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Development of a Reference Dataset to Evaluate PEMS Post-Processing Software

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Development of a Reference Dataset to Evaluate PEMS Post-Processing Software

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Development of a Reference Dataset to Evaluate PEMS Post-Processing Software

Hemanth K. Kappanna

Abstract

Since the implementation of in-use emissions standards, an outcome of the consent decree between heavy-duty diesel engine manufacturers and the Environmental Protection Agency (EPA), there has been an increased interest in the research and development of portable emissions measurement systems (PEMS) that are capable of analyzing exhaust emissions continuously while a vehicle or equipment powered by an internal combustion engine is performing its intended vocation. Ultimately for an engine to pass in-use emissions requirements, the brake specific emissions of regulated pollutants measured over valid Not-to-Exceed (NTE) events must be less than or equal to 1.25 or 1.5 times the engine emission certification standards, based on the engine model year (MY), plus an additional margin known as in-use measurement allowance. The vehicle has to satisfy the in-use emissions standard for 90% of the NTE events provided the brake specific emissions over the rest of the events are less than two times the certification level to comply with in-use emission regulations.

As in-use emissions measurement and regulation together form a requirement since 2004 for certification of engines, it is imperative to develop procedures of oversight similar to ones that exist for laboratory-based engine certification. Therefore, a reference data set that incorporates all the in-use emissions regulations used to quantify the measured emissions over an NTE event, including the conditions used to validate an NTE event is developed in the direction of providing a means to validate commercial PEMS data analysis software.

A reference data set was designed and used to evaluate the post-processing software of two commercial PEMS devices. A black box testing methodology was implemented to evaluate the performance of the post-processing software. Specifically, the input data set was developed to execute different sections of the program based on logical conditions required to branch into a particular section therefore verifying the truth in executing a logical condition and the interpretation of in-use emissions regulation. Also, the brake specific emissions results to be expected from the given input data set were known *a priori* to verify the accuracy of the equations used in calculating the final emissions results. The dataset was also used to evaluate PEMS data post-processing software developed at WVU.

The test results indicated that definition of NTE emissions performance was not in agreement for the post-processing software evaluated. Being that compliance is required for manufacturers to sell engines without penalty, it is critical that the metric by which compliance is assessed must be accurate and robust. As such, the reference data set developed will serve in identifying interpretation errors of in-use emissions regulations as well as calculation error and reduce the chances of triggering false positives and negatives that could prove costly to engine manufacturers as well as air quality regulating agencies. This reference data set will also serve in effective implementation of any modification of existing or additional new in-use emissions compliance requirements and verify it across different in-use emissions data post-processing software supplied by PEMS manufacturers and developed in-house. Test results showed that PEMS post-processors outcome were not in agreement with expected total number of 166 NTE events as the in-house, PEMS A and PEMS B returned 216, 288 and 190 NTE events respectively. The reference dataset was instrumental in identifying interpretation error in the in-house data post-processor leading to a revised version of the software that matched the expected results.

This dissertation is dedicated to my teachers
and my brother Ravi K. Kappanna.

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List of Acronyms

AECDs: Auxiliary Emissions Control Devices
AT Regen: Aftertreatment Regeneration
BS: Brake Specific
BSFC: Brake Specific Fuel Consumption
CAA: Clean Air Act
CAN: Controller Area Network
CARB: California Air Resources Board
CFR: Code of Federal Regulation
CLD: Chemiluminescence Light Detector
CO: Carbon Monoxide
CO_2: Carbon Dioxide
CRC: Coordinated Research Council
CRT: Continuously Regenerating Trap
CT: Compliance Test
CVS: Constant Volume Sampling
DOC: Diesel Oxidation Catalyst
DPF: Diesel Particulate Filter
ECM: Engine Control Module
ECU: Engine Control Unit
EDF: Empirical Distribution Function
EFM: Exhaust Flow Meter
EGR: Exhaust Gas Recirculation
EMA: Engine Manufacturers Association
EMTC: Emissions Measurement and Testing Committee
EPA: Environmental Protection Agency
ESC: European Stationary Cycle
ETCS: Electronic Throttle Control System
FDA: Food and Drug Administration
FEL: Family Emission Limit
FTIR: Fourier Transform Infra Red
FTP: Federal Test Procedure

HDDE: Heavy-Duty Diesel Engines

HDIUT: Heavy-Duty In-Use Emissions Testing

HFID: Heated Flame Ionization Detector

HHD: Heavy Heavy-Duty

HHDDT: Heavy Heavy-Duty Diesel Transient

h-NDIR: Heated NDIR

I/M: Inspection and Maintenance

IMT: Intake Manifold Temperature

LDVs: Light Duty Vehicles

LFE: Laminar Flow Element

LHD: Light Heavy-Duty

LNT: Lean NOx Trap

LTRs: Limited Testing Regions

MEL: Mobile Emissions Laboratory

MEMS: Mobile Emissions Measuring System

MHD: Medium Heavy Duty

MY: Model Year

NAAQS: National Ambient Air Quality Standards

NASA: National Aeronautics and Space Administration

NDIR: Non-Dispersive Infra Red

NHTSA: National Highway Transportation and Safety Administration

NMHC: non-Methane Hydrocarbon

NOx: Oxides of Nitrogen

NPRM: Notification for Proposed Rule Making

NRTC: Non-Road Transient Cycle

NTE: Not-to-Exceed

OBD: On-Board Diagnostics

PEMS: Portable Emissions Measurement Systems

PGN: Parameter Group Number

RF: Regeneration Factor

RMCSET: Ramped Modal Cycle Supplemental Emissions Test

RMSE: Root Mean Squared Error

SAE: Society of Automotive Engineers

SAO: Smooth Approach Orifice

SCR: Selective Catalytic Reactor

SEA: Selective Enforcement Audit

SET: Supplemental Emissions Test

SIPs: State Implementation Plans

SPN: Suspect Parameter Number

SRS: Software Requirement Specification

SwRI: Southwest Research Institute

THC: Total Hydrocarbon

TWLTR: Time Weighted Limited Testing Region

WHTC: World Harmonized Transient Cycle

WVU: West Virginia University

ZrO_2: Zirconia

1 INTRODUCTION

1.1 Background

The landmark settlement between seven manufacturers of heavy-duty diesel engines and the US EPA in 1998 for violating the Clean Air Act (CAA) by selling engines equipped with "defeat devices" resulted in consent decrees for each engine manufacturer, which required the manufacturers to meet future NOx emissions standards by Oct 1, 2002, two years earlier than the set date of 2004 by adopting advanced emission reduction technologies and to conduct new emissions compliance testing to quantify emissions during real-world operating conditions. This led to a new discipline of emissions testing known as in-use emissions testing, which involves measurements of emissions using a PEMS from heavy-duty diesel engine powered equipment or vehicles while performing its regular duty cycle. The in-use emission testing is indispensable in detecting "defeat devices" because they are designed to reduce the effectiveness of emission control devices or strategy during normal operating conditions to realize better fuel economy, but allowing the engines to meet EPA emissions standard during engine certification tests in the laboratory. It was estimated that about 1.3 million tons of excess NOx was emitted in 1998 alone from the engines equipped with such "defeat devices" [1].

During this settlement, the engine manufacturers disputed the use of "defeat devices" and claimed them to be auxiliary emission control devices (AECDs). AECDs are defined as physical devices or elements of design such as an algorithm in an electronically controlled engine which activates, delays, modulates, or deactivates the operation of emission control systems based on the inputs from the sensors measuring temperatures, pressures, engine speed, vehicle speed, etc. in order to manage the performance of engine and emissions control devices at its optimum condition, and protect them from conditions that leads to breakdown of the system [2]. These claims led the US EPA to set forth stringent regulations for the usage of AECDs that required the engine manufacturers to disclose all such devices and provide justification for the use of each one of them. It also requires the engine manufacturers to demonstrate the use of an AECD during Federal Test Procedure (FTP), an engine certification test for emissions compliance, if they are activated during normal operation and use of the vehicle. EPA also required the use of AECDs to be limited to engine startup to reduce unburned hydrocarbons, engine overheating conditions, and for operations at high altitudes where ambient pressure is lower than 82.5 kPa (above 5,500 feet). Nonetheless, the engine manufacturers were mandated to demonstrate the lowest level of NOx that was possible to achieve with the use of any AECDs before they are approved. In addition to the above requirements, EPA required the engine manufacturers to demonstrate that the engines will meet the emissions standards through Supplementary Emissions Test (SET), a steady state engine dynamometer test, and in-use testing of the engines to prove they were not employing defeat devices during normal operating conditions. Furthermore, the consent decrees required the engine manufacturers to meet future emissions standards two years before the deadline of 2004 to reduce excess levels of ambient pollution caused by the engines that were sold with the alleged defeat devices and collectively invest up to 1 billion dollars to develop new engine technologies and emissions control systems to meet future emissions standards [3 - 8]. These actions led to industry-wide research in developing new engine technologies and aftertreatment devices to achieve EPA mandated emissions standards along with new sets of regulations and emissions measurement methods to measure lower emissions concentrations not only in the laboratory, but also in field. As a result, the emerging field of in-use emissions measurement received much needed impetus to become an accepted method for in-use certification of heavy-duty diesel engines that were traditionally certified only in the laboratory based on a standard engine test cycle called FTP cycle.

The settling heavy-duty diesel manufacturers identified West Virginia University (WVU) to lead the in-use emissions measurement of the engine families that were ear-marked for in-use emissions compliance by the US EPA. The project was conducted in four phases testing engines of MY 1999 through 2003, which included pre- and post-consent decree engines. A total of over 150 vehicles of different configurations and engines from different manufacturers were tested during this project. This project was focused on sourcing or developing a device capable of measuring gaseous emissions onboard a vehicle performing its intended vocation. Consequently, WVU developed a portable emissions measuring device known as Mobile Emissions Measuring System (MEMS) that served as the benchmark system for the existing commercially available PEMS devices. WVU also played a key role in developing in-use emissions measurement protocols that became the EPA standard for measuring in-use emissions [9]. In-use emissions testing has generated interest in areas other than emissions compliance, such as engine design improvement, emissions inventory modeling, demonstration of the potential of retrofit devices used to improve the engine efficiency without degrading exhaust emissions, and developing engine test cycles to include engine operating conditions not represented in the FTP cycle to address increased emissions at those conditions; for example duty cycle of a diesel powered vehicle equipped with urea-based selective catalytic reactor (SCR) whose exhaust temperatures are below the catalyst light-off temperature in order to reduce NOx. In-use emission testing is also adopted as a type approval test for heavy-duty engines in the EU, but with different set of requirements than followed in the USA and is known as the moving averaging work window method. In this method, in-use emissions are measured over a period of time and later the emissions accrued over a window of time during which the accumulated work of the engine is equal to or greater than the work performed over certification cycle should meet the conformity factor, which is a ratio of measured emissions over the work window to the applicable certification limit of the pollutant [10]. The in-use emissions regulations as per US EPA requires the emissions of an engine operating in an NTE zone, a region under the maximum torque curve defined by the engine speed, torque and power, continuously for a period of at least 30 seconds to be lower than 125 to 150%, based on the engine MY and certification standard, of the certification level of that pollutant to pass the emissions compliance test [11].

1.2 US EPA In-Use Emissions Compliance

At the conclusion of the in-use emissions testing program performed by WVU and establishing initial framework on conducting in-use emissions test, under the auspices of consent decrees, EPA and California Air Resources Board (CARB) required the engine manufacturers to carry out in-use emissions test of on-highway diesel engines of MY2007 and later vehicles to generate additional in-use emissions data and ensure that the engines met the emissions standards throughout their useful life under normal operating conditions. However, there were ongoing efforts, by the engine manufacturers, PEMS manufacturers and EPA, to refine and improve the quality of in-use emissions measurement to achieve laboratory-grade accuracies. The outcome of which were the projects to develop portable PM measurement devices, capable of measuring gravimetric PM, and to determine measurement allowance for gaseous and PM emissions measured using PEMS. The measurement allowance is an additive factor used to determine the final in-use emissions compliance limit. It represents the margin of error used to compensate for the inaccuracies of a PEMS device when compared to laboratory-grade emission analyzers and flow measuring devices. Further amendments were made to in-use emissions regulations to account for the inabilities of new aftertreatment technologies such as diesel particulate filter (DPF), urea-based SCR, lean NOx trap (LNT), etc. to perform at optimum levels under all operating conditions in the NTE zone. These exceptions to meet in-use emissions standards are known as exclusions similar to the one provided for engine operation at high altitudes, low temperature conditions, and conditions leading to engine overheating.

In 2004, EPA announced a notification for proposed rulemaking (NPRM) establishing a manufacturer-run in-use emissions testing program for 2007 and later MY heavy-duty diesel vehicles [12]. This program was a result of an agreement between EPA and the Engine Manufacturers Association (EMA) to ensure that the benefits of stringent emissions regulations are realized under normal operation and use of the vehicles. The manufacturer-run, in-use NTE testing requires the manufacturers to measure the in-use exhaust emissions from on-highway vehicles using PEMS during their typical on-road operation in addition to engine certification tests such as FTP and SET to ensure that the diesel engines comply with all applicable emissions standards throughout their useful life. It was also agreed that the engine manufacturers will provide the EPA with significant quantities of emissions data generated under this program in order to evaluate that engines comply with the specified emissions requirements, to develop in-use emissions factors to model emissions inventory, and use the data in establishing future emissions standards to meet the National Ambient Air Quality Standards (NAAQS) in several non-attainment regions. This program includes two phases of testing with a minimum of five and a maximum of ten vehicles per engine family in phase I, without requiring phase II tests if there are at least eight vehicles that meet vehicle pass criteria in case the first five out of six vehicles fail to pass. Phase II tests are initiated in the event of not meeting the phase I requirements where ten more additional vehicles including different engine configurations within the engine family are subjected to in-use testing with additional requirements such as the driving routes and ambient conditions in which a vehicle operate being assigned by the EPA.

1.3 Problem Statement

Since the implementation of heavy-duty diesel engine emissions regulation in 1974 under the CAA, all heavy-duty diesel engines have been certified for emissions compliance in a laboratory by operating them over a standard engine test cycle using an engine dynamometer. An FTP heavy-duty transient cycle is used for on-highway engine and different steady state tests for non-road engines based on the application. Emissions measured over these cycles, including engine deterioration factor, account for the emissions over the lifetime of an engine and must be below the standards specified by EPA to comply with emissions regulations. Over the past four decades, these test procedures have been standardized several times over to account for advances in emissions measurement technology and stringent emissions compliance standards in order to achieve repeatability and reproducibility of emissions results, not only in a single laboratory during different period of testing, but also for inter-laboratory precision in emissions results. One of the approaches used to verify the standardization of inter-laboratory precision is the comparison of emissions results from round-robin testing of a single engine across different facilities over different emission certification cycles.

