumption performance	☒
In-use evaluations	☒
Extended interval emissions and fuel consumption performance	☐
Emissions method comparisons	☒

Test personnel will evaluate ECT performance under a well-defined simple cycle and in-use duty cycles. Southern Research Institute (Southern) will provide a Horiba OBS-2200 PEMS for the simple cycle and in-use tests. Environment Canada (EC) will deploy their dynamic offroad emissions sampling system (DOES2) ISS in parallel with the PEMS for the simple cycle tests. Realtime TPM concentrations will also be measured using a Dekati electrical tailpipe particulate sensor (ETaPS) if available.

Table 3-2. Measurement Systems and Test Parameters		
Parameter		
Gaseous Emissions	CO	☒
	CO_2	☒
	NO_X	☒
	THC	☒
Particulate Emissions	TPM	☒
Unregulated Emissions	Speciated TPM[a]	☒
	Gaseous emissions[a]	☒
Fuel Consumption	Gravimetric	☐
	Differential mass flow	☐
	Volumetric	☐
	Carbon balance	☒
Control Strategy Cost (generic protocol Appendix B3)		☒
Control Strategy Operating Impacts[b] (generic protocol Appendix B4)		☒
[a]See Table 3-3 for details [b]Data are likely to consist of management and dispatcher business data, anecdotal discussions, etc.		

Table 3-3 specifies additional test methods for unregulated emissions. Checked table entries indicate test methods required for this test series.

Table 3-3. Additional Test Methods				
✓ if Req'd	**ECT Type**	**Analyte**	**Sampling System / Location**	**Method**
	SCR	NH_3	ISS / downstream of SCR	Citric acid-treated filter; ion chromatography analysis
		NH_4 in TPM	ISS / downstream of SCR	extraction of TPM filter; ion chromatography analysis
	PDPF	NO_2	Semtech-D PEMS	Simultaneous NO_X and NO_2 output signals
			Horiba OBS-2200 PEMS	3 test runs with NO_2 converter enabled alternated with 3 test runs with NO_2 converter disabled
✓	All	Elemental carbon to organic carbon (EC / OC) ratio in exhaust	ISS / upstream of ECT	Quartz TPM filter analyzed by "improved" NIOSH Method 5040

4.0 NONROAD EQUIPMENT, CONTROL STRATEGY, AND HOST SITE SELECTION

Table 4-1 lists the nonroad equipment to be tested.

Table 4-1. PEMS and ISS Test Matrix

Equip. Type	Make	Model	MY	Engine Model	bhp	ECT Type	Make	Notes
Loader	Daewoo	Mega 200	2003	DB58TIS	143	DPF - CRT	JMI	Use quartz filters upstream of ECT for EC / OC analysis
	Case	821B	1998	6T-830	190	FTF	Extengine	
	Daewoo	Mega 200	2003	DB58TIS	143	FTF	Nett	
	Case	821B	1998	6T-830	190	DPF	Clean Air Systems	

Special considerations:

- The same operator(s) must be assigned to run the nonroad equipment (and support equipment, if needed) during simple cycle development, baseline, and candidate tests. See §5.2 for further discussion.
- The Case 821 and Daewoo Mega 200 engines are mechanically controlled and will require installation of engine speed (rpm) sensors for duty cycle development.

4.1. NONROAD EQUIPMENT SELECTION

The Daewoo and Case loaders selected for field demonstration are common, representative of the entire rubber tire loader population, and of the DSNY fleet. For example, DSNY operates 70 Daewoo Mega 200 loaders.

Test personnel will use the generic protocol, Appendix B1, "Nonroad Equipment Information" to acquire nonroad equipment information prior to testing. This will ensure that the selected machines truly represent the DSNY fleet. Information to be gathered includes:

- time since the last major overhaul
- state of repair
- maintenance history
- major modifications

4.2. CONTROL STRATEGY SELECTION

Table 4-1 (see §4.0) lists the control strategies to be tested during this campaign. The generic protocol Appendix B2, "Control Strategy Information" and B3, "Control Strategy Cost Information" will be completed for each control strategy prior to field testing. At the conclusion of the campaign, test and site personnel will fill out and attach Appendix B4, "Control Strategy User's Interview".

Additional information regarding control strategy feasibility, selection, and implementation are available in separate documents. ECTs were obtained through an open solicitation of ECT vendors for participation in the testing program. Control technologies were selected based on interest to the program, feasibility, availability, and cost to the program.

Special considerations:
Control devices will be installed on the test equipment prior to testing. Baseline tests will therefore take place upstream of the control device. Candidate tests will take place downstream of the control device.

4.3. HOST SITE SELECTION

Host site selection is crucial to the success of any test campaign. Test personnel are responsible for ensuring that all parties are aware of their roles, responsibilities, and resource requirements. To ensure this, a Participation Agreement has been completed and signed by both the testing agency and host site / equipment operator. Test personnel will complete the generic protocol Appendix B5, "Host Site Information" for details regarding the host site.

For planning purposes, Table 4-2 shows major test tasks and responsibilities. Responsible parties listed below and in Table 4-2 are "H" for host site, "T" for test organization, and "O" for other parties such as the control device vendor. Section 9.0 provides responsible party contact information.

"H": DSNY
"T1": Southern Research Institute
"T2": Environment Canada
"O1": Johnson-Matthey Incorporated
"O2": Nett
"O3": Extengine

Table 4-2. Test Tasks, Resources, and Responsibilities		
✓ if Req'd	Description	Respon-sible Party(s)
✓	Instrument, sensor, and datalogger installation for duty cycle development, in-use observations (test organization will usually supply sensors; installation with help from host site maintenance technicians)	H, T1, T2
✓	Site coordination for work / pit location, test material acquisition, handling, etc. (support equipment and operators may be needed, depending on duty cycle design)	H, T1
✓	Dispatch, including operator assignment	H
✓	Simple cycle development	H, T1
	Synthesized duty cycle development	--
✓	Nonroad equipment operator labor during duty cycle development and test runs	H
✓	In-use operations observations	T1
✓	Control strategy acquisition and installation	H, O2, O3
✓	Control strategy training	H, O1 - O3
✓	Control strategy certification of proper operations	O1 - O3
✓	PEMS installation and integration including storage battery or generator power supply (PEMS supplied by test organization; site maintenance technicians may be needed to help fabricate and install brackets, hold-downs, enclosures, and other accessory equipment)	H, T1
✓	ISS installation and integration, including generator power supply (ISS supplied by test organization; site maintenance technicians may be needed to help fabricate and install brackets, hold-downs, enclosures, and other accessory equipment)	H, T2
✓	Baseline control strategy test runs	H, T1, T2
✓	Candidate control strategy test runs	H, T1, T2
✓	In-use evaluation test runs	H, T1
	Initial extended interval test runs	--
	Final extended interval test runs	--
✓	PEMS, ISS, and other equipment / sensor removal	H, T1, T2
✓	Control strategy removal and disposition (if required)	H, O1 - O3
✓	Fuel storage and inventory control	H, T1
✓	Fuel acquisition	H

5.0 DUTY CYCLES

Table 5-1 lists parameters that will be monitored and logged during duty cycle development, cycle criteria definition, duty cycle validation, in-use evaluations, and test runs. The checked boxes are applicable to this test. Section 6.6 lists sensor descriptions, manufacturers, models, ranges, and accuracy specifications.

Table 5-1. Parameters to be Monitored and Logged	
ECM - Equipped Engines	**Mechanically - Controlled Engines**
☒ Percent load	☒ rpm
☒ RPM	☐ Turbocharger outlet temperature (T_{turb}) or ☒ exhaust gas (T_{exh}) outlet temperature
☐ Turbocharger boost pressure	☐ Exhaust gas flow surrogate, (sqrt ΔP) high
☐ Exhaust gas temperature (optional)	☐ Exhaust gas flow surrogate, (sqrt ΔP) low
☐ Net brake torque (optional)	☐ Fuel supply flow rate (optional)
☐ Fuel consumption (optional)	☐ Fuel return flow rate[a] (optional)
☐ Other (describe below)	☒ Other (describe below)
[a]Fuel consumption is the difference between fuel supply and return flow rates on diesel engines.	

Other monitored and logged parameters include the exhaust gas flow rate, as monitored by the PEMS.

5.1. HOST SITE OPERATIONS EVALUATION

The nonroad equipment selected for this test campaign, its functions, duties, typical in-use maneuvers, events, or duty cycles are:

- Daewoo Mega 200: lot clearing, snow removal
- Case 821B: moving salt/sand, snow removal, and lot clearing

Duty cycles to be run in this test: Simple ☒ Synthesized ☐ In-Use ☒

5.2. SIMPLE CYCLE DEVELOPMENT

The generic protocol Appendix B6, "Simple Cycle Development and Test Run Instructions" provides instructions for developing the simple cycle and performing test runs.

IMPORTANT:
Good test results depend on minimizing operator variability. It is therefore essential that the same operator run the nonroad equipment during simple cycle development, baseline, and candidate test runs for a particular ECT / nonroad equipment combination. Some simple cycles may require support equipment, such as trucks to move material, dozers to groom piles, etc. It is essential that those operators also be the same during simple cycle development, baseline, and candidate testing.

Host site managers, dispatchers, operators, and test personnel will discuss the selected equipment's most-used functions and maneuvers, and then define typical events, including idling and shutdowns. Event definitions may consist of a single action (simple event) or multiple actions in series (composite event). Appendix B7, "Duty Cycle Event List" from the generic protocol provides a log form for the event list.

In-use vehicle operations will be observed for a short duration (1-2 hours). Depending on availability, equipment may also be outfitted with exhaust gas temperature and rpm data logging devices. Observations will be logged, including identification of events and event durations. Such observations will be documented in generic protocol Appendix B7.

The defined events will be arranged in a logical sequence to ensure that representative events are accounted for with durations appropriate to the test period and the observed equipment usage. Once this simple duty cycle is established, cycle criteria will be developed by dispatching the nonroad equipment to perform the complete duty cycle.

Allowable cycle criteria values will be defined in accordance with section §5.4 below, and the sequence and cycle criteria recorded in generic protocol Appendix B8, "Simple and Synthesized Duty Cycle Description, Elapsed Times, and Cycle Criteria".

At the end of each test run, event elapsed times and the mean value for each cycle criteria will be documented in the generic protocol Appendix B9, "Cycle Criteria Worksheet and Test Run Validation". The test run cycle criteria values will be compared to those defined in generic protocol Appendix B8 to validate each test run.

5.3. SYNTHESIZED DUTY CYCLE DEVELOPMENT

Not applicable

5.4. CYCLE CRITERIA

For simplicity, the cycle criteria for this test program will be defined similarly for all engine types (mechanically or electronically controlled). The cycle criteria definitions are:

- Criteria_1: RPM multiplied by exhaust gas flow
- Criteria_2: RPM multiplied by T_{exh}

For a single test run cycle to be valid, these criteria must be within 5 percent of the established cycle criteria developed during the duty cycle development (see §5.2 and generic protocol Appendix B8).

5.5. IN-USE DUTY CYCLES

Equipment will be dispatched into its normal operations for an approximately 4 hour test period. At a minimum, this test phase will be completed with PEMS equipment on board. No prescribed cycles will be utilized in this case. The equipment should be in its normal in-service operation, with no interference in its work, except for allowances to verify PEMS calibrations and make test equipment adjustments or data downloads.

6.0 TEST PROCEDURES

This section discusses preparation and step-by-step procedures for each type of test. The concluding subsection provides the required instrument and analyzer specifications.

6.1. PREPARATION

Prior to testing, maintenance personnel will ensure that the selected nonroad equipment is operating properly. A standard preventive maintenance procedure will be utilized to evaluate and document the nonroad equipment condition prior to testing. The equipment configuration should be as consistent as is possible for all test runs. Prior to testing, test personnel will record the following parameters in the Appendix B15, "Test Run Record":

- inlet air restriction
- exhaust gas restriction
- control setting (on, off, or automatic) for the major parasitic loads (lights, air-conditioning, heater, fan clutch)

The selected nonroad equipment may have additional parasitic loads, such as a continuously-operating hydraulic pump / motor combination, which should be set to operate consistently during all test runs.

Other parasitic loads and their control settings for simple cycle test runs will be:

- communications (radio) system -- on
- cab heater -- off
- air conditioning -- off
- headlights -- on

In-use evaluations will not restrict the use of parasitic loads, as evaluations of real operations are desired.

6.1.1. ECT Preparation

The ECT must be installed, degreened according to manufacturer specifications (typically 25 to 125 hours) prior to testing. Manufacturers must also certify proper operation of the control strategy and nonroad equipment prior to testing.

6.1.2. Test Fuel

Fuel to be used in the test: nonroad diesel ☐ current specification on-highway diesel ☐
ultra-low sulfur diesel ☒ biodiesel blends ☐ gasoline ☐
diesel fuel / water emulsions ☐ diesel fuel with additive ☐

Specify biodiesel blend, water emulsion type and concentration, additives, etc.: Not applicable

Special Considerations: If available, testing should be completed using number 2 ultra-low sulfur diesel (ULSD), but may be completed with number 1 ULSD if necessary. In either case, test fuel must be consistent throughout the test campaign.