The advent of in-use emissions compliance of heavy-duty diesel engines, which involves interpretation of new regulations that apply to measurements as well as identification of valid NTE events and calculation of brake specific emissions over each event, increases the probability of error in asserting the test results. In addition, in-use emissions testing also poses a challenge in verifying the repeatability and reproducibility of emissions results from a single vehicle since the testing is not performed on a standard test route which makes it difficult to verify the precision of test methods across different PEMS devices. Although, the above challenge can be addressed by measuring in-use emissions from a single test vehicle using several PEMS devices, it becomes difficult to operate the test vehicle to achieve all possible NTE excluding operating conditions, as some are based on the engine technology and requires creating a test route, which defeats the purpose of in-use emissions testing and increases the cost. Currently, the in-use emissions regulation requires emissions measurement from a PEMS device to be verified against laboratory-grade devices by measuring emissions simultaneously from an engine over an FTP transient test cycle before deploying it for use in the field. This aids in verifying the accuracy of emissions measurement and analyzing the emissions data, but falls short in verifying other requirements of in-use emission regulation.

The lack of effort by the EPA to tease out the discrepancy in the emissions results from different PEMS devices over diverse in-use measurement scenarios and the use of dedicated PEMS device manufacturers or their testing services by the engine manufacturers, has created a need for developing a method to identify and address the discrepancies that are anticipated from in-use emissions tests among commercially available PEMS devices

1.4 Objectives

The primary objective of this work is to develop a reference dataset to evaluate the correctness and validity of in-use emissions data post-processing programs. The dataset will aid in identifying interpretation and calculation errors in areas which include validation of NTE events, correction of measured emissions as a function of ambient temperature and humidity, sampling method namely wet and dry sample, and finally in determining vehicle pass/fail results by comparing the calculated brake specific emissions against in-use compliance standards. It will also serve as a means to homogenize the results among different data post-processing software over a given dataset allowing the post-processing applications to be used interchangeably, and to verify the implementation of any amendments to in-use emissions compliance and regulations.

This work will also include a discussion on the method followed in developing the reference dataset in accordance to the in-use emissions regulations. The second objective is to evaluate the response of different stand-alone data reduction software provided along with the PEMS device as well as the response of data post-processing software that are developed in-house. Finally, the third objective is to explain the reasoning behind the engine operating conditions that excludes an NTE event during in-use emissions compliance test mandated by US EPA.

A discussion on the fundamentals of quantifying measured emissions with a detailed description of the variables involved will be presented to develop a background for understanding emissions data post-processing. Note that the data related to PM emissions measurement and the corresponding data analysis is not discussed in this work due to the following facts:

1. The methodology used to derive PM concentrations is different among various PEMS devices based on the instrument used to measure PM including the models, which are implemented in the data post-processing software, in arriving at the continuous PM concentration values.
2. There have been different metrics followed to regulate PM emissions, which includes either PM mass (US EPA) [13] or number concentrations (Euro) [14], hence there is no clear direction on which path will be chosen to regulate PM.
3. Also, there has been a request from the EMA to use on-board diagnostics (OBD) PM sensors as the basis for PM regulation due to the cumbersome nature of the PEMS PM measurement system as stated by Daniel Carder, one of the attendees in Emissions Measurement and Testing Committee (EMTC) meetings.

2 LITERATURE REVIEW

2.1 Introduction

Ever since the promulgation of emission regulation for automobiles and heavy-duty diesel engine emissions under the aegis of the CAA of 1970 [13, 16], all light-duty vehicles (LDVs) and heavy-duty engines are certified for emissions compliance over a standardized emissions test cycle in a test cell environment. The standardized test cycles are developed using the data collected from vehicles being driven under real-world conditions; the Cape 21 study used in the development of FTP cycle for heavy-duty diesel engines [17], and similar data collecting exercise to develop chassis test cycle for light duty vehicles. Albeit, standardized test cycles are developed based on real world engine activity data and emissions limits are fixed based on them, and also used to estimate emissions inventories in reality the air quality still suffers from increased pollution. Furthermore, the steady increase in emissions compliance standards has still not reduced the problem of degrading air quality in urban areas. The increase of vehicular population and degrading air quality have resulted in several air quality management districts failing to reach prescribed air quality goals forcing them to develop State Implementation Plans (SIPs) in order to reach the desired goals. Along with other measures used to improve air quality, the SIPs call for increased scrutiny and regulation on the automotive and transportation sectors ultimately resulting in additional financial burden on the public and federal agencies as well. Therefore, in order to address the air quality standards in pace with an increase in population of vehicles on the road, the EPA and CARB initiated the development of instruments and procedures to measure emissions on-board of a vehicles performing its intended activities. This initiative led to the development of the portable emissions sampling system called the ROVER. The goal of in-use emissions measurement is to quantify the emissions from engines operating at the speed and torque values other than what is observed in the emissions certification cycle. The emissions measured during operation of an engine or vehicle other than the standardized test cycle is referred to as off-cycle emissions.

Heavy-duty diesel engines, used in both on-road and off-road applications, have always been certified on an engine dynamometer for set brake-specific emissions standards based on the engine MY and the type of application. The emissions certification is performed by exercising a vehicle or an engine over a pre-defined test schedule using chassis or engine dynamometers in accordance to the emissions measurement regulations listed under title 40 Code of Federal Regulations (CFR) part 86 [13]. Traditionally on-road engines are tested on transient cycles while off-road engines are tested on steady-state cycles. Since the introduction of emissions certification standards, the EPA required engine manufacturers to adhere to standard test procedures in order to maintain consistency in emissions results among different engine manufacturers and also to reproduce similar test results when tested at the EPA's facility. This standardization in emissions measurements led to the development of several emissions correction factors used to compensate for changes in ambient conditions of the test cell, different measuring techniques used by emissions analyzers to quantify emissions, and statistical techniques to qualify the emissions measuring equipment, engine dynamometer, and other measuring devices for its suitability to measure emissions at the required precision, accuracy, and repeatability standards. These emissions measurement procedures are developed as a joint effort by emissions regulators at the EPA and engine manufacturers who have to comply with emissions standards, emissions measuring device manufacturers, and independent consultants and laboratories involved in emissions research and measurement. It is evident from the progression of emissions standards, which was in the range of 10.7 to 4.0 g/bhp-hr of NOx for MY1988 to MY1998 and further reduced to 0.2g/bhp-hr for MY2010 and later heavy-duty truck engines requiring the emissions measurement devices to be updated to measure emissions at low concentrations. This warrants new technology to be implemented as a primary measurement standard along with other changes in sample conditioning when measuring emissions at low concentrations. For example, over the past several years it has been shown that Fourier transform infra-red (FTIR) spectrometer measurement technology has the potential to measure multiple emissions constituents at lower concentrations and is capable of replacing traditional chemiluminescence light detector (CLD), non-dispersive infra-red (NDIR), and heated flame ionization detector (HFID) used for measuring oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), and total hydrocarbons (THC) emissions as a result standards have been developed by Society of Automotive Engineers (SAE) to provide recommended practices and minimum performance standards for different engine related application [18]. Eventually, after careful consideration of the new measurement technologies and changes required to measure emissions at lower concentrations, the EPA and EMA deliberate on the validation of technology to meet strict measurement requirements before arriving at a conclusion to implement required changes to emissions measurement regulations. As a result of these changes emissions measurement regulations has undergone several modifications since its implementation. In view of the stringent emissions standards, all post MY2007 heavy-duty diesel engines have to comply with EPA's newly adopted measurement regulations introduced under 40 CFR part 1065, which addresses the conditions to be maintained during emissions measurement to quantify emissions at low levels and reduce variability between repeat tests. Conversely, there has been no effort focused on synchronizing the emissions calculations, which involves interpretations of regulatory language in order to manipulate several measured quantities in arriving at the final brake-specific emissions values of the test engine. As an exception to the above statement, EMA and the EPA have established a round-robin testing protocol where a standard reference engine from each engine manufacturer is tested in different engine emissions test laboratories recognized for emissions certification, and laboratories recognized for emissions measurement research in order to harmonize the brake-specific emissions results among different laboratories and thereby reduce discrepancy in the emissions results of selective enforcement audit (SEA) tests [19]. The SEA tests are conducted by the EPA, either in their emissions test cell or in a research facility, both of which are part of the round-robin testing protocol. The engines subjected to SEAs are sourced from in-use vehicles and tested in the laboratory after removing the engine from the vehicle.

Since the consent decrees between EPA and heavy-duty diesel engine manufacturers in 1998 and establishing a manufacturer-run in-use emissions test program for post MY2007 heavy-duty diesel vehicles the in-use emissions testing regulations have undergone a considerable change. This includes the number of exclusions allowed to meet NTE emissions standards based on the emissions reduction technologies, measurement allowance applicable for different methods of quantifying emissions. Furthermore, the value of NTE emission threshold based on the certification standards, the percentage of time weighted emissions pass rate, and the upper limit of emissions for the valid NTE events that fail the emissions threshold. The in-use emissions testing and measurement regulations are drafted by a joint committee of EMA and the EPA after deliberations with the PEMS device manufacturers and other research groups similar to the engine certification testing for emissions. The evolution of in-use emissions measurements, PEMS devices, regulations, and the standardization protocols used to develop these regulations will be discussed in detail in the following sections below. Furthermore, the need for standardizing the emissions data post-processing software and the methods used to verify the standardization based on the least intrusive testing approach will also be discussed in the following sections.

2.2 Evolution of Previous On-Board Vehicle Emissions Measuring Devices

The impetus for the development of on-board emissions began with the need for portable emissions measuring devices to be used for inspection and maintenance (I/M) programs to check and take action on vehicles which were gross polluters at the beginning of the introduction of emissions regulation under the CAA of 1970. The I/M program was further developed to conduct quick tests of in-use LDVs on a chassis dynamometer using a short duration test to collect emissions data in order to characterize emissions produced by fleets of different MY vehicles in the regions labeled as air quality non-attainment areas. The I/M emissions data was further used to develop models along with vehicle certification emissions data to predict emissions inventory of different regions based on the fleet of vehicles, MY of the fleet, vehicular activity and other factors related to maintenance and use of devices to disable emissions control technologies. Since there was no I/M program established for heavy-duty diesel vehicles, EPA and other state environmental protection agencies such as CARB encouraged the development of on-board emissions measuring devices capable of quantifying emissions from heavy-duty diesel engines while they are performing their intended activities on-road or off-road. Early on-board emissions measuring devices were developed using garage or I/M grade analyzers to qualitatively determine the deviation of in-use emissions from certification standards. These devices were bulky and un-reliable in measuring transient emissions due to the primitive measuring technologies used to quantify emissions. Over the last 20 years there has been a significant development in the on-board emissions measuring devices that are capable of measuring emissions within ±2% of the lab grade analyzers, a requirement for the commercial grade PEMS [20].

As consent decrees marked the beginning of official development of a rugged on-road PEMS that is comparable to laboratory grade emissions measurement devices in terms of accuracy and repeatability. Gautam et al., of WVU was instrumental in developing a portable on-road emissions measurement system known to be MEMS. The instrument was compared against WVU's FTP laboratory, and another PEMS known as ROVER developed previously by EPA. The instrument was also subjected to in-field evaluations before assigning the device for the development of in-use emissions protocol as well as using it as official in-use emissions as part of the consent decrees. The MEMS employed a solid state zirconia (ZrO_2) sensors for measuring NOx, and NDIR analyzer for CO_2, including CO and HC. However, the HC measurement using NDIR was not of sufficient resolution. The exhaust flow measurement was determined using an Annubar® cross-sectional averaging flow meter as it could account for the pulsating exhaust from internal combustion engines. Engine torque and speed data were acquired through Engine Control Unit (ECU) broadcasted through multiple communication protocols. The torques data was inferred based on the manufacturer supplied maximum torque curve and the percent load data broadcasted via ECU along with the curb idle torque values. The emissions data thus collected were later post-processed using in-house data reduction software, developed to confirm for the in-use emissions regulations that were being established at that time. The instrument evaluation with respect to laboratory and ROVER results showed that the NOx values measured using MEMS were within 0.5% of laboratory results and a maximum difference of 7.9% was reported between ROVER and the laboratory because of the use of electrochemical cell to measure NOx in ROVER. Note that ROVER did not consist of any means to convert NO_2 to NO hence the higher difference between ROVER and laboratory measurements. Also, ROVER did not have the capability to acquire ECU broadcasted engine speed and torque signals. Furthermore, the comparison between MEMS and ROVER with respect to laboratory grade analyzers based on in-use emissions test cycles exercised over engine dynamometer showed that difference in integrated NOx mass emissions over 30 second windows, ranged from -7.79% to 2.94% for MEMS and -11.23% to 4.27% for ROVER. This shows the superior capability of MEMS in comparison to the earliest research grade portable emissions measuring device [9].

Horiba Inc. one of the commercial PEMS manufacturers have been improving upon their commercial grade device from 2002 where they have conducted several studies showing the implementation of advanced emissions analyzers, flow measuring devices, data acquisition and signal processing have resulted in close agreement of emissions mass between laboratory grade analyzers and PEMS devices. In a study conducted by Nakamura et al., in developing wet-based NDIR analyzer to measure CO and CO_2 emissions for an on-board emissions measurement system showed that a heated NDIR (h-NDIR) was capable of measuring CO and CO_2 accurately with the use of an algorithm specifically developed to correct for interference from co-existing gas. The results showed that H_2O interference to the CO_2 and CO measurement was less than ±1% and ±2% for span points respectively against 12% by volume of H_2O [21]. In 2005 Nakamura et al., studied the use of fast response differential pressure transducers to measure pulsating exhaust flow from IC engines using pitot tube flow meters. The pitot tube flow meter inherently shows erroneous reading when measuring pulsating flows due to the non-liner relationship between the differential pressure and the flow rate. In order to overcome this error fast acting pressure transducers, whose response frequency is much higher than the frequency of pulsation, were employed to determine the flow rates without averaging the pressure signals and then the flow signals is averaged to arrive at the final flow values. This method of determining rate of pulsating flow showed a good correlation with reference flow meters such as smooth approach orifice (SAO) and ultrasonic flow meters [22]. In 2007 Horiba evaluated their commercial grade OBS-2200 PEMS device against 1065 specifications in association with Southwest Research Institute (SwRI) where the on-board emissions measurement system which operated under partial vacuum confirmed its performance in accordance to CFR requirements. Furthermore, the uniform response and time alignment verification showed that the ratio of the rise time between fastest and the slowest analyzer is 87.5% meeting the 40 CFR 1065 requirement allowing difference of the response time to be minimized within 0.2 seconds. Additionally, the comparison between OBS-2200 and laboratory instruments showed that the F and t statistic results of all the emissions constituents measured over different test cycles were less than the 90% and 95% confidence criteria qualifying the device to be used for in-use emissions measurement [23].