The host site and fuel distributor will supply fuel for all testing from a common lot. A fuel analysis sheet for the specific lot will be provided. Attachment 1 provides an example of current fuel specifications.

6.1.3. PEMS Integration

Test personnel will install the PEMS and its power supply with assistance from the host organization. Estimated labor time is four hours for the PEMS integration plus one hour for the generator or battery bank for each piece of nonroad equipment tested.

Required brackets, hangers, or racks must accommodate the following test equipment:

- OBS-2200 enclosure, 27.5" x 36.75" x 23.5" (l x d x h), approximately 100 lb
- gas cylinder rack, 23" x 8.5" x 23" (l x d x h), approximately 85 lb

EPA guidance states that PEMS may obtain on-board power up to 1.0 percent of the machine's nominal horsepower capacity. The Horiba OBS-2200 requires approximately 800 watts, maximum, of 24-volt direct current (VDC) power. This means that any nonroad equipment larger than 110 horsepower with a 24-volt electrical system is large enough to power this PEMS.

The PEMS will employ exhaust pipe adaptors to determine exhaust gas flow rates. Test personnel will determine the required adaptor and boot sizes immediately prior to test instrument installation.

Figure 6-1 is a schematic of the required exhaust sampling port locations.

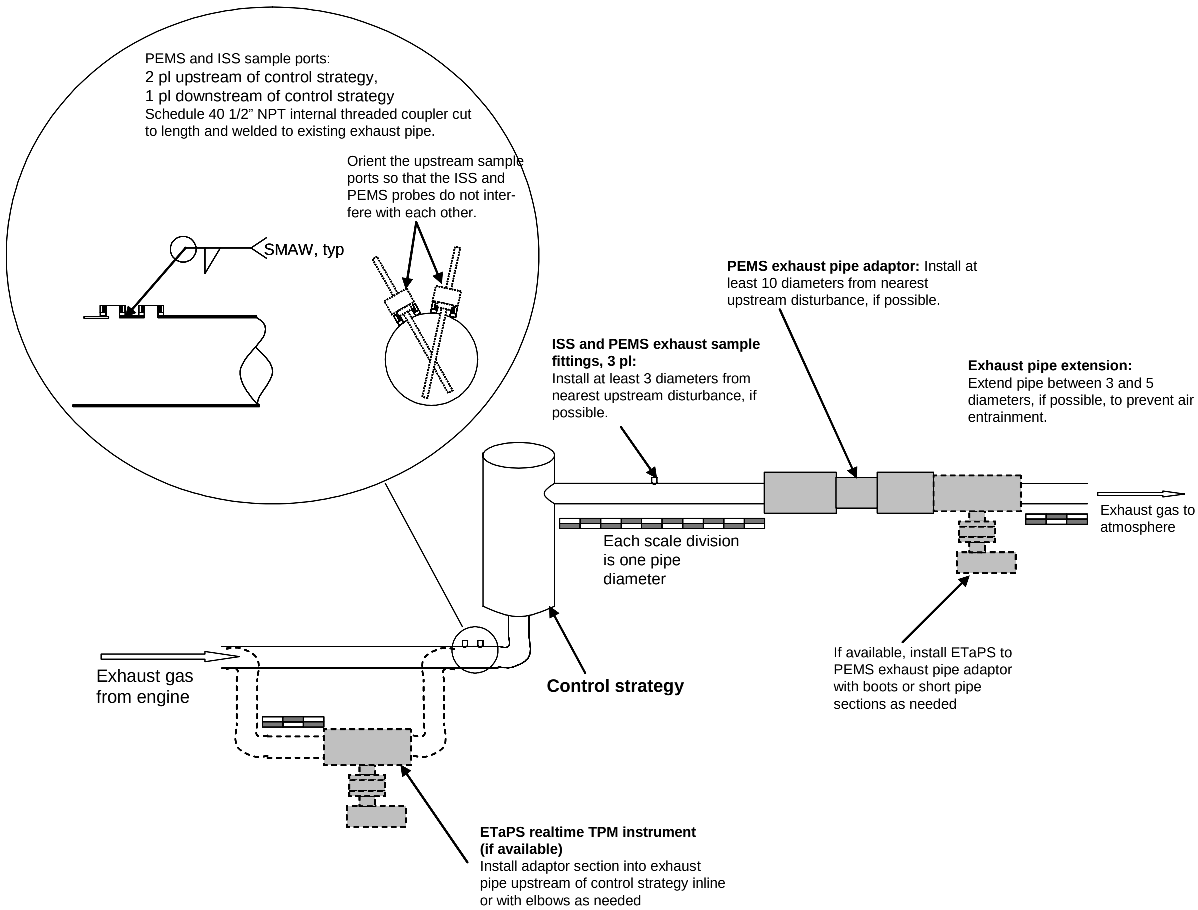

Figure 6-1. Sample Port Locations

6.1.4. <u>ISS Integration</u>

Test personnel will install the ISS and its power supply with assistance from the host organization. Estimated labor time is four hours for the ISS integration plus one hour for the generator.

Required brackets, hangers, or racks must accommodate the following equipment:

- DOES2 enclosure, 25 x 15 x 14 (l x d x h), approximately 80 lb
- pump box, 14 x 14 x 20 (l x d x h), approximately 60 lb
- generator, 36 x 20 x 20 (l x d x h), approximately 200 lb
- laminar flow element (LFE), size varies

Test personnel will install the LFE onto the engine's intake air system with the appropriate brackets, elbows, and adaptors. Figure 6-3 shows a typical installation.

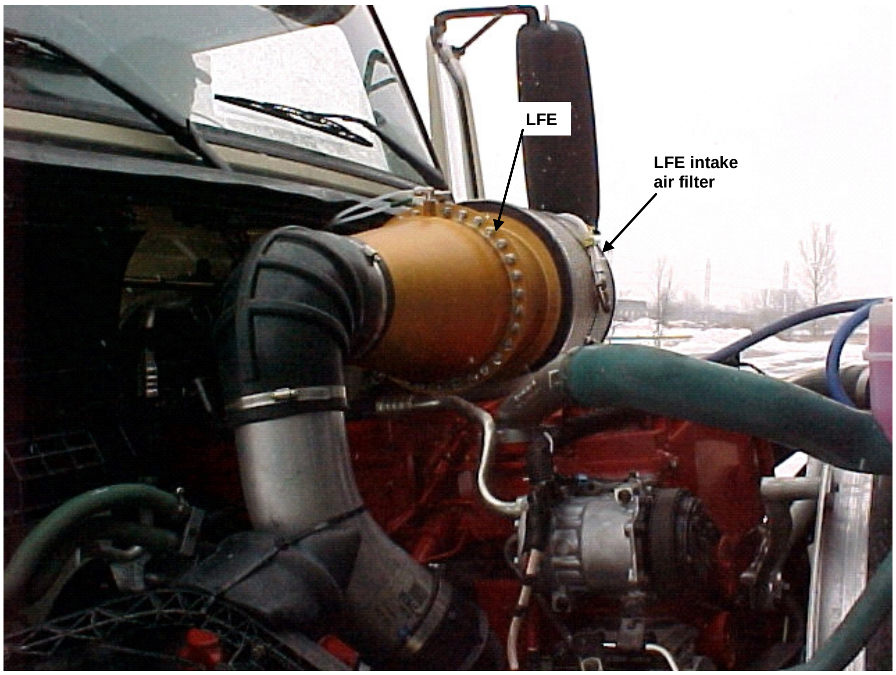

Figure 6-3. LFE Installation Example

6.2. CONTROL STRATEGY PERFORMANCE TESTS

Control strategy performance tests will consist of at least three baseline and three candidate test runs performed under simple duty cycles. Test personnel may perform more test runs up to a maximum of six each in order to:

- show a statistically significant difference between the baseline and candidate conditions
- refine the confidence interval on the difference

Sections 6.2.1 and 6.2.2 of the generic protocol provided the following step-by-step instructions.

Note: data collected from simultaneous application of PEMS and ISS in these test runs will also be utilized to evaluate PEMS and ISS correlations.

IMPORTANT:
Good test results depend on minimizing operator variability. It is therefore essential that the same operator run the nonroad equipment during simple cycle development, baseline, and candidate test runs for a particular ECT / nonroad equipment combination. Some simple cycles may require support equipment, such as trucks to move material, dozers to groom piles, etc. It is essential that those operators also be the same during simple cycle development, baseline, and candidate testing.

Baseline Test Runs

1. Ensure that all applicable preparations (see §6.1) are complete, that all required instruments and sensors are installed and functioning properly. Note that sample probe location for baseline testing should be upstream of the ECT.
2. Synchronize all clocks to the PEMS datalogger timestamp.
3. Energize the PEMS and ISS (analyzer bench and sampling pumps) for its specified warmup period (30 minutes for PEMS and ISS). Use power mains for PEMS warmup to avoid depleting the batteries.
4. Switch PEMS to battery or generator power supply without interruption.
5. Start the nonroad equipment and dispatch it to perform one complete simple duty cycle for warmup. Shut it down immediately following the duty cycle for a 20 ± 5-minute soak period during PEMS warmup. Follow the manufacturer's recommendations regarding turbocharger cooling at shutdown.
6. Conduct PEMS initial zero and span checks. Perform at least one NMHC contamination check per test day.
7. Collect ambient air samples for background CO, CO2, NOX, and THC correction.
8. Perform ISS tunnel leak check, collect NMHC and TPM (as needed) tunnel blank and background samples at least once per day. Analyze ISS gaseous samples immediately or during the following test run.
9. Start PEMS and ISS sampling.
10. Start the nonroad equipment and operate the engine at midrange idle for 30 seconds. Reduce engine speed to low idle for 10 seconds. Operate the engine at midrange idle for 15 seconds. Reduce the engine speed to low idle for 5 seconds and immediately start the test run. This operating profile will provide readily recognizable data patterns which will help later analysis.
11. Immediately dispatch the nonroad equipment to perform one complete simple duty cycle.

12. Shut down the nonroad equipment immediately following the duty cycle for a 20 ± 5-minute soak period during data download and post-run checks. Follow the manufacturer's recommendations regarding turbocharger cooling at shutdown.
13. Stop ISS sampling and immediately inspect ISS sample train, sample bag, and filter housings for condensed moisture. Invalidate the test run if moisture is present
14. Recover and inspect TPM filters (if used) for condensed moisture. Invalidate the test run if moisture is present. Store TPM filters under refrigeration or in a cooler until analyzed.
15. Conduct PEMS final zero and span checks.
16. Recover sample bags and analyze ISS gaseous samples immediately. Perform all applicable zero, span, and drift checks.
17. Install new ISS filters and sample bags
18. Review cycle criteria (3 complete cycles needed to develop cycle criteria; see generic protocol §5.4) to establish the run's validity.
19. Repeat steps 10 through 18 until 3 valid test runs are complete. If the soak period between runs exceeds 25 minutes, dispatch the nonroad equipment to perform one complete duty cycle for warmup as in step 5.
20. Forward the TPM filters for gravimetric or additional analysis (see Table 3-3.)
21. Calculate the mean and confidence interval on the results for each parameter (see §7.1). Conduct additional test runs if the confidence interval is a significant fraction of the expected performance.

Note: Connect the PEMS to the power mains and exchange the PEMS batteries as needed without interruption to avoid having to repeat its warmup period.

<u>Candidate Test Runs</u>

Conduct candidate test runs according to the baseline test run procedures (steps 1 through 21). The number of candidate test runs should at least equal the number of baseline runs. The sample probe location should be changed such that sampling is completed downstream of the ECT.

Calculate and report the mean and confidence interval on the difference between the baseline and candidate results according to procedures in §7.1. Conduct additional candidate test runs (up to 6) if necessary.

Test staff will collect control strategy cost and performance data required in Appendix B3 for each ECT tested.

6.3. IN-USE EVALUATIONS

In-use Evaluations will be completed utilizing PEMS instrumentation only because it provides real-time emissions determinations. Evaluations should be completed at the equipment's host site where it is in normal service. In-use evaluations will last approximately four hours with the sampling probe location alternating hourly between upstream and downstream of the ECT. Note that the nonroad equipment operator(s) need not be the same as those employed during baseline and candidate testing. Step-by-step procedures are as follows:

1. Ensure that all applicable preparations (see §6.1) are complete, that all required instruments and sensors are installed and functioning properly. Sample probe location should initially be upstream of the ECT.
2. Synchronize all clocks to the PEMS datalogger timestamp.
3. Energize the PEMS for its specified warmup period (typically 30 minutes). Use power mains for PEMS warmup to avoid depleting the batteries.
4. Conduct PEMS initial zero and span checks. Perform at least one NMHC contamination check per test day.
5. Collect ambient air samples for background CO, CO2, NOX, and THC correction.
6. Switch PEMS to battery or generator power supply without interruption.
7. Start PEMS sampling.
8. Start the nonroad equipment and operate the engine at midrange idle for 30 seconds. Reduce engine speed to low idle for 10 seconds. Operate the engine at midrange idle for 15 seconds. Reduce the engine speed to low idle for 5 seconds and immediately start the test run. This operating profile will provide readily recognizable data patterns which will help later analysis.
9. Dispatch the equipment into its normal operations.
10. Rendezvous with the equipment every hour to do a zero-span check and switch the sampling probe location to the opposite of its previous location upstream or downstream of the ECT.
11. Re-start PEMS sampling and operate the engine at midrange idle for 30 seconds. Reduce engine speed to low idle for 10 seconds. Operate the engine at midrange idle for 15 seconds. Reduce the engine speed to low idle for 5 seconds and immediately start the test run. This operating profile will provide readily recognizable data patterns which will help later analysis.
12. Perform steps 10 and 11 until at least two in-use duty cycles have been recorded at both upstream and downstream of the ECT.
13. Conduct PEMS final zero and span checks.
14. Evaluate in-use test data in accordance with procedures specified in the generic protocol §7.2 and Appendix C with respect to identification of 'events' and evaluations of event emissions for comparisons.

6.4. EXTENDED INTERVAL TESTS

Not applicable

6.5. EMISSIONS METHOD COMPARISONS

See Section 6.2 for step-by-step test procedures. Test data for comparisons will be collected simultaneously with baseline and candidate test runs.

6.6. INSTRUMENT SPECIFICATIONS, CALIBRATION, AND PERFORMANCE CHECKS

The emissions and performance determinations described in this protocol require numerous contributing measurements, sensors, instruments, analytical procedures, and dataloggers. This section provides general specifications which, if met, will help ensure repeatability within a test campaign and comparability with other programs. Table 6-1 lists the instrument and sensor accuracy specifications recommended for use with this protocol. It also indicates the instrument manufacturer, model, and specification verification dates.

Table 6-1. PEMS and ISS Specifications

Parameter	✓ if used	Logging Frequency	Accuracy	Repeatability	Manufacturer	Model(s)	Meets Spec.	Date Verified
Engine speed	☒	1 Hz	5.0 % of point or 1.0 % of max[a]	2.0 % of point or 1.0 % of max	Baumer Electric	FPAM 18N3151	☐	
Torque estimator, BSFC	☐	1 Hz	8.0 % of point or 5.0 % of max	2.0 % of point or 1.0 % of max[b]			☐	
Pressure transducers	☒	1 Hz	5.0 % of point or 5.0 % of max	2.0 % of point or 0.5 % of max	Horiba	OBS-2200	☐	
Ambient barometric pressure	☒	6 second	0.07 "Hg (250 Pa)	0.06 "Hg (200 Pa)	Horiba	OBS-2200	☐	
Temperature transducers (T_{turb}, T_{out}, T_{amb})	☒	1 Hz	1.0 % of point or 5.0 °C	0.5 % of point or 2.0 °C	Horiba	OBS-2200	☐	
Dewpoint / RH[c]	☒	6 second	5.0 °F	2.0 °F	Horiba	OBS-2200	☐	

Table 6-1. PEMS and ISS Specifications								
Parameter	**✓ if used**	**Logging Frequency**	**Accuracy**	**Repeatability**	**Manufacturer**	**Model(s)**	**Meets Spec.**	**Date Verified**
Exhaust flow	☒	1 Hz	5.0 % of point or 3.0 % of max	2.0 % of point	Horiba	OBS-2200	☐	
Instrumental analyzer concentration	☒	1 Hz	4.0 % of point	2.0 % of point	Horiba	OBS-2200	☐	
Fuel flow via carbon balance	☒	1 Hz	4.0 % of point	2.0 % of point	Horiba	OBS-2200	☐	
ISS Only								
Instrumental analyzer concentration	☒	1 Hz	2.0 % of point	1.0 % of point	Environment Canada	DOES2	☐	
Gravimetric TPM balance	☒	n/a[d]	0.1 % (see §1065.790)	0.5 µg	Environment Canada	DOES2	☐	
Main flow rate	☒	2 Hz	1.0 % FS[e]	n/a	Environment Canada	DOES2	☐	
Dilution air flow rate	☒				Environment Canada	DOES2	☐	
Sample flow rate	☒				Environment Canada	DOES2	☐	
Differential pressure (if used)	☒				Environment Canada	DOES2	☐	

[a]"max" refers to the maximum value expected during testing.
[b]Quantification of ECM torque estimator accuracy may be difficult because §1065.915(b)(5)(i) regulations requiring this on nonroad engines are not effective until 2010.
[c]relative humidity (RH)
[d]Not applicable (n/a)
[e]Full scale (FS)

Table 6-2 lists recommended calibration intervals and performance checks. Note that test personnel must perform some performance checks, such as leak checks, analyzer zero and spans, etc. before and after each test run while others may be performed either in the field or laboratory. Table 6-4 in the generic protocol provides specific references to step-by-step calibration procedures.

Table 6-2. Recommended Calibrations and Performance Checks				
System or Parameter	**Description / Procedure**	**Frequency**	**Meets Spec.?**	**Date Completed**
Engine speed	11-point linearity check	At purchase / installation	☐	
Pressure transducers	NIST-traceable[a] calibration	Within 12 months	☐	
Temperature transducers (T_{turb}, T_{out}, T_{amb})			☐	
Dewpoint / RH			☐	
Exhaust flow			☐	
All instrumental analyzers	11-point linearity check	Within 12 months	☐	

Table 6-2. Recommended Calibrations and Performance Checks				
System or Parameter	**Description / Procedure**	**Frequency**	**Meets Spec.?**	**Date Completed**
CO_2 (NDIR detectors)[b]	H_2O interference	Within 12 months	☐	
CO (NDIR detectors)	CO_2, H_2O interference		☐	
Hydrocarbons (FID)[c]	Propane (C_3H_8) calibration		☐	
	FID response optimization		☐	
	C_3H_8 / methyl radical (CH_3) response factor determination		☐	
	C_3H_8 / CH_3 response factor check		☐	
	Oxygen (O_2) interference check		☐	
NO_X	CO_2 and H_2O quench (CLD)[d]		☐	
	Non-methane hydrocarbons (NMHC) and H_2O interference (NDUV detectors)[e]		☐	
	Ammonia interference and NO_2 response (zirconium dioxide detectors)		☐	
	Chiller NO_2 penetration (PEMS with chillers for sample moisture removal)		☐	
	NO_2 to NO converter efficiency	Within 6 months or immediately prior to departure for field tests	☐	
PEMS	Comparison against laboratory CVS system	At purchase / installation; after major modifications	☐	
	Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of point)	Before and after each test run or as needed during in-use evaluations	Refer to generic protocol Appendix B15, "Test Run Record"	
	Perform analyzer drift check (≤ ± 4.0 % of cal gas point)	After each test run		
	NMHC contamination check (≤ 2.0 % of expected conc. or ≤ 2 ppmv)	Once per test day		
Exhaust gas or intake air flow measurement device	Differential pressure line leak check (ΔP stable for 15 seconds at 3 "H_2O)	Once per test day		
ISS	Comparison against laboratory CVS system	At purchase / installation; after major modifications	☐	
	Zero / span analyzers (zero ≤ ± 2.0 % of span, span ≤ ± 4.0 % of point)	Before and after each test run	Refer to generic protocol appendix B15, "Test Run Record"	
	Inspect sample lines, filter housings, and sample bags for visible moisture (none is allowed)	After each test run		
	Perform analyzer drift check (≤ ± 4.0 % of cal gas point)			
ISS	NMHC background check and dilution tunnel blank	Once per test day	Refer to generic protocol	
	TPM background check and			

Table 6-2. Recommended Calibrations and Performance Checks				
System or Parameter	**Description / Procedure**	**Frequency**	**Meets Spec.?**	**Date Completed**
	dilution tunnel blank		appendix B15, "Test Run Record"	
	Dilution tunnel leak check			
	Sample bag leak check (< 0.5 % of normal system flow rate)			
	TPM filter face temperature (not to exceed 47 °C or 117 °F)	continuously during sampling		
Fuel flow	11-point linearity check	At purchase (coriolis meters only); within 6 months or immediately prior to departure for field tests (turbine or gear meters)	☐	
TPM gravimetric balance	NIST-traceable calibration	Within 12 months	☐	
	Reference sample weights	Within 12 hours of filter weighings	☐	
ISS main, dilution, and sample flow rates	11-point linearity check	Within 12 months	☐	
[a]National Institutes of Standards and Technology (NIST) [b]non-dispersive infrared (NDIR) [c]flame ionization detector (FID) [d]chemilumenescence detector (CLD) [e]non-dispersive ultra violet (NDUV)				

Table 6-3 lists sensors used for duty cycle development, mechanically-controlled engine parameters (such as exhaust gas flow rate surrogate sensors, which include a suitable pitot, ΔP sensors, and thermocouple) and other sensors to be used during this test campaign.

Table 6-3. Duty Cycle, Engine, and Auxiliary Sensors					
Description	**Manufacturer**	**Model**	**ID or Serial Number**	**Range**	**Accuracy**
Photoelectric sensor for RPM	Baumer Electric	FPAM 18N3151	S293	0 – 50 Hz	± 3.3 % at 1800 rpm
HOBO Data Logger	Onset	H21-002		0 - 120 Hz	
HOBO Pulse Input Adapter	Onset	S-UCA-M006			
Exhaust flow rate	Horiba	OBS-2200		0 - 2300 acfm (varies within size)	± 1.5% FS
Exhaust temperature	Horiba	OBS-2200		0 °C – 800 °C	± 1.0% FS

7.0 DATA QUALITY AND ANALYSIS

This section outlines general data analysis procedures for each type of test and data quality requirements for all tests. Appendix C from the generic protocol supplements the discussion with statistical concepts and equations.

7.1. CONTROL STRATEGY PERFORMANCE TESTS

The checked boxes in the following subsections indicate the analyses which will be performed for this test campaign.

7.1.1. Emissions Reductions and Fuel Consumption Changes for Simple and Synthesized Duty Cycles

The following calculations will be made for each parameter (CO, CO_2, NO_x, THC, TPM, and fuel consumption, as applicable). Refer to Appendix C from the generic protocol for procedures and attach documentation of calculations to the test report.

- ☒ mass emissions (g/run) mean and σ_{n-1} for all baseline and candidate test runs
- ☒ Fuel consumption rate (gal/run, gal/hr)
  - ☒ carbon balance method (from PEMS data)
  - ☐ gravimetric (day tank weight change)
  - ☐ mass-flow fuel meters
  - ☐ volumetric-flow fuel meters
- ☒ fuel-specific emission rate (g/gal) mean and σ_{n-1} for all baseline and candidate test runs
- ☒ brake-specific emission rate mean (g/bhp-h) and σ_{n-1} for all baseline and candidate test runs, if torque or horsepower data are available from an ECM
- ☒ the difference between the baseline and candidate mean results
- ☒ the statistical significance of the difference
- ☒ the 95-percent confidence interval on the difference

7.1.2. Emissions Reductions and Fuel Consumption Changes for In-use Duty Cycles

The following calculations will be made for each parameter (CO, CO_2, NO_x, THC, TPM, and fuel consumption, as applicable). Refer to Appendix C from the generic protocol for procedures and attach documentation of calculations to the test report.

- ☒ mass emissions (g/hr, g/event) mean and σ_{n-1} for each test period and individual events
- ☒ Fuel consumption rate (gal/event, gal/hr)
  - ☒ carbon balance method (from PEMS data)
  - ☐ gravimetric (day tank weight change)
  - ☐ mass-flow fuel meters
  - ☐ volumetric-flow fuel meters

☒ fuel-specific emission rate (g/gal) mean and σ_{n-1} for each test period and individual events
☒ brake-specific emission rate mean (g/bhp-h) and σ_{n-1} for all baseline and candidate test runs, if torque or horsepower data are available from an ECM
☒ the difference between the baseline and candidate mean results for each test period and for individual comparable events
☒ the statistical significance of the difference
☒ the 95-percent confidence interval on the difference

7.1.3. <u>Control Strategy Cost Analysis</u>

Analysis of control strategy costs consists primarily of summing and reporting the data collected in Appendix B3, "Control Strategy Cost Information" of the generic protocol. Costs should be separated into the following general categories:

☒ capital purchases
☒ shop-made modifications, specialty items
☒ downtime (or demurrage), installation, and training labor (both vendor and equipment owner staff)
☒ operating materials, supplies, and reagents
☒ operating labor (for required maintenance, operation, etc.)

7.1.4. <u>Control Strategy Engine and Operational Performance Impact Analysis</u>

The following methods will be used to assess control strategy performance:

☐ ECM data is available: calculate the difference between the baseline and candidate horsepower and fuel consumption, normalized to brake horsepower

☒ ECM data is suspect or not available: calculate the difference in mean fuel consumption between baseline and candidate tests as observed during simple or synthesized duty cycles

☒ In-Use duty cycles: fuel consumption difference between baseline and candidate conditions over a consistent time period. Indicate time period of comparison (per shift, per day, etc.) _______________

Fuel consumption changes: ☐ brake-specific ☐ per shift ☒ per hour
☒ other (describe): duty cycle-specific

Test personnel will gather other control strategy impact information as described in Appendix B4, "Control Strategy User's Interview" from the generic protocol.

7.2. IN-USE EMISSIONS TESTS

This section discusses application of basic descriptive statistics, but analysts should be open to other possibilities depending on the circumstances of a particular test campaign. Appendix C and §7.2 from the generic protocol provides additional analytical concepts such as methods for identifying and comparing in-use events.