As a result of advancements in the portable emissions measuring analyzers and technology current state-of-the-art PEMS devices mostly uses fast response pitot tube type exhaust flow measuring devices, NDIR analyzers for measuring CO, and CO_2, NDUV and miniaturized CLD analyzers for measuring oxides of nitrogen, HFID for hydrocarbons, also capable of measuring wet concentrations. Furthermore, FTIR analyzers have been developed to suit for PEMS application so that multiple gases can be measured with one analyzers even at concentrations close to background levels. Additionally, with the standardization of on-board diagnostics all PEMS devices are able to acquire engine operation data through ECU over standard protocols. A detailed description of the development of on-board emissions measuring instruments until the development of MEMS arranged chronologically can be found in the reference [24]

2.3 Measurement Allowance Program

The US EPA has been regulating in-use emissions constituents from on-road vehicles from 2005 under the engine manufacturer run Heavy-Duty In-Use Testing (HDIUT) program. The HDIUT program was initiated after the completion of in-use emissions testing program conducted by WVU using MEMS. MEMS development was sponsored by the engine manufacturers as part of the consent decrees agreed upon between the settling engine manufacturers and the US EPA. The MEMS program proved successful in showing the need for conducting in-use emissions in order to study the emissions performance of heavy-duty diesel engines under in-use operating conditions and to regulate off-cycle emissions. At the conclusion of the MEMS program, there were two competing measurement systems. The first was the commercially designed Semtech-D developed by Sensors, Inc. The second system was the research-grade ROVER in-use emissions measuring device developed by the US EPA along with other PEMS devices developed by competing emissions measurement device manufacturers. Among the different lessons learned after the MEMS measurement campaign it was found that due to the use of either I/M or garage-grade analyzers in PEMS devices the in-use emissions results were greatly influenced by the ambient conditions in which the emissions were measured along with other measurement biases when compared with laboratory-grade analyzers used for engine certification tests concurrent to 40 CFR Part 1065 measurement standards. This led to the establishment of the PEMS measurement allowance program to determine an additive allowance to compensate for the errors in measuring emissions using PEMS. The program was a joint effort of US EPA, EMA, and the CARB. The additive measurement accuracy margin was determined experimentally using the Semtech-D PEMS device in comparison to laboratory-grade emissions measurement facilities provided by SwRI [25].

The main objective of the measurement allowance program was to experimentally determine and validate the additive accuracy margin to be used for in-use emissions compliance testing of heavy-duty vehicles using PEMS. Additionally, this program also served in standardizing the error in measuring emissions between the PEMS device and laboratory-grade emissions analyzer while promoting further development of PEMS to reduce the error margin. The measurement allowance program was conducted in three phases to determine the accuracy margin for gaseous emissions. The three phases involved laboratory evaluations of PEMS, statistical modeling and simulation of error propagation, and the final phase of model validation with in-use emissions results and determination of the final accuracy margin value. Laboratory evaluation of PEMS was conducted by comparing the results with test cell emissions measurement devices by running emissions certification tests in the laboratory. Furthermore, the PEMS device was subjected to environmental perturbation by placing the device in an environmental chamber that is capable of varying the temperature, pressure, electromagnetic radiation, background hydrocarbon levels, humidity and also inducing vibrations while measuring emissions from an engine and comparing the results with laboratory analyzers that are maintained under stable environmental conditions to study the influence of environmental conditions on the measurement accuracy of PEMS. The statistical modeling and simulation of the error propagation involved modeling the error in emissions measurement between PEMS and laboratory analyzers for different factors and implementing the Monte Carlo technique to randomly select various sources of PEMS measurement error, the result of which is used to determine the additive accuracy margin. The final phase of validating the error propagation model and determining the accuracy margin involved testing the PEMS device against laboratory-grade emissions analyzer placed in a container which in-turn is transported on a regular class 8 tractor trailer powered by a heavy-duty diesel engine. The emissions from the in-use operation of the heavy-duty vehicle were simultaneously measured using the PEMS device and the laboratory-grade emissions analyzer and the difference between the measurements was validated against the statistical model to arrive at the final additive accuracy margin [26].

2.3.1 Laboratory Evaluation of PEMS

Laboratory evaluation of PEMS involved comparison of engine emissions measured using a commercial-grade PEMS device approved by the EPA for in-use emissions measurement with that of a laboratory-grade 40 CFR Part 1065 compliant emissions measuring equipment/facility. The error in measuring emissions between laboratory-grade emissions measuring equipment and PEMS were determined by running steady-state and transient engine tests in the prescribed NTE zone. The transient tests included a series of 30-second NTE events repeated several times in a random order. These experiments were conducted over three different engines belonging to MY 2005 and 2006, one Heavy Heavy-Duty (HHD) engine, one Medium Heavy-Duty (MHD) engine and one Light Heavy-Duty (LHD) engine while measuring emissions with three PEMS devices of the same type, simultaneously on each engine in order to capture the variability in the test articles as well as the unit-to-unit variability of PEMS. Note, that although test engines were pre-2007 MY engines, they were retrofitted with Johnson Matthey Continuously Regenerating Trap (CRT) particulate filters. The emissions measurement error between PEMS and laboratory-grade equipment determined in the tests above are paired for the given PEMS unit, test engine, steady-state test point, average emissions of a transient test mode, and other characteristics of the measuring equipment. Furthermore, the paired points of measurement errors are pooled together to develop error surfaces leading to an empirical relationship between different variables. An error surface can be visualized as a three-dimensional chart showing the error in measuring emissions or a factor used to quantify brake-specific emissions linked to the test condition. For example, the error in measuring NOx concentrations for steady-state tests is evaluated for a reference mean NOx concentration measured by the lab-grade analyzers. Note that the difference in the emissions between PEMS and the laboratory measurement is determined by subtracting laboratory results from PEMS values, and is referred as delta or error.

Laboratory evaluation of PEMS also included examining the influence of ambient conditions, in which a PEMS is operated on its measurement accuracy. This test was conducted by placing the PEMS in an environmental chamber where known gas concentration is measured while varying the temperature, pressure, humidity, and ambient hydrocarbon levels inside the chamber. Also the influence of vibration and electromagnetic radiation on the measurement accuracy was quantified in a similar way. A total of 37 error surfaces were developed to be used in the statistical model to estimate the accuracy margin of PEMS emissions measurement. These error surfaces are classified broadly into six groups:

1. Steady-State error surfaces – characterizes the precision and bias errors between PEMS and laboratory-grade emissions measurement system quantified over repeated steady-state engine tests.

2. Transient error surfaces – characterizes only the precision errors between PEMS and reference emissions measurement method quantified over repeated transient testing of 30-second NTE events. The order in which the NTE events were run in each repeat was also randomized. Transient error surfaces were generated for gaseous pollutants, exhaust flow rate as well as the dynamic errors in the Engine Control Module (ECM) broadcast signals such as engine speed, torque, and fueling rate.

3. Torque and Brake Specific Fuel Consumption (BSFC) error surfaces – since the brake-specific emissions determined by PEMS during in-use emissions measurement campaign are completely dependent on ECM broadcast, engine speed, and torque as well as quantifying emissions mass rate in the absence of exhaust flow meter depends on the fueling rate broadcasted by engine ECM, it becomes imperative to evaluate the accuracy of the ECM broadcasted parameters in reference to laboratory measurement system. These comparisons were performed using steady-state tests in an engine dynamometer test cell capable of simulating various ambient conditions such as temperature, altitude, and humidity. Furthermore, the effect of fuel properties in predicting the engine torque and fueling rates were also quantified using three different fuels of varying properties representing a wide range of fuel being used in heavy-duty vehicles across the country.

4. Exhaust Flow Measurement error surfaces – these error surfaces were generated by comparing the PEMS exhaust flow measurement values with laboratory reference flow meters using steady-state tests in an engine dynamometer test cell. The error surfaces are generated by varying the measurement conditions such as the influence of wind speed downstream of the flow meter and increased backpressure upstream of the flow meter, as well as for different installation configurations including the optimum condition required for accurate flow measurement in addition to increased number of pipe bends upstream of the flow meter.

5. Environmental Testing error surfaces – as PEMS is used to measure in-use emissions of heavy-duty diesel vehicles performing their intended activity, at various geographical locations over an eight hour work day, it is subjected to different ambient operating conditions and other external factors such as vibration and electromagnetic radiation that could influence the emissions measurement accuracy. These sources of errors are characterized by configuring the PEMS to measure standard reference gases while subjecting it to environmental perturbations, such as temperature, pressure, humidity in an environmental chamber and quantifying the delta between PEMS measurement and the reference gas concentration being measured.

6. Miscellaneous error surfaces – these error surfaces were generated using a diverse source of errors which includes time alignment of different emissions measurement data, PEMS unit-to-unit variability, engine production variability, etc. The error surfaces were developed using experimental data collected during the project as well as the engine manufacturer supplied data.

All of the emissions error surfaces were generated using dilute laboratory measurements as the reference value. The laboratory reference values used for quantifying the delta of different PEMS measurement components required for quantifying brake-specific in-use emissions are summarized in Table 1. Laboratory evaluation of PEMS involved comprehensive auditing of the laboratory reference measurements as well as PEMS measurement system in accordance to 40 CFR part 1065 procedures as shown in Table 2. During the course of the laboratory evaluation of PEMS, there were several challenges in following the original test plan due to the fact that experimental results were different than anticipated leading to adaptation of the test plan to overcome these challenges. The change in the test plan along with decisions to include/exclude certain data points in the test results were made under the oversight of the steering committee. The steering committee was comprised of representatives from EPA, EMA, CARB and PEMS manufacturers. For more detail refer to the document [26].

Table 1: Measurement Allowance Program - Laboratory Reference Methods [26]

PEMS Measurement	Laboratory Reference	Reference Method
Gaseous Analyzers – engine testing	Dilute Emission Analyzers[1]	Dilute mass calculated using CVS flow, then raw concentrations back-calculated using laboratory raw exhaust flow
Raw Exhaust Flow	Measured Intake Air Flow and Fuel Flow	Air Flow measured using Laminar Flow Element (LFE).
Predicted Torque (from CAN)	Measured Torque	Shaft mounted in-line torque meter
Predicted BSFC (from CAN)	Measured Fuel flow and power	Fuel Flow measured using coriolis type meter.
Gaseous Analyzers – environmental chamber testing	Standard reference gas concentrations	Reference values validated on all bottles at SwRI

[1] Reference non-methane hydrocarbon (NMHC) levels were based on laboratory raw measurements due to very low levels.

Table 2: Measurement Allowance Program – 1065 Lab & PEMS Audit Tests [27]

Description	CFR Reference	Lab Raw	Lab Dilute	PEMS
Linearity	1065.307	x[1]	x[1]	x[2]
Torque Meter	1065.310	x	X	
Fuel Flow	1065.320	x		
Intake Flow	1065.325	x		
Exhaust Flow	1065.330	x		
CVS Verification	1065.341			x
H_2O Interference on CO_2	1065.350		x	
H_2O and CO_2 Interference on CO	1065.355	x	x	x
FID Optimization	1065.360	x	x	x
Non-stoichiometric raw FID O_2 Interference	1065.362	x[3]	x[3]	x[3]
Non-methane cutter penetration fractions	1065.365	x		x
CLD H_2O and CO_2 quench	1065.370	x	x	
NDUV HC and H_2O Interference	1065.372			x
Chiller NO_2 penetration	1065.376			x
NO_2-to-NO converter check	1065.378	x	x	

[1] Linearity for laboratory on gas analyzers, flow meters, torque meter, pressures, temperatures

[2] Linearity for PEMS on gas analyzers, exhaust flow meters

[3] Verify methane response factors only, THC instruments

In conclusion to the laboratory evaluation of the PEMS, it was found those PEMS measurement errors in reference to the laboratory measurement were inconclusive as it did not follow any trend for most of the key measurement parameters. These manifested in the form of abrupt changes in error magnitudes at similar reference levels over three different engines. The data used to generate error surface for NMHC and CO emissions were collected over a narrow range of engine operation as their values were close to the detection limit of the PEMS analyzers due to the use of aftertreatment device to reduce PM. The environmental chamber testing of PEMS also resulted in inconclusive data due to functional failure of the testing; or the observed effects were small relative to other error sources. Hence, environmental test data had a negligible effect in calculating the final measurement allowance.

2.3.2 Statistical Modeling and Simulation of Error Propagation

As per the test plan, 35 error surfaces representing steady-state test precision and bias errors, transient test precision errors of brake specific-emissions using PEMS in relation to laboratory reference standards including the error in measuring reference emissions concentrations under the influence varying environmental conditions in which a PEMS device operates was determined in the aforementioned laboratory evaluation of PEMS. In addition to the 35 error surfaces, two more error surfaces representing the effect of time misalignment of emissions concentration with exhaust flow values and ECM torque and speed signals were also considered as a potential source of error leading to a total of 37 sources of error. Note that the time alignment error was not considered as an additive error like other error sources; instead it is used as a multiplicative adjustment factor and applied to the brake-specific emissions results after all other error terms are added to the result.

The Monte Carlo simulation method was chosen to determine the incremental error in measuring brake-specific emissions using PEMS in reference to laboratory-grade measuring equipment because it would have been prohibitively expensive in terms of time as well as resources to determine the same using experimental method. The experimental method of determining measurement allowance would have involved quantifying the error in quantifying brake-specific emissions using PEMS against a mobile laboratory standard reference method on a large number of vehicles. Furthermore, the Monte Carlo simulation method allows for random selection of error sources resulting in a normal distribution of brake-specific emissions differences in reference to the ideal brake-specific emissions quantified using the laboratory reference method. During the program of determining the measurement allowance for in-use emissions measurement, it was recognized that the in-use brake-specific emissions could be calculated using one of the three different methods. The three methods used to quantify in-use brake specific emissions using PEMS include direct measurement of emissions concentrations, exhaust flow using a flow meter, and engine brake torque and speed using either inline sensors or ECM broadcast values. Method 1 referred to as “Torque-Speed” method uses exhaust flow values and ECM broadcast torque and speed values to quantify brake-specific emissions. Method 2 involves the use of brake-specific fuel consumption values along with carbon balance of the fuel to determine the engine work instead of engine speed and torque; it is referred to as "BSFC" method. This method requires the exhaust flow meter values to be linear with engine load. In Method 3, the in-use brake-specific emissions are determined completely based on ECM signals and do not have the influence of exhaust flow meter error; it is referred to as the "ECM Fuel Specific" method. The general equations used to calculate brake-specific emissions in the above three methods are illustrated in the following equations:

Method 1:

$$e_{emissions} = \frac{M_x \sum_{i=1}^{N} x_i \cdot \dot{n}_i \cdot \Delta t}{\sum_{i=1}^{N} \frac{2\pi NT}{60 \cdot 3600} \Delta t} \tag*{\textbf{Eq. (1)}}$$

Method 2:

$$e_{emissions} = \frac{M_x \sum_{i=1}^{N} x_i \cdot \dot{n}_i \cdot \Delta t}{\frac{M_C}{w_{fuel}} \sum_{i=1}^{N} \frac{\dot{n}_i \cdot (x_{THC} + x_{CO} + x_{CO2}) \cdot \Delta t}{BSFC}} \tag*{\textbf{Eq. (2)}}$$

Method 3:

$$e_{emissions} = \frac{\frac{M_x \cdot w_{fuel}}{M_C} \sum_{i=1}^{N} \frac{x_i \cdot \dot{m}_{fuel_i}}{(x_{THC} + x_{CO} + x_{CO2})} \cdot \Delta t}{\sum_{i=1}^{N} \frac{2\pi NT}{60 \cdot 3600} \Delta t} \tag*{\textbf{Eq. (3)}}$$

The Monte Carlo simulation results were based on emissions values and operating data of reference NTE events to which the additive measurement errors are applied randomly from the repository of experimentally determined empirical error models or surfaces. The simulation is repeated up to 30,000 times for each reference NTE event applying measurement error values to the brake-specific (BS) emissions determined using laboratory measurement standards referred to as "ideal" BS emissions. The ideal BS emissions after applying errors are referred to as BS emissions "with errors." The simulation was run for 195 reference NTE events that were sourced from transient lab experiments run at SwRI for the measurement allowance program, pre-pilot in-use emissions measurements data, and the experimental data provided by the five settling engine manufacturers. The determination of measurement allowance and other aspects of the simulation such as convergence, elimination of simulation results due to drift etc. were based on the BS emissions threshold values of each pollutant. The emissions threshold values were fixed based on the MY2007 heavy-duty diesel engine emissions certification standards as shown in Table 3. For more details in relation to the development of simulation model, convergence criteria, periodic drift check criteria, etc. the reader is encouraged to refer either the final report of measurement allowance program or the reference [28].