The following descriptive statistics should be generally useful to describe the events which occur within an in-use emission test or to describe the test as a whole. Check those applicable to this test.

☒ In-use overall mean, σ_{n-1}
☒ individual event means, σ_{n-1}
☐ Frequency distributions

7.3. EXTENDED INTERVAL TESTS

Not applicable

7.4. EMISSIONS MEASUREMENT METHOD COMPARISONS

Analysts should, for each parameter (CO, CO_2, NO_X, THC, and fuel consumption, as applicable):

☒ report the ISS mass emissions (g/run) for each test run
☒ calculate the mass emissions mean and σ_{n-1} for all test runs
☒ calculate the PEMS mass emissions
☒ calculate the mass emissions mean and σ_{n-1} for all PEMS test runs
☒ calculate the difference of the ISS and PEMS mean results
☒ evaluate the statistical significance of the difference
☒ calculate the 95-percent confidence interval on the difference.

See Appendix C of the generic protocol for the appropriate statistical analysis procedures.

Analysts will compare TPM measurements from the ETaPS PM sensor with the integrated measurements from the ISS. The ETaPS voltage output signal will be correlated to PM emissions based on an evaluation of the ETaPS performed by Southern prior to testing. In the evaluation, PM emissions as measured from integrated gravimetric data and from the Dekati Mass Monitor, a real-time instrument for particulate emissions measurements, were correlated to the voltage output signal from the ETaPs.

7.5. DATA QUALITY

All test campaigns should meet the following qualitative data quality objective (DQO):

Sensors, measurements, step-by-step test methods, and the resulting determinations will meet or exceed this protocol's and reference method specifications as outlined in §5.0 through §6.6.

8.0 REPORTS

Reported results, data summaries, and statistical analyses depend on the individual test campaign. Table 8-1 provides a general list of items to be included in each type of report. The checked items are applicable to this test.

Table 8-1. Reported Results List

Test Type or Description	Control strategy performance evaluation	In-use emissions tests	Extended interval tests	Emissions measurement method comparisons
Emission rates	☒	☒	☐	☒
Fuel consumption	☒	☒	☐	☐
Difference between baseline and candidate emissions and fuel consumption	☒	☒	☐	☒
Control strategy costs	☒	☐	☐	☐
Control strategy performance impacts	☒	☐	☐	☐
Simple or synthesized duty cycle specifications	☒	☐	☐	☐
In-use duty cycle descriptive statistics	☐	☒	☐	☐

The test organizations will maintain all data files as follows:

> <u>Electronic files</u>: backed up on a thumb drive at the end of each day and transmitted to central office for storage and archiving.
>
> <u>Hard copy files</u>: the field team leader will maintain a field book with copies of hard copy files; originals will be kept at Southern Research Institute

Bob Richards of Southern, 919/806-3456 x26, will be responsible for managing the data files. Environment Canada will be responsible for performing and reporting DOES2-based mass emission calculations. Staci Haggis of Southern, 919/806-3456 x24, will be responsible for performing PEMS and remaining data calculations.

9.0 CONTACTS

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Appendix B
Field Data Forms

Appendix B1. Nonroad Equipment Information

Test-specific Information *(REQUIRED)*

Use a combination of letters, numerals, and underscores (no spaces) for Test_ID, Site_ID, Equip_ID, etc. Example: "Loadr01".

Project Name: ____________________ *Project_ID*: ___________ *Test_ID*: _________ *Date*: _________
Site name: ______________________________ *Site_ID*: __________ *Equip_ID*: _____________
Compiled by (Company): ____________________________________
Name (printed): _______________________________ *Signature*: ________________________________

Owner and Equipment Data *(REQUIRED)*

Owner's Equipment ID or name: ______________ *Description*: __________________________________
Contact name: ____ *Phone*: _______________
Address: _____________________________ *City*: __________________ *State*: ____ *Zip*: __________

Equipment data		Engine data			
Manufacturer		Manufacturer		# cylinders	
Model year		Model		Displacement	
Model		Engine family		Install / overhaul date	
Serial number		Serial number		Expected life (h)	
Hourmeter		horsepower			

Optional Information

ECM protocol: ☐n/a ☐SAE J1939 ☐ J1708 ☐other: __________________
Drive train: ☐torque converter / automatic ☐hydrostatic ☐manual geared ☐powershift ☐diesel electric ☐ AC drive ☐ DC drive ☐other: __________________
Main hydraulics max. psig: ______ *Nominal pump gpm*: ________
Electrical system alternator capacity (amperes): _____________ ☐12 VDC ☐24 VDC
Dealer name: _________________________________ *Dealer phone*: _____________________________
Engine dealer name: _____________________________ *Engine dealer phone*: ______________________
Implements, features (such as bucket size, blade capacity, ripper, winch, auger size, other descriptions.):
____
____

Modifications (indicate whether made to the engine, equipment, transmission, chassis, other, and if factory or shop-made): ____
____
____

Accessories: ☐Air-conditioning ☐Auxiliary hydraulics ☐other (describe): ______________________
____

Describe the 3 most recent routine maintenance events and the 3 most recent major repair events below.

Routine Maintenance			**Major Repairs**		
Date	**Description**	**Outcome**	**Date**	**Description**	**Outcome**

Appendix B2. Control Strategy Information

Use a combination of letters, numbers, and underscores (no spaces) for Test_ID, Site_ID, Cntrl_ID, etc. Example: "DPF01".

Project Name: ____________________ *Project_ID*:____________ *Test_ID*: __________ *Date*: __________
Compiled by (Company): ____________________________________
Name (printed): ______________________________ *Signature*:________________________________
Technology type: ____ *Cntrl_ID*: _________________
Manufacturer: ____________________ *Contact name*: ____________________ *Phone*: ______________
Distributor: ______________________ *Contact name*: ____________________ *Phone*: ______________
Product name: _________________________________ *Model*: _________________________________

Description and operating principle: ____
____
____

Recommended applications: ____
____

Certifications, verifications, supporting data citations: ____
____
____

Specifications

Dimensions (h x w x l or dia x l): ________________________________ *Weight*:____________ *(lb / kg)*
Required accessories, reagents, etc.: ☐*datalogger / computer* ☐T_{exh} *sensor* ☐*backpressure sensor*
☐*other temp sensors (describe)*:________________________ ☐*ΔP sensor* ☐*shore power*
☐*reagent (describe)*: ________________________ *tank size*: ___________ *weight (full)*: ___________
☐*other sensors or accessories (describe specialized brackets, shock mounts, etc.)*: __________________
____

bhp range: ___________ T_{exh} *range* (^{o}F): __________ *Exhaust flow rates*: ______________ *(acfm / scfm)*
Installed exhaust backpressure at full load: ________ *("Hg / psig)*
Time / temperature limitations: ____
Ambient temperature range: _________ *Other limiting parameters (describe)*: ____________________
____

Installation and Commissioning

Brackets, hangers, cables, tanks, etc. (describe and attach drawings): ____________________________
____
Estimated installation downtime (hr): ____________ *Labor (hr)*: _____________
Breakin or degreening procedure (describe): ____
____
Diagnostics procedures (summarize): ____
____
Operating procedures and maintenance schedules:____
____
____
Received (date): _____________ *Initials*: ________ *Installed (date)*:_____________ *Initials*: _______
Breakin / degreening complete (date): _____________ *Initials*: __________
Operations certified OK; Signature: _______________________________________ *Date*:____________
Representing: ____

Appendix B3. Control Strategy Cost Information

Project Name: ___________________ *Project_ID*:____________ *Test_ID*: _________ *Date*: _________
Compiled by (Company) : _______________________ *Cntrl_ID*: ______________________________
Name (printed): _______________________________ *Signature*: ______________________________

Purchased Equipment and Supplies			
Category	**Description**	**$ Estimate**	**$ Actual**
Capital equipment			
Support equipment			
Inventoried spares			
Reagents and supplies			
Tooling, brackets			
Electronics, cables, etc.			

Shop-made Fabrications and Nonroad Equipment Modifications						
Category	**Description**	**Labor, h**	**Rate, $**	**Labor $**	**Materials $**	**Total $**
Tooling, brackets						
Modifications						

Installation Demurrage and Labor				
Description	**Estimate, h**	**Actual, h**	**Rate, $**	**Total $**
Nonroad equipment downtime for installation				
Installation labor				
Training labor (maintenance and operations)				
Training expenses (hired consultants, supplies, etc.)				

Operating Expenses			
Begin Date	**End Date**	**Description**	**$ Total**
		Reagents and supplies (list):	
		Routine maintenance parts (include interval):	
		Routine maintenance labor (describe):	
		Estimated overhaul parts (include interval):	
		Estimated overhaul labor (describe):	
		Unscheduled repair parts, labor (describe):	

Appendix B4. Control Strategy User's Interview

Project Name: ____________________*Project_ID*:___________*Test_ID*: _________*Date*: _________
Compiled by (Company) : _______________________ *Equip_ID*: ___________ *Cntrl_ID*: _________
Name (printed): _________________________________ *Signature*: ________________________________

This Appendix is intended to document anecdotal information about the control strategy implementation and performance. The performance, dispatching, and other operating effects on the selected nonroad equipment should also be discussed.

Control strategy acquisition, installation, implementation

Ratings: 1 = poor, 3 = average, 5 = excellent
Rate distributor's customer service :_____ *Operator training* : ____ *Maintenance training* : _____
Rate repair parts availability :_____ *Physical access for technicians* : _____

Ratings: 1 = easy / entry level skills, 3 = moderate, 5 = hard / expert level skills
Rate installation difficulty :_____ *Troubleshooting diagnosis* : ____ *Maintenance, repair activities* :____
Rate verification of proper operations : _____

Describe control strategy acquisition, installation, implementation, and maintenance issues: __________

What tasks must be performed to keep the control strategy operating properly? What level of difficulty?

What maintenance frequency was recommended? How does this compare with the actual maintenance history seen at this site? ____

Control strategy performance

Ratings: n/a = can't tell, 1 = poor, 3 = average, 5 = excellent
1 = easy and convenient, 3 = somewhat inconvenient, 5 = significant hassle
Rate ease of day-to-day operations : _____
Rate performance :_____ *Describe control strategy performance issues* : __________________________

Control strategy impacts

(1 = no effect, 3 = noticeable effects, 5 = significant impacts)
Rate impacts on day-to-day operations for the selected nonroad equipment : _____
Rate impacts on equipment performance : _____ *Power* : _____ *Operator sight lines / visibility* : ______
Rate perceived health effects : _____ *Shop environment effects* : _____ *In-use or work face effects* : ___
Rate machine balance changes : _____ *Rate operating weight impacts* : ____

Discuss the impacts (gear selections, machine capacity, noise, odors, etc.) : _______________________

How have dispatching schedules changed? For better or worse? Why? :_________________________

Other comments: ____

Appendix B5. Host Site Information

Use a combination of 3 to 5 letters and 0 to 2 numbers (no spaces) for Test_ID, Site_ID, etc. Example: "NYC01".

Project Name: ____________________ *Project_ID*:_____________________________ *Date*: __________
Compiled by (Company) : _________________________ *Site _ID* : __________
Name (printed) : ________________________________ *Signature* : _______________________________

Site name : _____________________________________ *Owner Company* : __________________________
Address : ______________________________________ *Address* : __________________________________
City, State, Zip : ________________________________ *City, State, Zip* : ___________________________
Contact person : _________________________________ *Contact person* : ____________________________
Title : ____ *Title* : ___________________________________
email : ____ *email* : ___________________________________
Site phone : _____________________________________ *Company phone* : ___________________________
Site fax : _______________________________________ *Company fax* : ____________________________
Site elevation (ft) : ___________________

Site safety training required? ☐ *y* ☐ *n* *If yes, provide completion dates and staff initials* : ___________
____

Fuel supplier :__________________*Contact name* : _____________________*Phone* : ________________
Site fuel tank capacity for test fuel : ________ *(gal) Refill frequency* : ___________

Site description : ____
____
____
____

Site operations (number and duration of normal shifts, dispatch patterns, etc.) :____________________
____
____

Summarize nonroad equipment description (s) for each piece of equipment to be tested or each Test_ID (see Appendix B1) : ____
____

Primary duty(ies) (such as "gravel loading", "spreading overburden", etc.). Include typical process rates, hours per day, or other measures for each piece of equipment to be tested : ____________________
____

Other duties : ____
____

Host site test contacts:

Operator name(s) : ____

Maintenance technician name(s) : ____

Dispatcher / manager name(s) : ____

Appendix B6. Simple Cycle Development and Test Run Instructions

The intent of this simple cycle development procedure is to reduce the workload on test personnel by allowing them to conduct cycle repetitions ("test runs") with minimal pauses for data analysis. Recording and reviewing elapsed times are the primary responsibility of test personnel during field work. They should strive to ensure that elapsed times are within ± 5 % of each other for individual events and the entire simple cycle. They should also conduct a sufficient number of test runs to ensure that, after analysts post-process the data, at least three valid test runs will be available for the final results.

Analysts are responsible for reviewing the field data during post-processing and selecting at least three test runs which contribute the least variability to the final results. The basis for their decisions will be the "cycle criteria", calculated according to steps 8 and 9. This review is not necessary if only three test runs are available.