Table 3: NTE Threshold Values Used for Measurement Allowance Program [28]

Pollutant	NTE Threshold	
	g/bhp-hr	g/kW-hr
BSNMHC	0.21	0.2816
BSNOX	2.00	2.6820
BSCO	19.40	26.0200

Monte Carlo simulation runs to produce BS emissions with errors for 195 reference NTE events for regulated emissions based on three different calculation methods resulted in nine distributions of 95th percentile delta or error in emissions using PEMS with reference to laboratory measurement standards. One measurement allowance is determined per distribution resulting in three measurement allowance values for each pollutant for each emissions calculations method. The measurement allowance is determined either by using the regression or median method. Regression method involves correlation of the 95th percentile difference with the ideal emissions values of the reference NTE events. The R^2 and root mean squared error (RMSE) value of the regression model should be greater than 0.90 and less than 5% of the median ideal emissions results respectively in order to use regression method for determining the measurement allowance value. Whereas, in the median method the median value of the 95th percentile delta from 195 reference NTE events is considered as the measurement allowance for the given emissions constituent and calculation method. Therefore, Monte Carlo methodology of error simulation based on assorted sources of errors resulted in nine measurement allowance values, corresponding to each pollutant and calculation methods. In order to determine the final additive measurement allowance for each pollutant the maximum error (in percent) based on the calculation method for each pollutant is multiplied with the corresponding threshold value to result in actual measurement allowance in engineering units. The percent measurement values for each pollutant and the calculation method along with the final values for each pollutant are shown in Table 4. The final measurement allowance is based on the Method 1 calculation as it was the only method which was validated during the experimental validation of the simulation results.

Table 4: Monte Carlo Simulation Measurement Allowance in Percent of NTE Threshold by Calculation Method and Final Additive BS Measurement Values [26, 28]

Pollutant	Method 1 (Torque-Speed)	Method 2 (BSFC)	Method 3 (ECM Fuel Specific)	Final Measurement Allowance
	[% Threshold]	[% Threshold]	[% Threshold]	[g/bhp-hr]
BSNOX	22.30	4.45	6.61	0.45
BSNMHC	10.08	8.03	8.44	0.02
BSCO	2.58	1.99	2.11	0.5

2.3.3 Validation of Measurement Allowance Model Simulation Results

The final goal of the Monte Carlo simulation, the validation of measurement allowance results, was to experimentally verify the error in measuring in-use emissions using PEMS in reference to a mobile laboratory measurement standard such that it is below 95 and above 5 percentile of the measurement allowance values of the simulation results for the corresponding calculation methods. CE-CERT's Mobile Emissions Laboratory (MEL) facility was chosen to be the in-use laboratory standard to validate the measurement allowance simulation results. The MEL comprises a trailer equipped with full-flow constant volume sampling (CVS) dilution tunnel whose samples are analyzed using laboratory-grade analyzers. The tractor trailer, whose in-use emissions must be quantified, is driven in specified routes to yield a considerable number of NTE events while measuring emissions simultaneously using a PEMS device. The delta between the PEMS and MEL measurements lies within the range of delta determined by the simulation model, and then the simulation results are validated experimentally. Before using the MEL for validating the Monte Carlo simulation results, it was correlated with the SwRI test cell measurements, which were used to generate the error surfaces used in the simulation model. The correlation of MEL and SwRI lab was performed using a heavy heavy-duty 14 –liter DDC S60 engine by measuring both steady-state and transient emissions separately by the two laboratories; the exhaust system was configured to switch between SwRI and MEL CVS tunnel, which was parked close to the test cell. The correlation work was carried out three days by running both steady-state and specially created transient NTE cycle in triplicates between the two facilities. The transient NTE cycle included a set of 30 short NTE events mixed with short periods of light load operation outside the NTE zone. The test results showed that the two laboratories correlated within 2% of NOx emissions.

The on-road validation of the model results were conducted using a test truck provided by Caterpillar, Inc. The test vehicle emissions were measured simultaneously by CE-CERT's MEL and one of the PEMS devices used for laboratory evaluation. The on-road testing was conducted over a period of nine days on different routes representing a wide variety of driving conditions and potential PEMS measurement noise factors. The vehicle emissions were measured by installing the PEMS in the truck cab as well as on the truck frame to study the influence of different ambient operating conditions on the measurement accuracy. A total of 429 NTE events were recorded during the nine day test campaign, of which 100 NTE events were chosen for model validation purposes. The down sampling of NTE events were done to equally weigh and evenly represent the NTE events recorded with PEMS devices being mounted in the cab and on the truck frame, and all the operating conditions of the vehicle as well as the ambient conditions in which the NTE events were generated respectively. Furthermore, down sampling also addressed the biasing error when comparing the field data to model results as some test routes resulted in more NTE events than others, when recorded at similar ambient conditions. In order to validate the model results with the experimental in-use emissions data, some of the error surfaces were excluded in the Monte Carlo error validation model as they were not recorded during on-road comparison of PEMS and laboratory reference emissions measurement systems. The excluded error surfaces were mainly Torque and BSFC error surfaces and the transient dynamic error surfaces used in capturing the variance between the ECM broadcast speed and fueling rate, since it is cumbersome and difficult to measure engine torque and fueling rate using laboratory reference measurement system while measuring in-use emissions. The BS emissions were generated by the model by disregarding the ECM vs. laboratory measurement error surfaces. This is referred to as the "BS emissions with validation error." The Delta BS emissions are generated based on Eq. (4) with respect to ideal emissions measured in the laboratory and are used to compare the delta BS emissions calculated between PEMS and the CE-CERT MEL's reference emissions measurement system to validate the model. All the three methods of determining BS emissions for all regulated emissions are validated in the aforementioned way.

$$\Delta BS\ emissions = BS\ emissions\ with\ Validation\ error - Ideal\ BS\ emissions \qquad \textbf{Eq. (4)}$$

$$\Delta BS\ emissions = PEMS\ BS\ emissions - CE - CERT\ MEL\ BS\ emissions \qquad \textbf{Eq. (5)}$$

The 5th and 95th percentile delta BS emissions values is determined based on 195 reference NTE events using the validation model and they are arranged from smallest to highest for each emission constituent and the corresponding calculation method to form an empirical distribution function (EDF). The region between the 5th percentile and 95th percentile EDF serves as the validation region for the Monte Carlo model using experimental data. The delta error in measuring BS emissions using PEMS is validated if 90% of the measurement error determined from the on-road experimental data lies between the 5th and 95th percentile delta error derived from the Monte Carlo model for each emission constituent and the calculation method [29]. A summary of model validation results for each pollutant and corresponding calculation is illustrated in Table 5.

Table 5: Summary of Model Validation Results [28]

Pollutant	Method 1 (Torque-Speed)	Method 2 (BSFC)	Method 3 (ECM Fuel Specific)
BSNOx	Yes	NO	No
BSNMHC	Yes	Yes	Yes
BSCO	No	No	No

It was found that delta error for BSNOx was validated only for Method 1 calculations, and BSCO emissions errors were not validated for any calculation method while BSNMHC emissions errors were validated for all three calculation methods. Therefore, the steering committee decided to use the measurement allowance determined based on Method 1 calculations as the final value since two of the regulated emissions experimental results validated the model. The lack of validation of BSCO emissions error derived by the model using experimental results was not considered critical since the CO emissions were close to noise levels due to the use of catalyzed DPFs. At the conclusion of the measurement allowance program, the final additive error margin for using PEMS to measure in-use emissions were given as the percentage value of the threshold emissions determined by the Monte Carlo simulation model based on the Method 1 BS emissions calculation method. The values are illustrated in Table 4.

2.4 Standardization of Emissions Measurement and Compliance Testing

The implementation of the CAA in 1970 by Congress also created a federal agency called the US EPA giving the authority in setting NAAQS. With this authority, the EPA can establish different programs to reduce air pollution while enforcing regulations on industries and business establishments to achieve the mandated air quality standards. The CAA was subjected to a major amendment in 1990 increasing the authority of the EPA to achieve nationwide air quality standards by implementing more cost-effective and innovative approaches to reduce air pollution; they also gained statutory powers to penalize businesses that fail to meet regulations and issue sanctions against individual states for not meeting prescribed air quality standards. EPA, being a federal agency, works in close association with individual state pollution control agencies by providing assistance in research, expert studies, engineering designs, and funding to support clean air progress. Under the CAA, the EPA sets primary and secondary air quality standards nationwide for six criteria air pollutants which include carbon monoxide, ground level ozone, lead, nitrogen dioxide, particulate matter and sulfur dioxide. The primary standards are set based on the detrimental effects of air pollution on human health and the secondary standards are set to prevent environmental and property damage. Any geographic area whose ambient air quality is cleaner than the primary standard is known as an attainment area, otherwise they are termed as non-attainment areas. Since 1970 and with the implementation of CAA, EPA has been successful in reducing air pollution to 72 percent notwithstanding an increase in industrialization and key factors indicating increased economic growth, such as gross domestic product that has increased to 219 percent, an increase in vehicle miles traveled to 165 percent, an increase in population and energy consumption by 53 and 47 percent respectively as of 2012 [30].

The nationwide emissions inventory depicts that nearly 10 percent of the smog forming volatile organic compounds, 90 percent of the NOx, and more than 80 percent of CO emissions are produced by fossil-fueled vehicles [31]. EPA has adopted a comprehensive approach to achieve air quality goals by regulating the vehicle manufacturing industry to produce cleaner engines, refiners to produce fuel of higher grade by removing compounds causing harmful emissions, for example removal of lead and reduction of sulfur; and mandating vehicle I/M programs in areas subjected to increased air pollution. EPA being the regulating authority with the responsibility of achieving or maintaining the air quality standards has progressively tightened the exhaust emissions standards of LDVs and heavy-duty diesel engines (HDDE) from 1.0 g/mile of NOx for MY1980 LDVs and 10.7 g/bhp-hr NOx for MY1988 HDDEs used to power on-road trucks to 0.05 g/mile NOx for MY2004 LDVs and 0.2 g/bhp-hr NOx for MY2010 HDDEs. Furthermore, EPA has been granted the authority to test or prescribe the method in which a vehicle or an engine should be tested in order to issue the certificate of conformity to emissions standards. As a result, EPA maintains and amends Title 40 – Protection of Environment in the CFR describing the standards to which LDVs and HDDEs are tested to certify such engines as emissions compliant. The emissions measurement standards and test cycles for HDDEs are listed in Part 86 subpart N and Part 1065 of CFR Title 40. Note that the measurement standards and regulations are finalized after establishing national research and development programs to conduct investigations, experiments, and surveys studying the effects of pollution including causes, extent of effects, and prevention and control of air pollution. The aforementioned research activities are administered by EPA by providing financial and technical support to other federal and local agencies including nonprofit private educational institutions or research organizations according to §7403 of the CAA [13]. As mentioned earlier, emissions from mobile sources are controlled by classifying the source into two broad groups, namely light-duty vehicle and heavy-duty engines based on the gross vehicle weight of the vehicle in where the engine is used to power. The LDVs, which are primarily used for personal transportation, are certified for emissions as a whole system based on vehicle chassis testing using FTP-75 test cycles. Conversely, the engines used to power heavy-duty vehicles, where the engines are pre-dominantly fueled by diesel, are used to power a diverse range of vocational services including on-road, non-road and stationary applications; hence heavy-duty engines are certified for emissions standards based on engine certification testing using the FTP test cycle. Emissions certification standards have been tightened due increased levels of vehicle populations over the past four decades. Moreover, engines and vehicles have been subjected to additional tests to comply with emissions standards due to the tightening of certification standards.

In an effort to standardize the way in which heavy-duty engines are certified, as they are produced by different manufacturers, the EPA in association with the Coordinated Research Council (CRC) sponsored the development of a standard test cycle for both chassis as well as engine dynamometer testing under a program known as CAPE-21, which was conducted between 1973 and 1975. The program was executed in two phases and also took place in two major business capitals, namely New York City and the Los Angeles Basin. In the first phase of the program, a use survey and the collection of heavy-duty vehicle driving patterns took place. In the second phase, the recording of engine operating data of heavy-duty vehicles during regular operation occurred. A total 290 truck-days and 21 bus-days worth of activity data were recorded from 44 trucks and 4 buses in each city. The vehicles were instrumented to collect engine speed, load factor, vehicle speed, throttle position and engine temperature along with other ambient conditions as experienced by the vehicle during the study. Monte Carlo simulation techniques along with statistical analysis were used to generate both chassis and engine dynamometer test cycles as described by Smith et al., [17]. The engine dynamometer test cycle used for heavy-duty engine certification for emissions is known as FTP cycle and illustrated in the figure below. The FTP cycle consists of four segments representing the driving conditions experienced in New York non-freeway traffic conditions, followed by Los Angeles non-freeway driving conditions, leading to Los Angeles freeway driving conditions signifying expressway driving with the repetition of New York non-freeway driving conditions as the final segment.

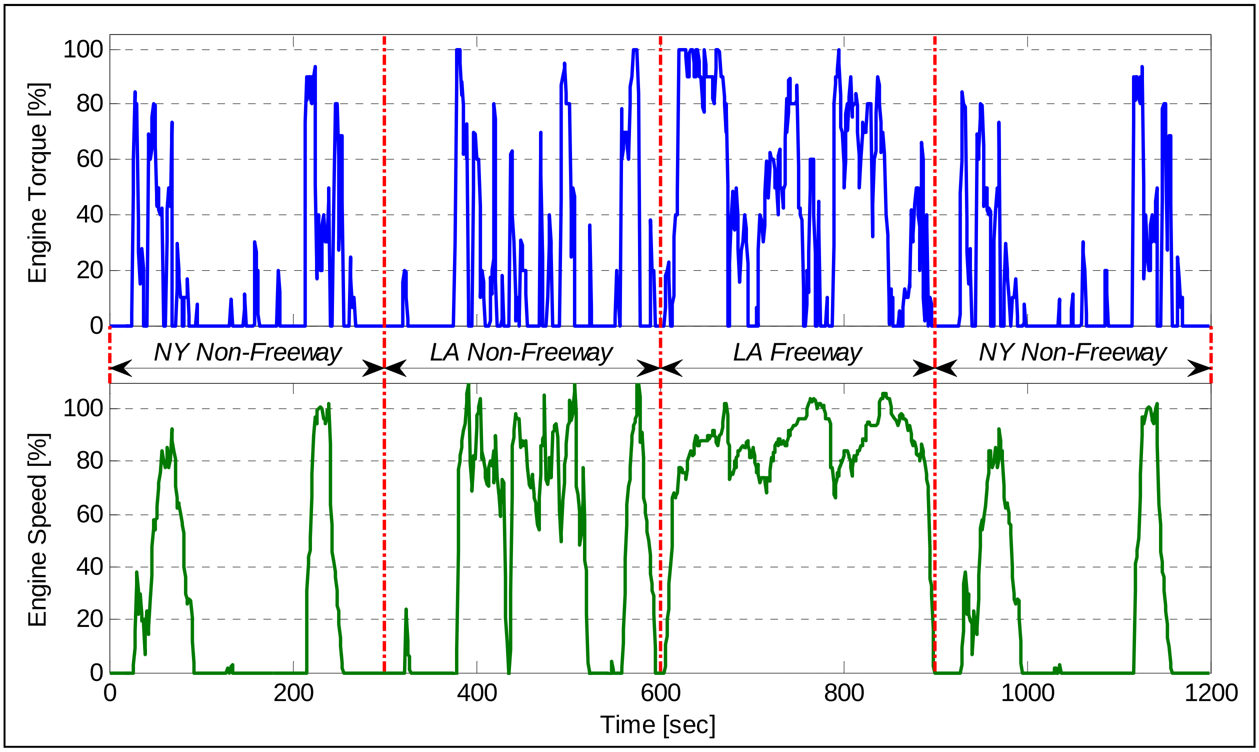


Figure 1: Engine Speed and Torque Trace of FTP Test Cycle [32]

The standard procedure for emissions certification requires the engine to be tested using the FTP cycle representing both cold and hot start conditions. The emissions measured during cold start operating conditions are weighed at 1/7th and consolidated with hot-start emissions values, which are weighed at 6/7th to yield the final engine brake-specific emissions result. This result is compared against the designated emissions certification values based on engine MY to comply with emissions standards. As the engine emissions standards were tightened and it was found that the off-cycle emissions from heavy-duty engines were higher than the certification standards, supplemental emissions tests were adopted to certify these engines for emissions compliance. The supplemental emissions test is a steady-state engine dynamometer test consisting of 13 steady-state modes. These tests were mandated as a result of the consent decrees agreed upon by the six major heavy-duty engine manufacturers and the EPA. The 13 steady-state modes includes operating the engine at three different engine speeds and four different load points in addition to idle test. The engine speed is determined based on the maximum torque curve of the engine, also known as the lug curve, based on the method described for the European Stationary Cycle (ESC). The emissions results from each mode carry different weight based on the representative time spent by the engine during regular operation. Note that for SET test it is required to use a single PM sampling filter through which the PM samples are collected by varying the dilution ratio, sampling time and or sample flow rate to represent different weighting factors assigned to each test mode. Therefore, the SET modes were combined in a similar way to form a single test cycle known as ramped modal SET cycle, or RMCSET test cycle, such that the weighting factor of each mode is translated into varying duration of each test mode. The steady-state test modes of a 13 mode SET along with duration of each test mode in a RMCSET test is illustrated in Table 6. Furthermore, during emissions certification testing the EPA or the authorized test administrator could request additional random testing modes between the three engine speeds and load factors. The threshold emissions values for these random test modes are determined based on interpolation of emissions results between the neighboring regular test modes. The rationale behind introducing RMCSET test along with random test modes in addition to FTP test for emissions certification of on-road engines, as a consequence of consent decree, is to have a better understanding of emissions results across a broader region under the lug curve along with random test modes indicating any significant deviation in emissions when compared to neighboring regular test modes. Additionally, EPA has mandated that non-road engines should also be certified for emissions compliance based on transient test cycle for US EPA Tier 4 non-road engines. This cycle is known as Non-Road Transient Cycle (NRTC) and it is executed in similar fashion to FTP with a cold start and a hot start. The cold start emissions result is weighted at 5% and the rest is complimented by hot start emissions to arrive at the final emissions test results.

Table 6: Ramped Modal Supplemental Emissions Test Modes [33]

RMC Mode*		MY 2010 & later		
		Time, s	Speed	Torque, %
1a	Steady-state	170	Warm Idle	0
2a	Steady-state	173	A	100
3a	Steady-state	219	B	50
4a	Steady-state	217	B	75
5a	Steady-state	103	A	50
6a	Steady-state	100	A	75
7a	Steady-state	103	A	25
8a	Steady-state	194	B	100
9a	Steady-state	218	B	25
10a	Steady-state	171	C	100
11a	Steady-state	102	C	25
12a	Steady-state	100	C	75
13a	Steady-state	102	C	50
14	Steady-state	168	Warm idle	0

* Each mode is followed by a transition mode of 20 seconds where no emissions data are collected

In the process of standardizing emissions measurement methodology for engines tested in a test cell, the EPA has developed several standards in association with the EMA, academic institutions, and national laboratories. These standards include dilution of raw exhaust using ambient air to stimulate the conditions observed when exhaust plumes mix with ambient air, methods to maintain constant volumetric flow through dilution tunnel over a transient test cycle, the conditions to which the dilution air has to be maintained in order to get repeatable results, methods to maintain proportional sampling in secondary dilution for quantifying PM emissions. Additionally, sample conditions; such as temperature, filter face velocity to be maintained for sampling PM. Furthermore, the statistical conditions to be satisfied by the engine dynamometer in executing test schedule on an engine, the properties, such as accuracy, repeatability, precision, linearity, interference from other emissions constituents etc. to be satisfied by emissions analyzers to qualify for emissions measurement. Also, properties of fuel used for certification testing, conditioning of fuel, conditioning of intake air and/or correction of emissions results to a standard intake air temperature and humidity, soak time between two consecutive tests and other related standardization as listed in CFR 40 Subpart N Part 86 and Part 1065. However, several other studies [34, 35, and 36] have shown that the method used to dilute the raw exhaust in a test cell does not resemble the exact dilution process observed in the nature where raw exhaust mixes with the ambient air while the vehicle is moving at different velocities. These studies include examining the formation of PM in a re-circulating wind tunnel; full scale non re-circulating wind tunnel where a heavy-duty truck is tested on a chassis dynamometer placed inside the wind tunnel while measuring the formation of PM, and chase studies where PM size distribution and number count is measured by following a heavy-duty truck on the road. Nevertheless, EPA has continued to recommend dilution of exhaust in conventional constant flow dilution tunnel with minor modification to the tunnel design for engine testing as a means to standardize the test cell testing process and aid in direct comparison of emission results. In addition to the aforementioned standards and regulations to test engines and vehicles in a test cell, the EPA has instituted a program called round-robin testing of engines and vehicles in association with EMA, public and private emissions certification laboratories [19]. In this program, a standard engine or vehicle is sent across different laboratories to verify their emissions results when measured as per regulations, so that engine manufacturer is confident that the engine produced by them would meet the emissions standards independent of the laboratory where it is certified when their engine is subjected to periodic SEA administered by the EPA. Note that the round-robin emissions tests of a single engine conducted across different laboratories aids in comparing laboratory-to-laboratory repeatability of test results as a whole, including the measurement systems, test procedures and post-processing of measured emissions data. Therefore, round-robin tests promoted further standardization of laboratory tests in order to achieve similar emissions results when the same engine is tested across different laboratories. As a result of this standardization in measuring emissions in a similar round-robin test of heavy-duty vehicles across five different chassis dynamometer conducted by Traver et al., it was found that test results correlated well with the exception of one. It was further concluded that the standardization and adoption of models to generate road-load curves would aid in reproducibility of results among the laboratories [37].

In a study conducted by AVL Inc., in association with SwRI for EMA comparing the emissions calculations proposed by 40 CFR 1065 and ISO 16183 for raw emissions calculations with regard to the influence of engine parameters, correction methods and other standardization techniques found that the time alignment of air and fuel flow signals along with emissions concentrations with the sampling location played a significant role in reducing the error in both standards. The experiment was conducted over heavy heavy-duty diesel transient (HHDDT) cycle and world harmonized transient cycle (WHTC) using a Caterpillar C13 engine. The exhaust mass flow determined using AVL BOOST, dry-to-wet correction per 40 CFR 1065 and reconstructed concentration signals using deconvolution method were used as the baseline to compare with the ISO 16183 and 40 CFR 1065 method of quantifying brake specific emissions. The errors in emissions were similar in values for both ISO and CFR methods in comparison to baseline calculation without applying any corrections. The correction in time alignment of flow and emissions signals showed significant effect cycle emission accuracy followed by correction applied for change in masses stored in system volumes and correction of concentration signals for convolution in the sample stream. The time alignment resulted in as much as 10.3% improvement in emissions accuracy over HHDDT cycle and -13.7 % over WHTC cycle reducing the error between the baseline and 40 CFR 1065 along with ISO 16183 to almost zero [38].

2.5 Software Testing

Software testing is the primary process used to verify and validate the quality of any program/software developed to perform a set of pre-defined functions as specified in the software requirements document. Software testing spans from examining the smallest building block, which includes even sub-routines invoked by a main program, known as unit testing to validating the final product, which is a complex integration of several program modules designed to perform several tasks in order to meet the design requirements. Note that each module, which is an integration of several smaller units, is tested after its integration in to a module as part of good software development practices. In other words, testing begins at the lowest level, where individual and related components are tested and proceeds to the higher level, where higher-order testing is conducted on fully integrated systems to verify fulfillment of customer requirements or software requirements specifications agreed upon by the code developer and the end user. Therefore, software testing is an integral part of software development life cycle and is associated with 50% of cost and resources required to develop a software code. Testing of software is a continuous process, which can be visualized as it is being tested each time a user runs the program for what it is intended for, but the conventional testing of the program is performed with the intention to make the final product free of errors/bugs before commissioning it as a finished product. Note that as it is highly impossible to develop test cases for exhaustive testing of any software it is a common practice to have limited release of the software referred to as alpha and beta launch where feedback from code testers and regular end users are used to improve the product as well as fix any flaws that go undetected during regular testing phase of the product. Also, during regular testing phase of the software the code developers become an integral part of the team after all they are the one who analyze and model customer requirements, develop the code, and its documentation. When the final software program needs to be tested, however, it is a requirement to involve an independent test group who do not have any vested interest in approving the software program is free of defects as in the case of developers who created the program. Furthermore, in industries those are vertically integrated it is a common practice to develop the software required to operate their product and subject it to testing by an in-house independent test group due to the competitive nature of the business. Nevertheless, such practice still results in serious defects in the product even after following strict standards and guidelines of quality assurance and testing. The prime example of such defects is fatal accidents involving unintended acceleration of passenger vehicle manufactured by Toyota Motor Corporation. The following section lists some well-known accidents illustrating the need for meticulous software testing, close adherence to standard software development and quality assurance practices, and the role of independent software testing group to reduce the software errors.

2.5.1 List of Software Bugs

Mars Polar Lander, the first ever mission to land a probe, known as Mars Polar Lander, in Mars South Polar Region was carried out in 1999. The Polar Lander carried cameras, a robotic arm and instruments to measure the composition of Martian soil. It also carried the Deep Space 2 microprobes in order to sample the Martian surface which involved penetrating into subsurface levels. The mission was a failure as the Polar Lander crash landed on to the Martian surface. The later investigations pointed out that the most likely cause for the failure was a false signal indicating the probe landed on the surface due to faulty coding to shut down the engine once the probe landed. The signals used to instruct the probe to land were meant to deploy when vibration was detected. It was later discovered, however, that the deployment of the probe legs also cause vibration due to turbulence, which was ultimately mistaken for a final landing, thus crashing the probe [39]. Another failed space mission was the Mariner 1 excursion to Venus in 1962. The mission failed for several reasons, but the main reason was attributed to the transcription error in the FORTRAN code of rocket guidance software residing in the on-board computer. The error was the omission of the bar from the expression “R-dot-bar sub n” indicating nth smoothed value of derivative of radius. This error resulted in incorrect compensation of the velocity steering the rocket off course eventually the missions was aborted by destroying the rocket [40].

Therac-25 radiation accidents, the death of six cancer patients due to accidental overdose of radiation through a computer controlled radiation therapy machine known as Therac-25 in a span of two years was described as one of the worst in the 35-year history of radiation therapy back in 1987. An investigation of the incidents was conducted by Levinson et al., through documents such as law suits, government records, and other correspondence letters obtained from U.S. Food and Drug Administration (FDA), which regulates these devices. Levinson et al., concluded that the main causal factors for the defective operation of the device among other systematic failure were attributed to defective software that handled the operational safety of the device. The lessons learned from these accidents were not to have overconfidence in software, confusing reliability with safety, lack of defensive design, complacency, unrealistic risk assessments, failure to eliminate root causes, inadequate software engineering practices, software reuse, lack of user and government oversight and standards on exhaustive testing of software used in these devices [41]. The lack of quality control on the design and testing of the software used in these safety-critical devices are attributed to the small firms who provide the components and the accompanying software to large corporations whose names are associated with these devices. As quoted by Houston of the US FDA [42], “A significant amount of software for life-critical systems comes from small firms, especially in the medical device industry; firms that fit the profile of those resistant to or uninformed of the principles of either system safety or software engineering.” This implies that fail safety system is not fool proof due to the use of third-party vendors who do not come under the purview of Government Regulation and Standards for medical software.

Unintended accelerations tied to electronic throttle control system (ETCS) in passenger cars, in 2010 it was widely reported that about 86 fatal road accidents were linked to unintended acceleration which mainly involved Toyota vehicles of different MYs since the introduction of electronic throttle control system also known as drive-by-wire technology. These finding resulted in recall of 8 million vehicles to be upgraded with new firmware to improve the safety-critical functions of the vehicle’s ECM [43]. Due to the serious nature and the total number of accidents National Highway Transportation and Safety Administration (NHTSA), in association with National Aeronautics and Space Administration (NASA), initiated a comprehensive enquiry of the possible failure of the electronic system, due to an unnoticed bug in the software leading to these unintended accelerations. Detailed testing and analysis of the ECM and ETCS-i system in the vehicles, mainly MY2005 Toyota Camry that reportedly had experienced unintended acceleration as testified by the users did not show any evidence of ETCS-i electronics being the likely cause of the failure. However, it was concluded that because there was no proof that the ETCS-i caused the failures related acceleration does not mean it could not occur [44]. Furthermore, experts in the field of embedded systems indicated the failure to software bugs quoting NASA’s report which states that the coding practices were not consistent with the industry standard and consisted of hundreds of thousand lines codes which made it difficult for the peer review panel to accomplish the close scrutiny of the code [45].