Step-by-step instructions for test personnel during field work:

1. Develop event definitions for the selected nonroad equipment in conjunction with host site managers, operators, and dispatchers.
    - assign a unique identifier, or *Event_ID*, to each event, such as "travel_1" or "load_1"
    - provide detailed descriptions for each event, such as:
        - "travel from dump point A to loading point X in 2nd gear with bucket at ¼ height" for "travel_1" event
        - "load bucket ¾ full and raise to ¼ height" for "load_1" event
    - estimate the approximate time duration for each event

IMPORTANT: Event descriptions are subject to professional judgment. Events may consist of individual motions or a series of combined motions. Loader cycles, for example, may occur too swiftly to break into individual events. This means that longer event descriptions, such as "travel forward, approach pile, load, and lift bucket" may be appropriate. Record the event identifiers (Event_ID), their descriptions, and approximate durations in Appendix B7.

2. Arrange the Event_IDs defined in Appendix B7 into a logical sequence. Shorter event sequences may be repeated or strung together if required to make up the simple cycle. The arrangement is arbitrary, but the combination of loaded, unloaded, and idle events would ideally be similar to those observed at the host site. For example, a complete simple cycle may be composed of a series of 10 loader cycles.

Record the Event_IDs in Appendix B8 in their proper order and assign a simple cycle identifier (*Cycle_ID*) such as "smpl_01".

3. Install a datalogger on ECM-equipped engines. Configure the datalogger to record the following parameters at 1 Hz:
    - percent load
    - turbocharger boost pressure
    - engine speed, RPM
    - exhaust gas temperature (optional)
    - net brake torque (optional)
    - fuel consumption (optional)

Install sensors and a datalogger on mechanically-controlled engines. Configure the datalogger to record the following parameters at 1 Hz:

- engine speed, RPM
- turbocharger outlet temperature (T_{turb}) or exhaust gas outlet temperature (T_{out})
- exhaust gas flow surrogate, $\sqrt{\Delta P}$ high (ΔP sensor range 0 - 10 "H_2O)
- exhaust gas flow surrogate, $\sqrt{\Delta P}$ low (ΔP sensor range 0 - 1 "H_2O)
- fuel supply flow rate (optional)
- fuel return flow rate (optional. Note: for diesel engines, fuel consumption is the difference between fuel supply and return flow rates)

5. Dispatch the nonroad equipment to perform the entire simple cycle while logging the engine parameters. This will show whether the simple cycle is feasible. Repeat the simple cycle until each event has been performed at least three times while logging.

6. While performing step 5, observe and record the time, to the second, at the start of each simple cycle. Use Appendix B8. Then, "on the fly", record the completion time for each Event_ID. Continue until data for at least three repetitions of each event are available.

NOTE: Do not attempt to calculate elapsed times for each Event_ID until after the recording session. Most in-use events occur too fast to allow use of a stop watch or lap-timer. If an event time is missed, continue on to the next event and repeat the entire cycle again until at least three repetitions of each Event_ID are available.

7. Calculate the individual Event_ID and overall Cycle_ID elapsed times. Enter them in Appendix B9. Calculate the mean and ± 5 % of the mean for the overall Cycle_ID and each Event_ID. Enter the results in Appendix B9. These are the elapsed time criteria.

During testing, record new Event_ID and Cycle_ID starting times and elapsed times on new copies of Appendix B8. Calculate the individual Event_ID and overall Cycle_ID elapsed times. Compare the results with the elapsed time criteria entered in Appendix B9. Valid test runs are those for which:

- elapsed time for each Event_ID is within ± 5 % of the mean for that event
- elapsed time for the entire Cycle_ID is ± 5 % of the mean for all duty cycles

It may not be possible, in some cases, to meet this goal. Test personnel should work with the operators to minimize the elapsed time variability.

IMPORTANT: Analysts will require accurate starting times and elapsed times for test run validation.

Step-by-step instructions for analysts during post processing:

NOTE: The following procedures are intended to minimize test result confidence intervals. Analysts may use them to select Run_IDs which have the least run-to-run variation. They should be employed when four or more Run_IDs are available for analysis.

8. Define one or two cycle criteria for each event. Cycle criteria definitions should be based on professional judgment. Examples are:

- any engine:
  - mean engine speed
  - engine speed sample standard deviation (σ_{n-1})
- ECM-equipped engines:
  - mean RPM multiplied by torque
  - mean percent load

- mechanically-controlled engines:
    - mean RPM multiplied by T_{turb}
    - mean RPM multiplied by $\sqrt{\Delta P}$

9. Obtain Event_ID start times and elapsed times from the Appendix B8 field data forms. Extract the appropriate timestamped data for three different Run_IDs from the datalogger files and calculate the cycle criteria for each Event_ID. Record the following in Appendix B10:

- cycle criteria descriptions
- cycle criteria value for each Event_ID for each of the three Run_IDs

Calculate the mean and σ_{n-1} for each Event_ID cycle criteria over the three Run_IDs and enter the values on Appendix B10.

Transcribe the cycle criteria mean for each Event_ID onto Appendix B11. Calculate 1.7 * σ_{n-1} for each Event_ID and enter the value on Appendix B11. Extract the appropriate timestamped data from the datalogger files for the remaining Run_IDs and calculate the actual cycle criteria value observed. Subtract the actual value from the expected value. The actual cycle criteria observed for valid test runs should be less than $\pm (1.7 * \sigma_{n-1})$ for each Event_ID.

Appendix B7. Duty Cycle Event List

Project Name : ______________________________ *Test_ID* : __________ *Date* : __________

Compiled by (Company) : __________________________________

Name (printed) : _____________________________ *Signature* :_____________________________

See Appendix B6 or B10 for instructions. Use additional sheets for more events if necessary.

Event_ID	Description	Approx. Duration (mm:ss)

Notes (Describe work location at host site, nonroad equipment description, duties, etc.):

____

____

____

____

____

Appendix B8. Event Times

Project Name : ________________________________ *Test_ID* : ___________*Date* : ___________

Compiled by (Company) : ________________________ *Cycle_ID* : ____________________

Name (printed) : ________________________________*Signature* :________________________________

See Appendix B6 for instructions. Use additional sheets if necessary.

Start Time:									
Index	**Event_ID**	**Clock Time**	**Elapsed Time**	**Clock Time**	**Elapsed Time**	**Clock Time**	**Elapsed Time**	**Clock Time**	**Elapsed Time**
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
Cycle Time (sum of Elapsed Times)				**Cycle Time**		**Cycle Time**		**Cycle Time**	

Notes:

____

____

____

____

____

Appendix B9. Simple Cycle and Synthesized Duty Cycle Elapsed Time Criteria

Project Name : ______________________________ *Test_ID* : ____________ *Date* : _____________

Compiled by (Company) : ______________________ *Cycle_ID* : ___________

Name (printed) : ____________________________ *Signature* : ______________________________

See Appendix B6 for simple cycle instructions. See Appendix B10 for synthesized duty cycle instructions. Use additional sheets for more events if necessary.

Index	**Event ID**	**Event Elapsed Time**	
		Mean	± 5 %
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
Cyle time (sum of elapsed times)			

Notes:____

____

Appendix B10. Analyst's Cycle Criteria Definitions and Values

Project Name: ________________________________ Test_ID: ____________Date: _____________

Compiled by (Company) ________________________ Cycle_ID: ___________

Name (printed): _______________________________ Signature: _______________________________

See Appendix B6 for simple cycle instructions. See Appendix B10 for synthesized duty cycle instructions. Use additional sheets for more events if necessary.

Criteria_1 definition: ____

Criteria_2 definition: ____

		Criteria_1 Values					**Criteria_2 Values**				
Index	**Event_ID**	**Run 1**	**Run 2**	**Run 3**	**Mean**	σ_{n-1}	**Run 1**	**Run 2**	**Run 3**	**Mean**	σ_{n-1}
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											

Notes: ____

____

____

Appendix B11. Cycle Criteria Worksheet and Test Run Validation

Project Name : ______________________________ *Test_ID* : __________

Cycle_ID : ___________ *Run_ID* : ______ *Date* : ____________*Valid Run? (y/n)* : ___

Compiled by (printed) : ______________________ *Signature* : _________________________________

Diff = Actual minus Mean. Check "OK?" if Diff is less than the tolerance, ± (1.7 * σ_{n-1}) for cycle criteria.

Index	Event ID	Criteria_1					Criteria_2				
		Mean	**1.7*σ_{n-1}**	**Actual**	**Diff**	**OK?**	**Mean**	**1.7*σ_{n-1}**	**Actual**	**Diff**	**OK?**
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											

Appendix B12
Synthesized Duty Cycle Development and Test Run Instructions

1. Install a datalogger on ECM-equipped engines. Configure the datalogger to record the following parameters at 1 Hz:

- percent load
- turbocharger boost pressure
- engine speed, RPM
- exhaust gas temperature (optional)
- net brake torque (optional)
- fuel consumption (optional)

Install sensors and a datalogger on mechanically-controlled engines. Configure the datalogger to record the following parameters at 1 Hz:

- engine speed, RPM
- turbocharger outlet temperature (T_{turb}) or exhaust gas outlet temperature (T_{out})
- exhaust gas flow surrogate, $\sqrt{\Delta P}$ high (ΔP sensor range 0 - 10 "H_2O)
- exhaust gas flow surrogate, $\sqrt{\Delta P}$ low (ΔP sensor range 0 - 1 "H_2O)
- fuel supply flow rate (optional)
- fuel return flow rate (optional. Note: for diesel engines, fuel consumption is the difference between fuel supply and return flow rates)

2. Dispatch the nonroad equipment and log normal in-use operations over 3 separate observation periods, generally longer than 1 hour each. Observe (or record by video) each operations period and record event descriptions as they occur on Appendix B11. This will aid event identification during operations analysis. Synchronize observations with the datalogger clock and timestamp.

3. Examine the three completed Appendix B11 forms for events that should be defined uniquely or repeated events that meet a single definition. Create event descriptions and identifiers (such as "Back1") based on the three observation periods. Repeated sequences of simple events may be combined into composite events. Event elapsed times (the difference between start time and end time), functions performed (such as backing loaded verses backing empty), work location, or other factors should contribute to event descriptions. For example, traveling for a short distance empty may require a different event definition than traveling for a long distance empty because the elapsed times would be significantly different. Assign a unique identifier, or *Event_ID*, to each event such as "Travel1" and enter the descriptions in Appendix B7. The Event_ID will serve as a shorthand designator for each observed event.

4. Analyze the event data recorded during each observation period (Obs_1, Obs_2, Obs_3) on three separate Appendix B12 forms. List Event_IDs from Appendix B7 in the order in which they occurred during the observation period. Transfer the observed elapsed time for each event from the Appendix B11 form for the observation period being analyzed. For each Event_ID, obtain the logged data and calculate the mean and σ_{n-1} for each logged parameter and enter the values in Appendix B12.

5. Aggregate the data from the three Appendix B12 forms into Appendices B13 and B14. For each Event_ID, calculate the mean elapsed time and σ_{n-1} for all three observation periods. Also calculate the mean and σ_{n-1} for each logged parameter. Enter the results on B13. Calculate event frequencies and time proportions over all three observation periods for each Event_ID and record on B14.

6. Use the analyses in Appendices B13 and B14 to create the synthesized duty cycle. Some considerations:

- specify the synthesized duty cycle as a logical sequence of Event_IDs
- event time proportions should be similar to those observed. For example, if "Back1" occupies 25 % of total elapsed time during observations, the synthesized duty cycle should include enough Back1 events to yield a similar time proportion.
- event frequencies should be similar to those observed. For example, if "Back1" represents 15 % of all events observed, Back1 events should comprise approximately 15 % of all synthesized duty cycle events.
- synthesized duty cycle durations typically range between 20 minutes and 1 hour

7. List the synthesized duty cycle events in sequence, accompanied by specified time durations, on Appendix B7. Dispatch the nonroad equipment to perform the synthesized duty cycle while logging the parameters listed in step 1 above.

8. For each Event_ID, record the elapsed times and the mean and σ_{n-1} for each logged parameter on Appendix B12. The values for each Event_ID should be within ± 5 % of those observed for that event during the in-use observation periods.

9. Perform the Wilcoxon Rank-Sum as described in Appendix D1.4 on the data gathered in step 7. If the test statistic Z_i is acceptable ($-1.96 \le Z_i \le 1.96$), the synthesized duty cycle fairly represents the in-use observations and the duty cycle is suitable for testing. Record the Z_i value on Appendix B8.

10. Develop the appropriate cycle criteria. Examples are:

- ECM-equipped engines
  - RPM multiplied by torque
  - percent load
- mechanically-controlled engines
  - RPM multiplied by T_{turb}
  - RPM multiplied by $\sqrt{\Delta P}$

Calculate the expected cycle criteria mean and σ_{n-1} values for each Event_ID based on the data gathered in step 7 above. Record the cycle criteria descriptions and expected values on Appendix B8.

11. Log the same engine and equipment parameters during each test run as were logged during the in-use observation periods.

12. At the end of each test run, enter the elapsed time for each event into Appendix B9. The elapsed time should be within ± 5 % of the value observed based on the data gathered in step 7 above.