2.5.2 Software Testing Methods

There are several software testing methods and techniques used at different stages of software development process as well as testing methods to validate the completeness of the software to the requirements specified by the customer or the purpose it is used for. Some of the primary testing methods will be discussed in the following sections. Two main software testing types are manual testing and automated testing. Under manual testing the software tester takes the role of end-user and creates different test cases, based on the requirement document, to test the software manually for any unexpected behavior or bug. Manual testing is mainly used for unit testing, integration testing, system testing and user acceptance testing. Conversely, under automated testing the software tester employs another software tool to develop scripts to automate the software testing process which are repetitive in nature. Automation of software testing is normally used for regression testing, stress, load and performance testing performed at different stages of software development life cycle. Software testing can be further classified into two main groups as functional and non-functional testing.

Functional testing is conducted based on the requirements, such as behavioral and informational aspects, to be met by the end product. Under functional testing the software is verified against design documents or software requirement specification (SRS) with known inputs for which the expected results are known *a priori*, therefore upon examining the actual results for the given input it will be effective in locating and fixing the cause of deviation or error in the software. The five underlying steps in conducting any functional testing are [46]:

1. Establish the functionality or the intended purpose of the software being tested;
2. Define test cases to test specific functionalities of the software;
3. Formulate results to be expected for a given test case scenario as per SRS;
4. Execute the test scenarios; and
5. Compare the actual and expected test results demonstrating the deviation or conformance to the SRS.

Functional testing is further classified into three different methods based on the knowledge of the underlying code and algorithm of the software being tested. Note that all these testing methods can be applied in various levels of functional testing. The functional testing methods are

1. Black Box Method
2. White Box Method and
3. Gray Box Method

2.5.2.1 Black Box Method

In this method of testing the software tester does not have access to the code or the algorithm of the software save for the software's functional requirements documents. The test cases are crafted based on the functional or behavioral aspects of the software, and the tester is aware of the results to be expected for the given test case. Hence this method enables in verifying the conformance of the software to design specification and does not aid in debugging or locating the source of error. This method of testing is normally used at integration testing, system testing, and user acceptance testing levels. The tester does not require comprehensive knowledge of the programming language as there is no access to the code. Since this method of testing is used by independent testing group, it clearly removes any bias towards testing the software for errors as opposed to testing conducted by code developers.

2.5.2.2 White Box Method

Also known as the glass box method, it is used at all levels of software development including unit testing, integration testing, regression testing, system testing and during user acceptance testing level.

White box testing is normally conducted by software development team in associating with the design team. As the name suggests the software tester has complete access to the code and hence ensure complete code coverage while testing any portion of the code before it is integrated into a system. To achieve comprehensive testing of the software at a minimal cost it, is recommended to conduct white box testing, by the software development team, as part of standard software development practices - thereby reducing the number of bugs and exorbitant cost in fixing them once the software is integrated as a system.

2.5.2.3 Gray Box Method

Also known as translucent box testing, it is a hybrid of the black and white box testing methods. In this method, the tester has a limited access to the code but complete access to the design document of the software. The testing team includes personnel with expert knowledge of the domain for which the software is being designed hence superior test cases can be designed to achieve higher code coverage than in a black box method. This kind of testing is normally employed before user acceptance testing level to ensure smooth operation of the software on different platforms and execution of the basic functionalities of the software.

Unit Test: is the most basic form of functional testing performed by the software developer as and when new functionalities are implemented in the software module. Standard software development practice requires test cases to be created before beginning the development of the software units so that the code is developed to the requirement and also being verified against the requirements. Since unit tests are independent of other software modules, these tests can be conducted in parallel on multiple components. Unit tests are a primary example of the white box testing method where the basic structure of the internal code is tested exhaustively using white box testing techniques to improve the quality of the software and thereby reducing the number of errors in the final product.

The characteristics of the aforementioned software testing methods used for functional testing are illustrated in Table 7.

Table 7: Characteristics of Software Testing Methods [47]

Test Criteria	Black Box	Grey Box	White Box
Code Access	Not required to have access to the code and internal working of the application.	Limited access to the code and complete access to the algorithm and design of the application.	Complete access to the software code, design documents, and software requirement specifications.
Code Coverage	Limited due to lack of access to the internal functioning of the code.	Higher than black box method due to limited access to the internal functioning of the code.	Most comprehensive due to complete access to the code, and design requirements.
Test Levels	Suitable for testing large code, hence employed for integration testing, system testing and user acceptance testing.	Suitable for higher level code testing similar to black box method but effective in detecting the errors.	Well suited for testing low level code, such as unit and integration testing levels.
Testing Group	Independent testing group with limited knowledge of code. Tested from user perspective.	Software developers and design team with domain expertise. Tested from both developer and end-user perspective to improve the efficiency of the product.	Software development team. Tested from developer's perspective.
Test Outcome	Identification of application error from end-user perspective.	Identification of application error including its location from both developer and end-user perspective.	Identification of source and location of the error within the code.
Test Effort	Least time consuming, and less exhaustive.	Intermediate to black and white box testing methods for both time required to test and the degree to which the code can be tested.	Most time consuming, and exhaustive.
Test Expenditure	Low, but errors detected at higher level of code development are expensive and time consuming to fix.	High, but the cost involved in identifying the errors is lower than that of black box testing method.	High, but errors detected at lower level of code development are easier to fix and reduces overall cost of software development.
Test Techniques	Equivalence partition testing, boundary value analysis, robustness testing, decision table, state transition diagram	A combination of both black and white box testing techniques is used where applicable.	Statement coverage, decision coverage, loop coverage, branch coverage and path coverage.

Integration Test: is a functional test which follows unit testing wherein multiple software modules are integrated and tested as a whole component to verify proper flow of information between individual software units and concurrence of end result with the expected output. There are two approaches to conducting integration testing namely the top-down approach, and the bottom-up approach. As the name suggests, the software is integrated incrementally either from the top or bottom while being tested concurrently. The systematic approach in performing integration testing leads to detection and isolation of errors easily and ensures complete testing of the interface between different software units.

Regression Test: is another form of functionality testing, it can also be referred to as transparency testing as this test is conducted when there is any change in the integrated software due to implementation of new features in the program, due to integration of new modules to expand the capability of the base software or due to rectification of any software errors that were uncovered during integration testing. The test suite includes a basic set of test cases that are re-executed each time to ensure the basic behavior or functionality of the software is unchanged due to modification of the software. Regression tests are normally automated to reduce the cost and time required for testing.

User Acceptance Test: is the most critical test conducted before deploying the software for end-user operation and it is conducted by the software quality assurance team. This test is performed to verify the compliance of the product to the software requirement specifications which are agreed upon by the developer and the client at the initiation of the project. It is also used to uncover any errors in deploying the end product on different software platforms along with any cosmetic issues such as spelling mistakes, broken links, redundant software code used during development and debugging of the software. Two levels of user acceptance testing are alpha and beta testing.

Non-functional testing of software involves validation and verification of the non-functional aspects of the software. The non-functional testing includes performance testing, stress and load testing, usability testing, security testing and portability testing. Under non-functional testing, the software is tested for the responsiveness, loopholes in the security of the system, the upper limit on the volume of data that can be handled, compatibility with different operating systems, the ease with which the code can be modified for future improvement, and the portability for reusing the code in similar applications.

3 PEMS DEVICE BRAKE SPECIFIC EMISSIONS CALCULATIONS

3.1 Exhaust Concentrations

Gaseous emissions including CO, CO_2, NOx, and THC are measured continuously from the raw exhaust. The analyzers used in measuring the aforementioned emission constituents are listed in Table 8 along with the method of analysis and measurement accuracies.

Table 8: List of Gas Analyzers and Specifications

Constituent Gas	Analysis Method	Analyzer Type	Range	Accuracy
Sensors Semtech-Ecostar [48]				
CO	Dry & heated	NDIR	0 - 8%	± 50 ppm or 2% rdg
CO_2	Dry & heated	NDIR	0 - 20%	± 0.1% or 2% rdg
NO	Dry & heated	NDUV	0 - 3000 ppm	± 0.3% or 2% rdg
NO_2	Dry & heated	NDUV	0 - 500 ppm	± 0.3% or 2% rdg
THC	Wet & heated	HFID	0 – 90 ppm C to 0 - 30,000 ppm C	± 0.3% FS or 1% rdg or ± 1% FS for low range
Horiba OBS-2200 [49]				
CO	Wet & heated	NDIR	0 – 0.5% to 0 – 10%	±2.5% of FS
CO_2	Wet & heated	NDIR	0 – 5% to 0 – 20%	±2.5% of FS
NOx	Wet & heated	CLD w NO_2 to NO converter	0 – 100 ppm to 0 – 3000 ppm	±2.5% of FS
THC	Wet & heated	HFID	0 – 1000 ppm C to 0 – 10,000 ppm C	±2.5% of FS
AVL MOVE [50]				
CO	Dry & heated	NDIR	0 – 4.9%	±30 ppm abs or ± 2% rel
CO_2	Dry & heated	NDIR	0 – 20%	±0.1% abs or ±2% rel
NO	Dry & heated	NDUV	0 – 5000 ppm	±0.2% of FS
NO_2	Dry & heated	NDUV	0 – 2500 ppm	±0.2% of FS
THC	Wet & heated	HFID	0 – 30000 ppm	±5 ppmC1 or ±2% rel

The design specifications of the analyzers above meet or exceed the accuracy, repeatability, linearity, noise, drift, and response time criteria listed in the in-use emissions measurement regulations in order to be qualified for in-use compliance testing. The Semtech PEMS device allows measurement of both NO and NO_2 simultaneously with the aid of a NDUV analyzer. Also, all emissions except for THC are measured and recorded on a dry basis, which is corrected to wet concentrations during data post-processing. Whereas, the OBS-2200 PEMS device uses a CLD in conjunction with NO_2 to NO converter for NOx analysis, which allows the analyzer to measure either NO (NO_2 to NO converter turned off) or total NOx (NO_2 to NO converter turned on), but not simultaneously. All emissions concentrations are measured on a wet basis thereby eliminating the need for dry-to-wet compensation of measured concentrations as opposed to the Semtech Ecostar.

3.2 Time Alignment of Real-time Emissions Concentrations

The individual emissions concentrations are shifted to account for transport delays from the sampling plane (reference point) to the analyzer heated transfer line, heated filter, and internal plumbing as well as to account for analyzer response time. This is done in order to time-align the measured concentration values with respective exhaust flow rate, which is measured at the sampling plane, for determining time specific emission mass rates. The time delay, which includes transportation and analyzer response times, is determined automatically in both PEMS devices during system leak checks and analyzer linearization verification procedures for a given sampling setup. The delay time is used to align emissions signals with exhaust flow before recording into the data file; hence, the emissions concentration reported in the data are time aligned. The delay times are reported in the output file.

Two of the widely used commercial PEMS devices, namely the Horiba OBS-2200 and Sensors Semtech Ecostar, both use the response and delay time tests to deduce the delay time of each analyzer for any change in the concentrations observed at the sampling plane. The delay times determined in the above method account for sample transportation delay from the sampling plane to the analyzer for a given constant sampling rate and do not account for the delay in exhaust flow from the exhaust manifold to the sampling plane caused due to transient operation of the engine. However, the delay time determined by the above method is found to be the most accurate method to time align emissions concentration to exhaust flow measurement when compared to other approaches that include time delay of the exhaust flow to reach the sampling plane and the visual method of aligning the signals.

3.3 Drift Correction of Real-time Emissions Concentrations

It has been observed that the analyzers used in PEMS devices are prone to drift due to extended periods of operation, hence it is required to correct measured concentrations for drift per CFR 40 part 1065. The analyzers are zeroed and spanned prior to data collection over a test route and their values are recorded. These are known as pre-zero and pre-span values. Upon completion of a test route, the analyzer response for zero and span gases are recorded before adjusting the analyzer to read zero and span values. These are known as post-zero and post-span values. If the test duration exceeds more than one hour, it is required by the PEMS devices to record the zero response of the analyzers to correct the emissions for zero drift [51, 52]. The PEMS devices automatically interrupt data collection for a period of 30 seconds for every hour to record post-zero values as well as make zero adjustments for each analyzer before continuing with data collection.

The latest version of the regulation mandates the use of the following equation for drift correction which is published under 40 CFR 1065 [53].

$$x_{drift\,corr}(t) = x_{ref\,zero} + \left(x_{ref\,span} - x_{ref\,zero}\right) \cdot \left[\frac{2 \cdot x(t) - \left(x_{pre\,zero} + x_{post\,zero}\right)}{\left(x_{pre\,span} + x_{post\,span}\right) - \left(x_{pre\,zero} + x_{post\,zero}\right)}\right] \qquad \textbf{Eq. (6)}$$

Where: $x_{drift\,corr}(t)$	drift corrected concentration value in respective unit (ppm or vol-%) at time *t*
$x(t)$	concentration value in respective unit (ppm or vol-%) at time t
$x_{ref\,zero}$	reference gas used to zero the analyzers
$x_{post\,zero}$	post-test zero concentration value in respective unit (ppm or vol-%)
$x_{pre\,zero}$	pre-test zero concentration value and is equal to $x_{ref\,zero}$
$x_{ref\,span}$	span bottle concentration value in respective unit (ppm or vol-%)
$x_{pre\,span}$	pre-test span concentration of each analyzer and is equal to $x_{ref\,span}$
$x_{post\,span}$	post-test span concentration value in respective unit (ppm or vol-%)

Note that when the in-use test duration exceeds more than one hour it is required to only check the zero drift of the analyzers and not the span drift. Therefore, the equation used to correct for analyzer drift over the interval of one hour is given by Eq.(7)

$$x_{drift\,corr}(t) = 0 + \left(x_{ref\,span} - 0\right) \cdot \left[\frac{2 \cdot x(t) - \left(0 + x_{post\,zero}\right)}{\left(2 \cdot x_{pre\,span}\right) - \left(0 + x_{post\,zero}\right)}\right] \qquad \textbf{Eq. (7)}$$

The difference between Eq. (6) and Eq. (7) is that the value of zero is substituted for $x_{ref\,zero}$ & $x_{pre\,zero}$, and the value of $x_{pre\,span}$ is substituted for $x_{post\,span}$ as there are no hourly span values recorded.

3.3.1 Drift Correction Calculations for PEMS A

The PEMS A software automatically performs a drift correction of the real-time emissions concentrations upon completion of hourly zero checks of the analyzers using the equation below. The PEMS A saves two data files, one with raw emissions concentrations and another with drift corrected concentrations, for every hour after performing drift corrections.

$$x_{drift\,corr}(t) = x(t) - \frac{x_{post\,zero}}{2} \qquad \textbf{Eq. (8)}$$

Where: $x_{drift\ corr}(t)$ drift corrected concentration value in respective unit (ppm or vol-%) at time t

$x(t)$ concentration value in respective unit (ppm or vol-%) at time t

$x_{post\ zero}$ post-test zero concentration value in respective unit (ppm or vol-%)

The PEMS A software uses a drift correction method that constitutes a simplified version of an earlier proposed formula published in 40 CFR 1065.657 (b) (3) [54]. The manuals for PEMS B do not provide any details of the method used to correct emissions concentration for analyzer drift.