13. Enter the mean value for each cycle criteria into Appendix B9. The value should be within ± ($1.7 * \sigma_{n-1}$) of the value observed based on the data gathered in step 7 above.

14. The test run is valid if the elapsed times and cycle criteria are within the stated elapsed time and cycle criteria tolerances.

Appendix B13
In-Use Operations Observations

Project Name: ______________________ Test_ID: __________ Date: __________

Compiled by (Company) ______________________ Obs_ID: ________

Name (printed): ______________________ Signature: ______________________

See Appendix B9 for detailed instructions. Use additional sheets for more events if necessary. Enter the observing period identification as *Obs_1, Obs_2,* or *Obs_3* under "Obs_ID" above. Use good judgment to separate events from one to the next.

Event Description	Start Time	End Time	Elapsed Time

Notes:

____

____

____

____

Appendix B14
In-Use Operations Analysis

Project Name: ______________________________ Test_ID: __________ Obs_ID: ___________ Date: _____________

Compiled by (printed): ___________________________________ Signature: ______________________________________

See Appendix B9 for detailed instructions. Enter the logged parameter descriptions (percent load, RPM, T_{turb}, etc.) in the appropriate columns (Parm_1, Parm_2, etc.). Obtain Event_ID event identifiers from Appendix B6.

Observation period start time: __________ End time: _________ Elapsed time: ___________

Index	**Event_ID**	**Event End Time**	**Event Elapsed Time**	**Parm_1:**		**Parm_2:**		**Parm_3:**		**Parm_4:**	
				Mean	σ_{n-1}	**Mean**	σ_{n-1}	**Mean**	σ_{n-1}	**Mean**	σ_{n-1}
1											
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											
19											
20											
21											
22											
23											
24											

Appendix B15
In-Use Operations Summary

Project Name: ______________________________ Test_ID: __________ Date: _________________

Compiled by (printed): ___________________________________ Signature: _____________________________________

Enter the logged parameter descriptions (percent load, RPM, T_{turb}, etc.) in the appropriate columns (Parm_1, Parm_2, etc.). Use Event_ID identifiers, elapsed times, and parameter data from Obs_1, Obs_2, Obs_3 log sheets (Appendix B11). For each event, compute the overall mean and σ_{n-1} for each logged parameter. For events which occurred 3 times or more, compute overall mean and σ_{n-1} elapsed time.

Event_ID	**Elapsed Time**		**Parm_1:**		**Parm_2:**		**Parm_3:**		**Parm_4:**	
	Mean	**σ_{n-1}**	**Mean**	**σ_{n-1}**	**Mean**	**σ_{n-1}**	**Mean**	**σ_{n-1}**	**Mean**	**σ_{n-1}**

Appendix B16
In-Use Operations Descriptive Statistics

Project Name: ______________________________ Test_ID: ___________ Date: ___________

Compiled by (Company) ___________________________

Name (printed): ______________________________Signature:______________________________

Use Event_ID identifiers, elapsed times, and Index numbers from Obs_1, Obs_2, Obs_3 log sheets (Appendix B11). Each time a given event occurred during in-use operations, record the index number in the appropriate "*Occurrences*" column.

Freq_evt is the total tally of index numbers over all three observation periods for each event. Freq_tot is the total tally of index numbers for all events. Freq_prop is Freq_evt divided by Freq_tot for each event.

Time_evt is the total elapsed time over all three observation periods for each event, as obtained from Obs_1, Obs_2, Obs_3 log sheets (Appendix B11). Time_tot is the total elapsed time over all three observation periods for all events. Time_prop is Time_evt divided by Time_tot for each event.

Event_ID	**Occurrences**					**Elapsed Times**	
	Obs_1 Index #s	**Obs_2 Index #s**	**Obs_3 Index #s**	**Freq_evt**	**Freq_prop**	**Time_evt**	**Time_prop**
			Freq_tot		**Time_tot**		

Appendix B17
Test Run Summary

Project Name: ______________________________ *Test_ID*: ___________

Site_ID: ____________ *Cntrl_ID*: ____________ *Equip_ID*: _____________

Compiled by (Company): ____

Name (printed): ____________________________ *Signature*: _____________________________

Test description: *(check one)*
☐Control strategy baseline ☐Control strategy candidate
☐In-use evaluation ☐Emissions method comparison
☐Extended interval initial ☐Extended interval final

Duty cycle: ☐Simple; *Cycle_ID*: _________ ☐Synthesized; *Cycle_ID*: __________ ☐In-Use

Fuel type: ☐ULSD ☐on-highway diesel ☐nonroad diesel (dyed) ☐other: ___________________
(Optional): *Batch / lift number*: ___________ *Delivery date*: _____________ ☐*Analysis attached*

IMPORTANT: Each test run MUST be accompanied by a "Test Run Record" which documents the emissions measurement equipment pretest and post-test zero, span, calibration, performance, or other checks. Appendix B16 provides a sample form.

Enter test run dates, Run_ID, start time, end time, elapsed times, and filenames below.

Date	**Run_ID**	**Start Time**	**End Time**	**Elapsed Time**

Date	**Run_ID**	**PEMS Filenames**

Date	**Run_ID**	**Datalogger or Other Filenames**

Appendix B18. Horiba OBS-2200 Test Run Record

Project Name: ____________________________ *Test_ID*: _________ *Date*: _____________

Site_ID: ________________________________ *Equip_ID*: _____________ *Run_ID*: ________

Name (printed): ______________________________ *Signature*: _______________________________

PEMS S/N:_______________________________ *Last 11-point Calibration Date*: _________________

Filename: ____

Test Run *Truck operator name*: ____________________________________

Start time (hh:mm:ss; use 24-hour clock): ______________ *End time*: _______________

Describe ambient conditions: ____

Wind speed (estimate): ____________ *Direction*: ______________ ☐ Fair ☐ Overcast ☐ Precipitation

IMPORTANT: Enter the calibration (or span) gas concentrations, 2 %, and 4 % of each value in the cells marked "*" below. After each OBS-2200 test run, acquire the appropriate zero drift and span drift values from the "..._b.csv" worksheets. Cell references are provided.

Subtract the zero drift and span drift responses in the "..._b.csv" file from the calibration (or span) gas concentration. Enter the result in the table and compare to the ± 2 % or ± 4 % criteria.

Enter "✓" if a parameter is acceptable, "X" or "Fail" if it is unacceptable. Discuss all "Fail" entries and indicate whether the run is invalid because of them in the Notes below.

PEMS Zero and Span Drift Checks

Analyte	Calibration (or span) gas concentrations (ppmv or %)	± 2 % of Cal (or span) gas value	✓ if Zero drift OK (≤ ± 2 % of span Cells I3 : I6)	± 4 % of Cal (or span) gas value	✓ if Span drift OK (≤ ± 4 % of span Cells J3 : J6)
CO	*	*		*	
CO_2	*	*		*	
THC	*	*		*	
NO_X	*	*		*	

Parameter	Criteria		✓ if OK
Allowable ambient temperature range (see _b.csv worksheet Cells M16 : EOF)	within ± 10 °F (6 °C) for T_{amb} ≤ 80 °F (27 °C)		
	within ± 5 °F (3 °C) for T_{amb} > 80 °F (27 °C)		
Allowable barometric pressure range (see _b.csv worksheet Cells N16 : EOF)	within ± 1" Hg (3.4 kPa)		
Allowable "Hangup" (NMHC contamination) (see _b.csv worksheet Cell Z5)	Enter expected THC concentration, ppmv as C		
	Enter 2 % of expected concentration		
	"Hangup must be < 2 % of expected concentration		

NMHC contamination and background check ≤ 2ppmv or ≤ 2 % of conc. ΔP line leak check must be stable for 15 seconds at 3 "H_2O. DSS sample bag and dilution tunnel leak check < 0.5 % of normal flow rate. Mean P_{bar} within ± 1.0 "Hg of mean for all test runs. Mean T_{amb} within ± 10 °F of mean for all test runs if T_{amb} is < 80 °F. Mean T_{amb} within ± 5 °F of mean for all test runs if T_{amb} is ≥ 80 °F. Drift = (Post-test span minus Pre-test span); must be ≤ 4.0 %.

Notes: ____

____

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____

APPENDIX C
ANALYTICAL PROCEDURES

1.0 STATISTICAL ANALYSIS

1.1. STATISTICAL SIGNIFICANCE

Test campaigns often include performance comparisons between a baseline and candidate, between two measurement systems, or other types of paired test conditions. All campaigns should specify at least three test runs under each condition. The difference between the mean result for each test condition is the basis for the comparison.

Analysts should first examine the data set for outliers (such as mean emission rates or other parameters) for each test run. They should consider removing those that meet criteria described in ASTM E178-02 [C1] prior to further analysis. More than three test runs are generally necessary for this because at least three data points are needed for the following calculations. The next step is to evaluate the statistical significance of the difference between the two test conditions. If the difference is significant, analysts can then calculate the difference's confidence interval.

After the 3rd test run, and after each following run, analysts will calculate a test statistic, t_{test}, and compare it with the Student's T distribution value with ($n_1 + n_2 - 2$) degrees of freedom as follows [C2]:

$$t_{test} = \frac{(\overline{X}_1 - \overline{X}_2) - (\mu_1 - \mu_2)}{\sqrt{s_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \qquad \text{Eqn. C-1}$$

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \qquad \text{Eqn. C-2}$$

Where:

X_1	=	mean result for first test condition
X_2	=	mean result for second test condition
$\mu_1 - \mu_2$	=	zero (H_o hypothesizes that there is no difference between the population means)
n_1	=	number of repeated test runs for first test condition
n_2	=	number of repeated test runs for second test condition
s_1^2	=	sample standard deviation for first test condition, squared

s_2^2 = sample standard deviation for second test condition, squared
s_p^2 = pooled standard deviation, squared

Selected T-distribution values at a 95-percent confidence coefficient ($t_{0.025,\ DF}$) appear in the following table [C2].

Table C-1. Selected T-distribution Values			
n_1	**n_2**	**Degrees of Freedom, DF (n_1+n_2-2)**	**$t_{0.025,\ DF}$**
3	3	4	2.776
3	4	5	2.571
4	4	6	2.447
4	5	7	2.365
5	5	8	2.306
5	6	9	2.262
6	6	10	2.228

If $t_{test} > t_{0.025,DF,}$ conclude that the data shows a statistically significant difference between the two test conditions. Otherwise, conclude that a significant difference does not exist. If significant, report the difference and its confidence interval (see §C1.3).

1.2. SAMPLE VARIANCE SIMILARITY

Use of equations C-1 and C-2 requires the assumption that the two test condition populations have similar variance. The ratio of the sample variances (sample standard deviation squared) between the two test conditions is a measure of this similarity [C3]. Analysts will calculate an F_{test} statistic according to equation C-3 and compare the results to the values in Table C-2 to determine the degree of similarity between the sample variances.

$$F_{test} = \frac{s^2_{\max}}{s^2_{\min}} \qquad \text{Eqn. C-3}$$

Where:

F_{test} = F-test statistic
s^2_{max} = larger of the sample standard deviations, squared
s^2_{min} = smaller of the sample standard deviations, squared

Table C-2 [C2] presents selected $F_{0.05}$ distribution values for the expected number of test runs and the acceptable uncertainty ($\alpha = 0.05$).

Table C-2. Selected $F_{0.05}$ Distribution Values					
	s^2_{max} number of runs	**3**	**4**	**5**	**6**
s^2_{min} number of runs	**Degrees of Freedom**	**2**	**3**	**4**	**5**
3	**2**	19.00	19.16	19.25	19.30
4	**3**	9.55	9.28	9.12	9.01
5	**4**	6.94	6.59	6.39	6.26
6	**5**	5.79	5.41	5.19	5.05

If the F-test statistic is less than the corresponding value in Table C-2, then analysts will conclude that the sample variances are substantially the same and the statistical significance evaluation and confidence interval calculations are valid approaches. If the F-test statistic is equal to or greater than the Table C-2 value, analysts will conclude that the sample variances are not the same and will consequently modify the confidence interval calculation according to Satterthwaite's approximation [C3]. The report will discuss Satterthwaite's approximation if the actual test data indicate that it must be applied.

1.3. 95-PERCENT CONFIDENCE INTERVAL

Analysts will calculate the 95-percent confidence interval if a statistically significant difference between the two test conditions is observed. The half width (e) of the 95 percent confidence interval is [C2]:

$$e = t_{.025,DF}\sqrt{s_p{}^2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)} \qquad \text{Eqn. C-4}$$

The difference between the two test conditions can then be reported as $(X_2 - X_1) \pm e$.

1.4. WILCOXON RANK-SUM TEST

The Generic Protocol §5.1.4 recommends the Wilcoxon Rank-Sum Test [C2] for evaluating whether a synthesized duty cycle represents the observed nonroad equipment behavior. Step-by-step procedures are:

1. Perform a trial run of the proposed synthesized duty cycle and log elapsed time, RPM, T_{turb}, T_{out}, exhaust gas flow (or a surrogate), percent power (ECM-equipped engines), torque (ECM-equipped engines), or other appropriate parameters.
2. Aggregate data for each parameter from one of the normal operations period data sets with that logged during the duty cycle trial run.
3. Rank the data in ascending order.