3.3.2 Drift Correction Calculations for PEMS B

The PEMS B manual claims that the emissions calculations are performed in accordance to various in-use emissions regulations as applied to emissions measurement and its quantification, spanning both CFR 40 part 86 and part 1065 [13, 55], but does not provide any explicit method or equation followed to correct for analyzer drift during in-use emissions measurement.

3.4 Exhaust Flow Measurement

Both PEMS A and PEMS B devices use averaging pitot static tubes of different sizes installed into exhaust tubes of different diameters to accommodate exhaust flow measurement from vehicles of different classes. These pitot tubes, along with the exhaust tubing in which they are installed, are calibrated against a NIST traceable flow measuring device and assigned with flow measurement coefficients. The coefficients are stored in a database in association with the serial numbers given to each pitot tube. The pitot tube calibration coefficients, along with measured absolute pressure and differential pressure of the exhaust flowing through the tube and the dimensions of the exhaust tube, are used to calculate the volumetric flow rate or mass flow rate of the exhaust. The outputs of the exhaust flow measuring module for both PEMS devices are:

1. Absolute pressure
2. Exhaust temperature at the point of exhaust flow measurement
3. Volumetric flow rate (PEMS A)
4. Mass flow rate (PEMS B)

3.4.1 Exhaust Flow Calculations for PEMS B

The exhaust flow is recorded as mass flow rate and reported in both mass and volumetric flow rate, which includes flow values at actual and standard temperature and pressure conditions. The governing equation used in the mass flow rate through the PEMS B exhaust flow meter (EFM) is derived from continuity and Bernoulli's equation, which is given by

$$\dot{m}(t) = K(RE) \cdot A\sqrt{\rho \cdot \Delta P(t)} \qquad \textbf{Eq. (9)}$$

Where: $\dot{m}(t)$ mass flow rate $\left[\frac{kg}{hr}\right]$ at time t

K(RE) the discharge coefficient, a function of Reynolds Number, for the given pitot tube and exhaust tube assembly

A area of flow cross section $[m^2]$

ρ density of the exhaust gas $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$

ΔP(t) differential pressure in the pitot tube at time t [Pa]

The density of the exhaust gases is determined based on the ideal gas law and is given by

$$\rho = \frac{P \cdot MW_{gas}}{R_u \cdot T} \qquad \textbf{Eq. (10)}$$

Where: ρ density of the exhaust gas $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$

P absolute pressure [Pa]

MW_{gas} user defined gas molecular weight $\left[\frac{\mathrm{kg}}{\mathrm{mol}}\right]$

R_u universal gas constant $\left[\frac{\mathrm{J}}{\mathrm{K \cdot mol}}\right]$

T temperature of exhaust gas [K]

The molecular gas weight M, is determined based on the fuel being used to operate the vehicle. It is observed in the user manual which states that "the effect of uncertainty in using a constant molecular weight is small since the flow rate of the exhaust is proportional to the square root of M."

However, the mass flow rate of the exhaust is converted to volumetric exhaust flow rate at standard conditions of 20° C and 1 atmosphere (or 101.325 kPa) before computing the rate of emissions. This is accomplished first by calculating the density of the exhaust at the above standard conditions, which is given by

$$\rho_{std}(t) = \frac{P_{std} \cdot MW_{exh}(t)}{R_u \cdot T_{std}} \qquad \textbf{Eq. (11)}$$

The molecular weight of the exhaust is determined by the molecular weight of the constituent gases weighed by their respective measured wet concentrations. The composition of the exhaust gas is approximated by the following constituent gases CO_2, N_2, O_2, and water vapor.

$$MW_{exh}(t) = \frac{1}{100}\sum [CO_2] \cdot 44.01 + [O_2] \cdot 32.0 + [N_2] \cdot 28.013 + [H_2O] \cdot 18.015 \qquad \textbf{Eq. (12)}$$

It should be noted that the density of the exhaust gas varies with its constituent concentrations since it is a function of molecular weight, hence standard density is calculated for each data point. Finally, the standard volumetric flow rate used in determining the emissions rate is given by

$$\dot{V}_{std}(t) = \frac{\dot{m}(t)}{3600 \cdot \rho_{std}(t)} \qquad \textbf{Eq. (13)}$$

Where: $\dot{V}_{std}(t)$ Volumetric flow rate of exhaust at standard conditions (293.15 K & 101.325 kPa), $\left[\frac{m^3}{s}\right]$

3.4.2 Exhaust Flow Calculation for PEMS A

The exhaust flow rate measured using the average pitot static tube is determined as a function of the measured differential pressure, static pressure, and the temperature of the exhaust, which changes based on exhaust flow rate. The equation to calculate the exhaust flow rate is given by

$$\dot{Q}_{ex}(t) = K \cdot \sqrt{\left\{\frac{P_{ex}(t)}{101.325}\right\} \cdot \left\{\frac{293.15}{T_{ex}(t)}\right\} \cdot \left\{\frac{\Delta h(t)}{\gamma_{ex}}\right\}} \qquad \textbf{Eq. (14)}$$

Where: $\dot{Q}_{ex}(t)$ exhaust flow rate at standard conditions $\left[\frac{l}{min}\right]$

K pitot tube calibration coefficient, for the combination of pitot tube and the exhaust section in which the pitot tube is inserted $[\mathrm{m}^2]$

$\mathrm{P_{ex}(t)}$ measured pressure of exhaust gas [kPa]

$\mathrm{T_{ex}(t)}$ measured temperature of exhaust gas [K]

$\Delta\mathrm{h(t)}$ differential pressure of pitot tube [kPa]

γ_{ex} density of exhaust gas $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$

Note that K is a constant for a given pitot tube and exhaust tube combination; the unit conversion factors are incorporated into it so that the recorded data of exhaust flow is in liters per minute. Furthermore, the standard exhaust flow rate determined by the above equation, assuming exhaust as an ideal gas with a known density for exhaust gas at standard conditions, is transformed in to molar flow used to determine mass rate of exhaust emissions; and it is given by

$$\dot{n}_{ex}(t) = \dot{Q}_{ex}(t) \cdot \left(\frac{1}{22.415}\right) \cdot \left(\frac{273.15}{293.15}\right) \cdot \left(\frac{1}{60}\right). \qquad \textbf{Eq. (15)}$$

Where: $\dot{n}_{ex}(t)$ molar flow rate of exhaust $\left[\frac{mol}{sec}\right]$ and

22.415 molar volume of an ideal gas at 1 atmosphere and 0° C or 273.15 K $\left[\frac{l}{mol}\right]$.

3.5 Calculation of Amount of Water Vapor in Ambient Air (i.e. Intake Air)

The experiments conducted by Krause et al., in 1972 [56] showed that the NOx emissions from diesel engines are influenced by the amount of water vapor in the intake air, resulting in lower NOx emissions with higher water fraction in the intake air and vice versa. This required correcting the measured NOx emissions to a reference value of intake air humidity in order to compare emissions results from different laboratories. Since in-use emissions are measured in varying ambient conditions, it is even more critical to correct the measured NOx in order to normalize the results. Hence, in-use emissions measurement regulations [57] mandate the correction of measured NOx emissions to a standard humidity level of 7.14 g of H_2O/ kg of dry air if the humidity of the intake is below 7.14 g/kg and correct it to 10.71 g of H_2O/ kg dry air if the intake air humidity is above 10.71 g/kg.

The amount of water vapor in the ambient air is calculated using different equations based on the method intake air humidity measurement. If intake air humidity is measured as a dew point temperature, then the amount of water vapor is given by [58]

$$x_{H2O}(t) = \frac{p_{H2O}(t)}{p_{abs}(t)} \qquad \textbf{Eq. (16)}$$

Where: $p_{H2O}(t)$	saturation water vapor pressure in $[kPa]$ at the measured dew point, $T_{sat} = T_{dew}$.
$p_{abs}(t)$	wet static absolute pressure in [kPa] at the location of dew point temperature measurement

If intake air humidity is measured in terms of relative humidity, then the amount of water vapor is given by [59]

$$x_{H2O}(t) = \frac{RH\%(t) \cdot p_{H2O}(t)}{p_{abs}(t)} \qquad \textbf{Eq. (17)}$$

Where: $RH\%(t)$	relative humidity as fraction
$p_{H2O}(t)$	saturation water vapor pressure in [kPa] at 100% relative humidity, $T_{sat} = T_{amb}$
$p_{abs}(t)$	wet static absolute pressure in [kPa] at the location of RH% measurement

Also, the amount of water vapor in the ambient air is expressed in terms of specific humidity which is given by [60]

$$H(t) = \left[\frac{6.211 \cdot RH\%(t) \cdot p_{H2O}(t)}{p_{abs}(t) - \left\{\frac{p_{H2O}(t) \cdot RH\%(t)}{100}\right\}}\right] \qquad \textbf{Eq. (18)}$$

Where: $H(t)$	specific humidity at time t $\left[\frac{\text{g of } H_2O}{\text{kg of dry air}}\right]$
$RH\%(t)$	relative humidity as percentage value
$p_{H2O}(t)$	saturation water vapor pressure in [kPa] at 100% relative humidity, $T_{sat} = T_{amb}$

$\mathrm{p_{abs}(t)}$ wet static absolute pressure in [kPa] at the location of RH% measurement

The specific humidity of the intake air can also be expressed in terms of fraction of water by substituting Eq. (17) into following form of Eq. (18).

$$H(t) = \left[\frac{621.1\left\{\frac{RH\%(t)\cdot p_{H2O}(t)}{100\cdot p_{abs}(t)}\right\}}{\frac{p_{abs}(t)}{p_{abs}(t)} - \left\{\frac{RH\%(t)\cdot p_{H2O}(t)}{100\cdot p_{abs}(t)}\right\}}\right] \qquad \textbf{Eq. (19)}$$

Hence,

$$H(t) = 621.1\left[\frac{x_{H2O}(t)}{1 - x_{H2O}(t)}\right] \qquad \textbf{Eq. (20)}$$

The significance of expressing the amount of water vapor in the intake air in terms of specific humidity will be explained in the section where the NOx humidity correction factor is discussed.

The saturation vapor pressure of water for humidity measurement over liquid water at ambient temperature from 0 to 100° C and over super-cooled water at ambient temperature from -50 to 0° C is given by the following equation in [61]

$$p_{H2O} = 10^{\left[a_1\left\{1-\frac{273.16}{T_{sat}}\right\}+a_2\left\{\log_{10}\left(\frac{T_{sat}}{273.16}\right)\right\}+a_3\left\{1-10^{a_4\left(\frac{T_{sat}}{273.16}-1\right)}\right\}+a_5\left\{10^{a_6\left(1-\frac{273.16}{T_{sat}}\right)}-1\right\}-a_7\right]} \qquad \textbf{Eq. (21)}$$

Where: T_{sat} is temperature at which saturation vapor pressure of water in ambient air is determined i.e. $T_{sat} = T_{amb}\ or\ T_{dew}$ in $[K]$

$a_1 = 10.79574$

$\mathrm{a_2} = -5.02800$

$\mathrm{a_3} = 1.50475 \times 10^{-4}$

$\mathrm{a_4} = -8.2969$

$\mathrm{a_5} = 0.42873 \times 10^{-3}$

$\mathrm{a_6} = 4.76955$

$\mathrm{a_7} = 0.2138602$

If humidity is measured over ice at ambient temperature from -100 to 0° C, the saturation vapor pressure of water is given by

$$p_{H2O} = 10^{\left[a_1\left\{\frac{273.16}{T_{sat}}-1\right\}+a_2\left\{\log_{10}\left(\frac{273.16}{T_{sat}}\right)\right\}+a_3\left\{1-\left(\frac{T_{sat}}{273.16}\right)\right\}+a_4\right]} \qquad \textbf{Eq. (22)}$$

Where: $\mathrm{T_{sat}}$ is temperature at which saturation vapor pressure of water in ambient air is determined i.e. $\mathrm{T_{sat} = T_{ice}}$ in [K]

$a_1 = -9.096853$

$a_2 = -3.566506$

$a_3 = 0.876812$

$a_4 = -0.2138602$

3.5.1 Calculation of Amount of Water Vapor in Intake Air for PEMS A

Since 40 CFR 1065.645 allows the use of other formulae to calculate saturation vapor pressure of water at dew point or ambient temperature, provided they are applied by considering good engineering judgment, the PEMS A user manual prescribes the following formula to determine saturation vapor pressure of water at ambient temperature.

$$p_{H2O} = e^{\left[\frac{a_1}{T_{amb}(t)+273.15}+a_2+a_3\{T_{amb}(t)+273.15\}+a_4\{T_{amb}(t)+273.15\}^2+a_5\cdot\ln\{T_{amb}(t)+273.15\}\right]} \quad \textbf{Eq. (23)}$$

Where: p_{H2O} saturation vapor pressure of water in $[Pa]$

$T_{amb}(t)$ ambient temperature at time t in [°C]

$a_1 = -6096.9385$

$a_2 = 21.2409642$

$a_3 = -2.711193 \times 10^{-2}$

$a_4 = 1.673952 \times 10^{-5}$

$a_5 = 2.433502$

The amount of water vapor in the intake air is determined based on the measured relative humidity using Eq. (17).