4. Search for 2 or more identical values in the ranked data. If any are present, assign the average ranking of their positions in the data set according to the following example:

Value	**Assigned Rank**
...	...
303.2	209
304.0	211
304.0	211
304.0	211
304.8	213
...	...

5. Dis-aggregate the normal operations period data from the duty cycle run.
6. Calculate the sum of the rankings assigned to the normal operations period, W
7. Calculate the mean and standard deviation of the W distribution as:

$$\mu_W = \frac{n_{ops,i}\left(n_{ops,i} + n_{DutyCycle} + 1\right)}{2} \qquad \text{Eqn. C-5}$$

$$\sigma_W = \sqrt{\frac{n_{ops,i} n_{DutyCycle}(n_{ops,i} + n_{DutyCycle} + 1)}{12}} \qquad \text{Eqn. C-6}$$

Where:

μ_W = mean of W distribution

σ_W = standard deviation of W distribution

$n_{ops,i}$ = number of records logged in the normal operations period “i”

$n_{DutyCycle}$ = number of records in the duty cycle run

8. Calculate the test statistic:

$$Z_i = \frac{W - \mu_W}{\sigma_W} \qquad \text{Eqn. C-7}$$

9. For $\alpha = 0.05$, $-1.96 \le Z \le 1.96$ implies that the duty cycle and normal operations data from logging period i come from the same population and that the synthesized duty cycle is a “fair” representation.
10. Perform the same analysis for the other two logged normal operations periods.

2.0 IN-USE DATA ANALYSIS TECHNIQUES

2.1. 30-SECOND OR DEFINED INTERVAL SLIDING WINDOW DESCRIPTIVE STATISTICS

The detailed in-use behavior of nonroad equipment is inherently noisy because of operator variability, transients, varying ambient conditions, and process material properties. Sliding window analysis may allow a more realistic assessment of in-use performance because it tends to average out the very short-term high and low values. A 30-second sliding window includes all the data in a rolling segment that is 30 seconds wide. The first window includes data from second number 1 through second number 30. The second window includes second number 2 through second number 31, and so on.

Figure C-1 shows the relationship between the 1-second realtime intake air flow on a rubber-tired loader, 30-second, and 60-second sliding windows. In this case, a 30-second sliding window interval strikes a compromise between the original data and the over-simplified 60-second interval. Analysis of the 30-second sliding window average descriptive statistics (maximum, mean, standard deviation, median, and frequency distributions) may be especially useful for control strategy performance analysis. The mean value between seconds 360 and 627, for example, could serve as the baseline comparison point if similar patterns exist in the candidate test results.

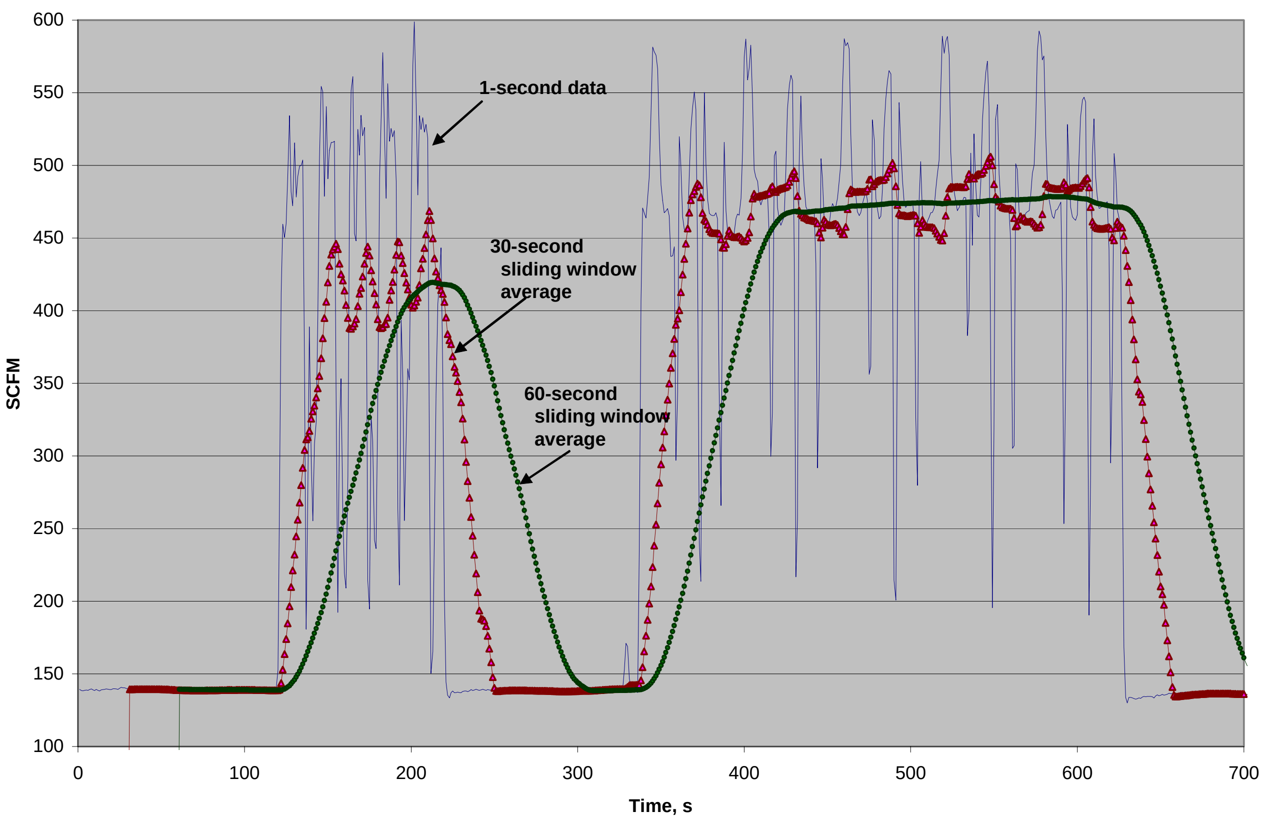

Figure C-1. Sliding Window Averages

Site-specific protocols may use defined interval widths other than 30-seconds as required.

2.2. OPERATING EVENT DESCRIPTIVE STATISTICS

In-use performance data will likely include repetitive patterns which are similar to the duty cycle events described in the Generic Protocol §5.1. These events, especially those which occur at elevated torque and RPM, are analogous to the NTE events of 40 CFR 86, and could serve for baseline / candidate performance comparisons. Figures C-2 and C-3 illustrate this concept.

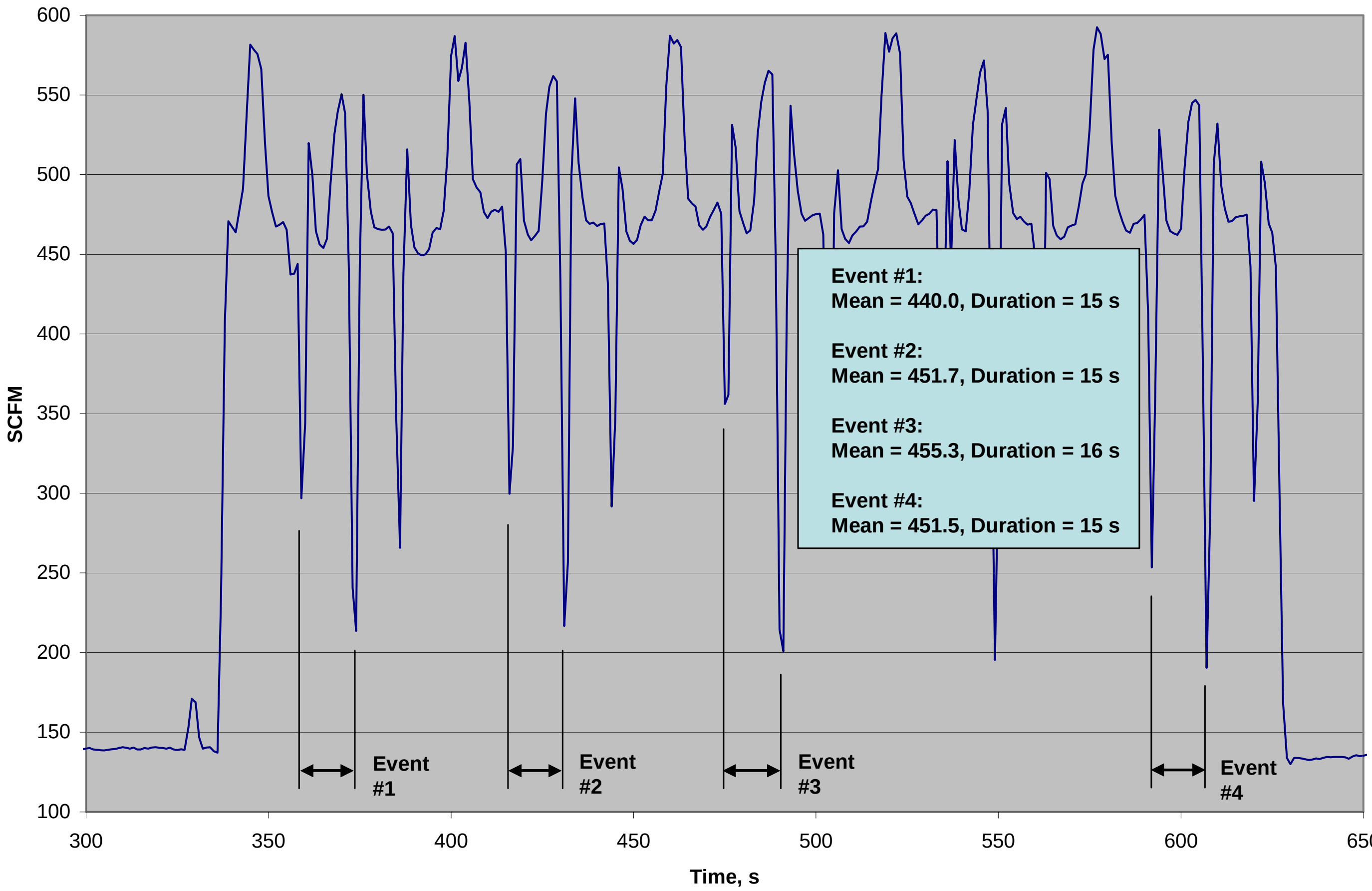

Figure C-2. In-use Events

Table C-3 presents some descriptive statistics on the 4 transient in-use events shown in Figure C-2. The events could form the baseline comparison point of a control strategy evaluation if similar patterns appear during both baseline and candidate testing, but the descriptive statistics can indicate whether a particular event should be included in the analyis.

Table C-3. Rubber Tire Loader Descriptive Statistics, SCFM						
Event_ID	**Maximum**	**Minimum**	**2^{nd} Minimum**	**Mean**	**Median**	**σ_{n-1}**
1	550	214	297	440	462	108
2	558	217	300	458	468	98
3	563	201	356	455	477	112
4	544	190	253	452	469	168

At first glance, all four events may appear to be eligible for inclusion in a data set. The means for each Event_ID are within approximately 2.5 percent of the overall mean. The medians are between 2.2 and 5 percent greater than the means. This can indicate that SCFM trends consistently upward during each event in a repeatable pattern. The minimum and maximum values are reasonably similar for all Event_IDs.

The 2^{nd} minimum and σ_{n-1} values for event number 4, however, show that it is quite different from the others even though the graphic representation in Figure C-2 makes it appear similar. In particular, σ_{n-1} for that event is about 60 percent higher than for all of the others while σ_{n-1} for events 1, 2, and 3 vary only about 14 percent between the lowest and highest values. For whatever reason, SCFM varied much more during event number 4 (as shown by the large σ_{n-1}), and analysts would have good reason to exclude it from calculating a mean value. This would be especially relevant for baseline / candidate control strategy evaluations based on in-use data.

Figure C-3 shows two "composite" events obtained from the rubber-tired loader data. A composite event is a repeated sequence of simple transient events such as those shown in Figure C-2, and similar statistical analyses could be applied.

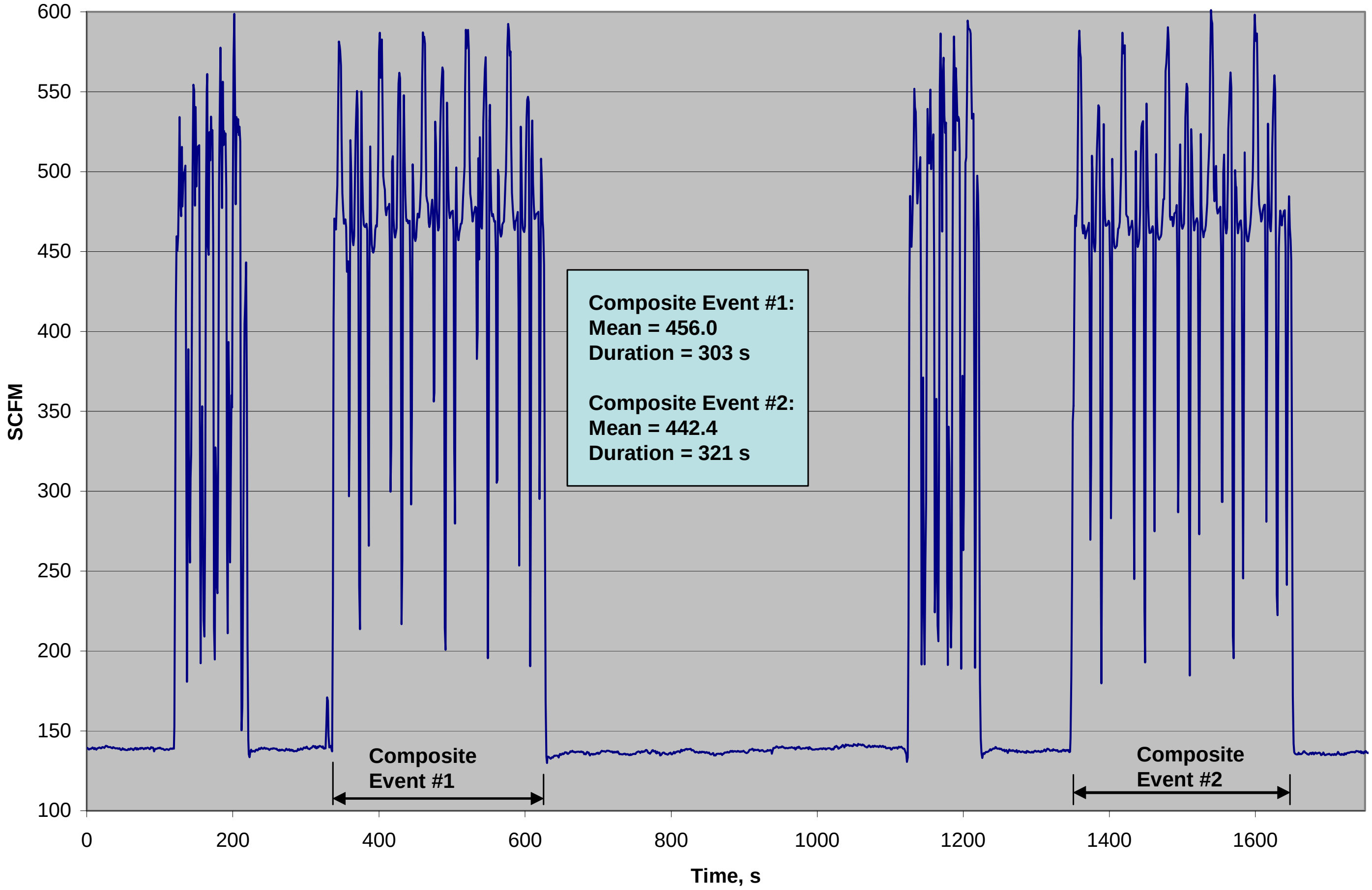

Figure C-3. Composite In-Use Events

2.3. NORMALIZATION

Different types of normalization or correlations could reveal trends or data subsets amenable to further analysis. Normalization is the ratio of two or more parameters, such as NO_X divided by bhp-h, which yields brake-specific NO_X. Other normalizations may be useful. Figure C-4 shows a time series plot of SCFM divided by RPM for a series of rubber-tired loader tests. C-5 provides the frequency distribution of this relationship. The events when SCFM / RPM is near 0.15 or 0.21 are likely to be of interest because they happen more often than any others.

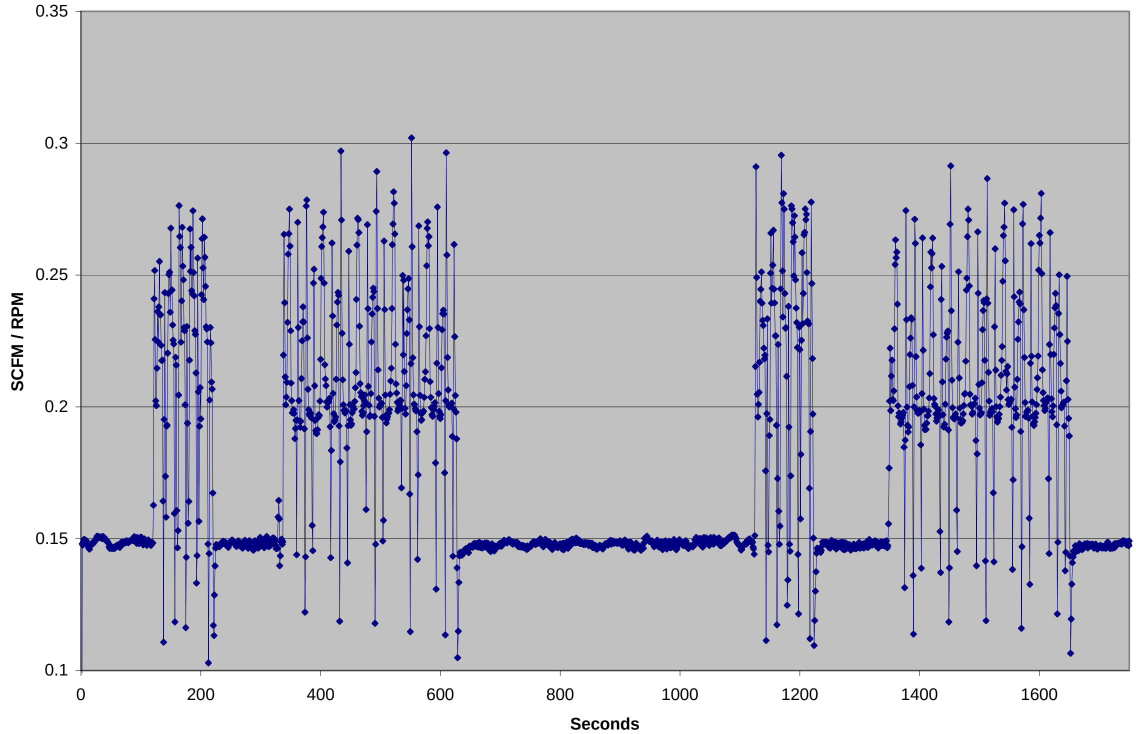

Figure C-4. SCFM Divided by RPM Time Series Plot

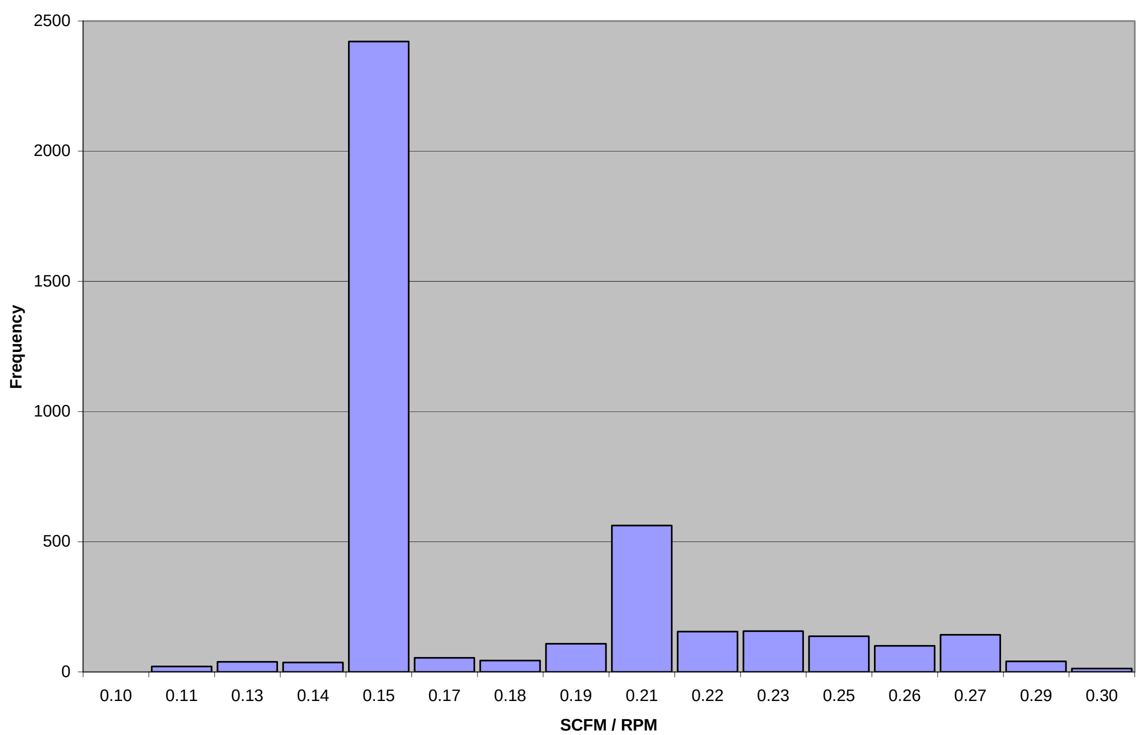

Figure C-5. Frequency Distribution of SCFM Divided by RPM

Correlations such as emissions as a function of engine power are also likely to be revealing. Figure C-6 shows SCFM as a function of RPM for a rubber-tired loader.

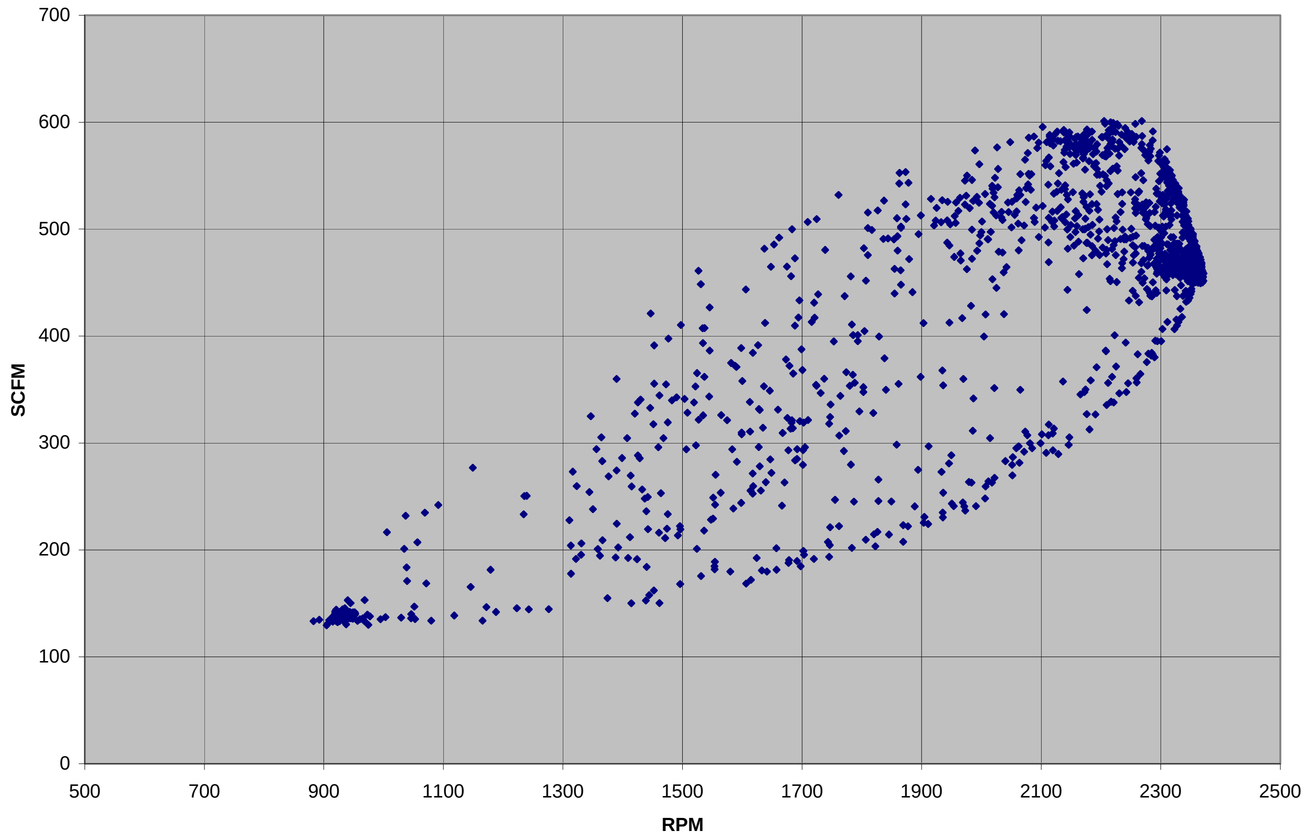

Figure C-6. SCFM versus RPM

In this case, the tight cluster of data points between 2280 and 2370 RPM and 440 and 490 SCFM shows that this is a frequently-occurring operating characteristic. The emissions associated with those data points may form a reasonable selection set for baseline / candidate comparisons.

3.0 REFERENCES

[C1] *Standard Practice for Dealing with Outlying Observations, ASTM E178-02*, ASTM International, West Conshohocken, PA 2002

[C2] *Statistics Concepts and Applications*, D.R. Anderson, E.J. Sweeney, T.A. Williams. West Publishing Company, St. Paul, MN. 1986

[C3] *A Modern Approach to Statistics*, R.L. Iman, W.J. Conover. John Wiley & Sons. New York, NY. 1983