3.5.2 Calculation of Amount of Water Vapor in Intake Air for PEMS B

As allowed in 40 CFR 1065.645, to use an appropriate formula to determine saturation vapor pressure of water vapor, PEMS B follows the empirical function given in the ASCE manual [62] to determine the saturation vapor pressure of water at dew point or ambient temperature of intake air using

$$p_{H2O} = e^{\left[\frac{16.78\cdot T_{sample}-116.9}{T_{sample}+237.3}\right]} \quad \textbf{Eq. (24)}$$

Where: p_{H2O} saturation vapor pressure of water in $[kPa]$

$T_{sample}(t)$ dew point or ambient temperature at time t in [n/a]

Based on the saturation vapor pressure of water determined at dew point or ambient temperature of intake air the fraction of water is found using Eq. (16) or Eq. (17)

3.6 Calculation of NOx Humidity Correction Factor k_h

Once the amount of water present in the intake air, either in terms of fraction of water or the specific humidity is determined, the factor k_h is used to correct the measured NOx concentrations to a reference value of intake air humidity as given by Eq. (25) and Eq. (26) as prescribed in 40 CFR §86.1342-90 [63] and §1065.670 [64] respectively for diesel fueled and compression-ignition engines.

$$k_h = \frac{1}{[1 - 0.0182(H - 10.71)]} \qquad \textbf{Eq. (25)}$$

and

$$k_h = (9.953 \cdot x_{H2O} + 0.832) \qquad \textbf{Eq. (26)}$$

It should be noted that k_h, given by the above equations, is used to correct NOx concentrations to standard reference intake air humidity of 10.71 g H_2O/kg dry air which is equivalent to 75 grains H_2O/lb dry air. However, Eq. (26) is an approximation of Eq. (25) and allowed only if the standard setting part does not prohibit according to §1065.670. Furthermore, the in-use emissions regulations per §86.1370-2007 [57] mandates correction of NOx concentrations either to 7.14 g/kg if the intake air humidity is below 7.14 g/kg or to 10.71 g/kg, if the intake air humidity is above 10.71 g/kg. This leads to no correction of NOx for intake air humidity if it is between 7.14 and 10.71 g/kg, unlike tests conducted in the laboratory where the measured NOx is corrected to single reference humidity of intake air of 10.71 g/kg. Hence the correction factor k_h, used for in-use emissions measurement, is given by

$$k_h(H) = \begin{cases} \dfrac{1}{[1 - 0.0182(H - 7.14)]}, & H < 7.14 \\ \dfrac{1}{[1 - 0.0182(H - 10.71)]}, & H > 10.71 \end{cases} \qquad \textbf{Eq. (27)}$$

3.6.1 Calculation of NOx Humidity Correction Factor k_h for PEMS A

The correction of NOx emissions for intake air humidity is performed by using the humidity correction factor k_h, which is determined by the following equation as prescribed in the user manual.

$$k_h = (9.953 \cdot x_{H2O}(t) + 0.832) \qquad \textbf{Eq. (28)}$$

Note that the above equation is equivalent to correcting measured NOx emissions to the reference humidity of 10.71 g/kg of water in dry air as given in §1065.670 [64] and does not take into consideration of correcting NOx to a reference value of 7.14 g/kg of water in dry air if the ambient humidity is less than 7.14 g/kg as mandated under the in-use emissions regulations §86.1370-2007. Also, the value of $x_{H2O}(t)$ is determined based on the saturation vapor pressure of water calculated using Eq. (23), which is different from the one provided in §1065.645 [61].

3.6.2 Calculation of NOx Humidity Correction Factor k_h for PEMS B

The NOx emissions correction factor for intake air humidity is allowed to be made following different methods as prescribed in the emissions measurement regulations. Therefore, for diesel engines, different humidity correction factors are applied based on the method chosen. For example, under Method

1, the k_h is calculated as per §86.1342-90 [63] which is given by Eq. (25), under Method 4 it is calculated using Eq. (26) as per §1065.670 [64], and under Method 3 it is calculated based on the in-use emissions regulations given by §86.1370-2007 [57] and based on the following equations. Note that the value shown in the parenthesis for absolute humidity H is the molar fraction of water equivalent to H.

$$k_h(H) = \begin{cases} (9.953 \cdot x_{H2O} + 0.8855), & H \leq \ 7.14 (or\ 0.011365) \\ (9.953 \cdot x_{H2O} + 0.8320), & H \geq 10.71 (or\ 0.016951) \\ \quad 1, & 7.14 < H < 10.71 \end{cases} \qquad \textbf{Eq. (29)}$$

Note that the above equation does not follow the conditions specified under §86.1370-2007 in two aspects; firstly, in-use emissions measurement regulations mandates to correct NOx emissions for intake air humidity to 7.14 g/kg of water in dry air if it is lower than 7.14 g/kg of water in dry air and not when it is equal to it, and similarly correct NOx for intake air humidity of 10.71 g/kg of water in dry air when measured humidity is higher than that. Secondly, §86.1370-2007 does not explicitly specify the equations used for determining the humidity corrections factor based on the fraction of water in the intake air. Also, the relation used for humidity correction factor when the intake humidity is less than or equal to 7.14 g/kg of water in dry air is not given in §1065.670 [64]. Furthermore, the fraction of water in intake air is determined based on the saturation vapor pressure of water calculated based on Eq. (24), which does not follow the method recommended under §1065.645 [61].

3.7 Dry-to-Wet Compensation of Real-Time Emissions Concentrations

The commercial PEMS devices are capable of analyzing raw exhaust emissions either on a wet or dry basis. If the emissions are quantified on a dry basis, then the measured concentrations have to be compensated for converting the sample from dry-to-wet, which is denoted by k_w. According to §1065.659 [65] dry-to-wet correction factor is given by

$$k_w(t) = \left[\frac{1 - x_{H2Oexh}(t)}{1 - x_{H2O[emission]meas}(t)}\right] \qquad \textbf{Eq. (30)}$$

Where:	
$x_{H2Oexh}(t)$	fraction of water per mole exhaust
$x_{H2O[emission]meas}(t)$	fraction of water per mole exhaust sample downstream of a sample dryer (eg. thermal chiller).

Note that the fraction of water in the exhaust sample downstream of the sample dryer is a function of the absolute pressure of the sample and the saturation vapor pressure of water, remaining in the sample, determined at the dew point temperature or the sample temperature. If $x_{H2O[emission]meas}(t)$ is greater than $x_{H2Oexh}(t)$ then k_w is set to 1. The fraction of water in the exhaust is determined based on the measured concentrations of emissions, chemical properties of the fuel, and chemical balance of the emission constituents assuming complete/stoichiometric combustion as per §1065.655 [66]. The procedure used to determine $x_{H2Oexh}(t)$ involves iterative process, which is listed below:

1 $$x_{H2Ointdry}(t) = \left[\frac{x_{H2Oint}(t)}{1 - x_{H2Oint}(t)}\right] \quad \textbf{Eq. (31)}$$

2 $$x_{CO2int}(t) = \left[\frac{x_{CO2intdry}(t)}{1 + x_{H2Ointdry}(t)}\right] \quad \textbf{Eq. (32)}$$

3 $$x_{O2int}(t) = \left[\frac{0.209820 - x_{CO2intdry}(t)}{1 + x_{H2Ointdry}(t)}\right] \quad \textbf{Eq. (33)}$$

4 $$x_{H2dry}(t) = \frac{x_{COdry}\left[x_{H2Oexhdry} - x_{H2Odil} \cdot x_{dil/exhdry}\right]}{K_{H2O-gas}\left[x_{CO2dry} - x_{CO2dil} \cdot x_{dil/exhdry}\right]} \quad \textbf{Eq. (34)}$$

Start with an initial guess value for $x_{H2Oexhdry} = 2 \cdot x_{H2Ointdry}$ in **Eq. (34)**

5 $$x_{THCdry}(t) = \left[\frac{x_{THCwet}(t)}{1 - x_{H2Oexhdry}(t)}\right] \quad \textbf{Eq. (35)}$$

6 $$x_{int/exhdry}(t) = \frac{1}{2 \cdot x_{O2int}}\left[\left(\frac{\alpha}{2} - \beta + 2 + 2\gamma\right)\left(x_{Ccombdry} - x_{THCdry}\right) - \left(x_{COdry} - x_{NOdry} - 2x_{NO2dry} + x_{H2dry}\right)\right] \quad \textbf{Eq. (36)}$$

Start with an initial guess values for $x_{Ccombdry} = x_{COdry} + x_{CO2dry} + x_{THCdry}$ in **Eq. (36)**

7 $$x_{Ccombdry}(t) = x_{CO2dry} + x_{COdry} + x_{THCdry} - x_{CO2dil} \cdot x_{dil/exhdry} \cdots \\ \ldots - x_{CO2int} \cdot x_{int/exhdry} \quad \textbf{Eq. (37)}$$

8 $$x_{H2Oexhdry}(t) = \frac{\alpha}{2}\left(x_{Ccombdry} - x_{THCdry}\right) + x_{H2Odil} \cdot x_{dil/exhdry} \cdots \\ \ldots + x_{H2Oint} \cdot x_{int/exhdry} - x_{H2dry} \quad \textbf{Eq. (38)}$$

Tolerance check to continue iteration

9 $$\text{If}\begin{cases} x_{H2Oexhdry_{new}}(t) - x_{H2Oexhdry_{guess}}(t) \leq \pm 0.01 \\ x_{Ccombdry_{new}}(t) - x_{Ccombdry_{guess}}(t) \leq \pm 0.01 \end{cases} \quad \textbf{Eq. (39)}$$

10 $$x_{H2Oexh}(t) = \frac{x_{H2Oexhdry}(t)}{1 + x_{H2Oexhdry}(t)} \quad \textbf{Eq. (40)}$$

Else repeat steps 5 thru 9 with

$$x_{H2Oexhdry_{guess}}(t) = x_{H2Oexhdry_{new}}(t)$$

11 and **Eq. (41)**

$$x_{Ccombdry_{guess}}(t) = x_{Ccombdry_{new}}(t)$$

Where:

$x_{H2Ointdry}(t)$	amount of water per mole dry intake air
$x_{H2Oint}(t)$	amount of water per mole of intake air
$x_{CO2int}(t)$	amount of carbon dioxide per mole of intake air
$x_{CO2intdry}(t)$	amount of carbon dioxide per mole of dry intake air
$x_{O2int}(t)$	amount of oxygen per mole of intake air
0.209820	fraction of oxygen per mole of ambient air
$x_{H2dry}(t)$	amount of hydrogen produced per mole of dry exhaust as a result of water-gas shift reaction observed at high temperature during combustion
$x_{COdry}(t)$	amount of measured carbon monoxide per mole of dry exhaust
$x_{H2Oexhdry}$	amount of water per mole of dry exhaust
x_{H2Odil}	amount of water per mole of dilution air, equal to zero for raw emissions
$x_{dil/exhdry}$	amount of dilution air per mole of dry exhaust, equal to zero for raw emissions
$K_{H2O-gas}$	water-gas shift reaction equilibrium coefficient, equal to 3.5.
x_{CO2dry}	measured amount of CO_2 per mole of dry exhaust.
$x_{int/exhdry}$	amount of intake air required per mole dry exhaust for stoichiometric combustion
$x_{Ccombdry}$	amount of carbon from fuel per mole of dry exhaust
α	average hydrogen-to-carbon ratio of the mixture of fuel.
β	average oxygen-to-carbon ratio of the mixture of fuel.
γ	average sulfur-to-carbon ratio of the mixture of fuel.
x_{THCdry}	measured amount of total hydrocarbons per mole of dry exhaust
x_{NOdry}	measured amount of nitrogen oxide per mole of dry exhaust
x_{NO2dry}	measured or calculated amount of nitrogen dioxide per mole of dry exhaust.

Note that the exhaust concentrations are time-aligned and drift corrected before being applied in the above equations. The above explained iterative process to solve carbon balance is illustrated as sequence of steps to follow in Table 9.

Table 9: Iterative Carbon Balance Sequence of Steps

Start @ Step 1
Continue to Step 2
Continue to Step 3
Initial guess for $x_{H2Oexhdry} = 2 \cdot x_{H2Ointdry}$
Continue to Step 4
Continue to Step 5
Initial guess for $x_{Ccombdry} = x_{COdry} + x_{CO2dry} + x_{THCdry}$
Continue to Step 6
Continue to Step 7
Continue to Step 8
Perform Convergence Check on $x_{H2Oexhdry}$ & $x_{Ccombdry}$
If true continue to Step 10
Else update $x_{H2Oexhdry}$ & $x_{Ccombdry}$ to new values
Repeat from Step 5 until convergence

3.7.1 Dry-to-Wet Compensation of Real-Time Emissions Concentrations in PEMS A

The PEMS A always measures the exhaust constituents on wet basis. However, there is an option to report the measured emission concentrations as ‘dry’ concentrations by using the internal H_2O analyzer, wherein the measured wet concentrations are converted to dry before reporting. In this case, the ‘dry’ reported concentrations need to be converted to wet concentrations before calculating the mass of emissions. This is accomplished by using the carbon balance method to quantify the fraction of water in the exhaust, which is used in converting the dry concentration of exhaust constituents to wet. The equations used by the PEMS A software for dry-to-wet compensation are shown below.

$$x_{H2Ointdry}(t) = \left[\frac{x_{H2Oint}(t)}{1 - x_{H2Oint}(t)}\right] \qquad \textbf{Eq. (42)}$$

$$x_{Cproddry}(t) = \frac{C_{EXCO2\_dry}(t)}{10^2} + \frac{C_{EXCO\_dry}(t)}{10^2} + \frac{C_{EXTHC\_dry}(t)}{10^6} \qquad \textbf{Eq. (43)}$$

$$C_{EXNO2\_dry}(t) = C_{EXNO\_dry}(t) \times FNO \qquad \textbf{Eq. (44)}$$

$$x_{prod/int\,dry}(t) = \frac{1}{1 - \frac{1}{2} \cdot \left[\frac{C_{EXCO\_dry}(t)}{10^2} - \frac{\alpha}{2} \cdot x_{Cproddry}(t) - \frac{C_{EXNO2\_dry}(t)}{10^6}\right]} \qquad \textbf{Eq. (45)}$$

$$C_{H2O\_dry}(t) = \frac{\alpha}{2} \cdot x_{Cproddry}(t) + \frac{x_{H2Ointdry}(t)}{x_{prod/int\,dry}(t)} \qquad \textbf{Eq. (46)}$$

$$C_{H2O}(t) = \frac{C_{H2O\_dry}(t)}{1 + C_{H2O\_dry}(t)} \qquad \textbf{Eq. (47)}$$

$$C_{EX\_X}(t) = C_{EX\_X\_dry}(t) \cdot [1 - C_{H2O}(t)] \qquad \textbf{Eq. (48)}$$

Where:	$C_{EX\_X}(t)$	Compensated concentration of the component X in time t
	$x_{H2Ointdry}(t)$	molar concentration of water vapor per mole of dry intake air
	$\mathrm{x_{H2Oint}}(t)$	molar concentration of water vapor in ambient air.
	$\mathrm{C_{EX\_X\_dry}}(t)$	measured and time-aligned concentration of the component X in time t [CO,CO_2: vol%; THC: ppmC; NOx: ppm]
	FNO	NO_2 to NOx ratio of exhaust gas [gasoline: 1, diesel: 0.25, with NO_2 storage catalyst: 0.75]
	α	average hydrogen-to-carbon ratio of fuel.

Note that Eq. (42) through Eq. (48) represents a predecessor [67] approach to the current 40 CFR §1065.655 based iterative carbon balance method, neglecting the contribution of dilution air since all emission constituents are measured from raw exhaust. The dry-to-wet compensation factor given in Eq. (48), is equivalent to k_w given by §1065.659 [65] because the dry concentrations reported by PEMS A are derived from the measured wet concentration of emissions in conjunction with measured concentration of water in the exhaust sample, which yields complete dry concentrations unless the measurement of water concentrations are erroneous.

3.7.2 Dry-to-Wet Compensation of Real-Time Emissions Concentrations in PEMS B

The PEMS B always measures the exhaust emissions on dry basis except for THC since the sample is passed through a chiller before being analyzed. Hence, it is required to perform dry-to-wet compensation of the measured concentration before calculating the mass rate of emissions. The dry-to-wet compensation factor is given by

$$k_w(t) = 1 - [H_2O]_{condensed} \qquad \textbf{Eq. (49)}$$

Where: $[H_2O]_{condensed}$ concentration of water vapor removed from the sample by condensation [ppm]

$$[H_2O]_{condensed} = [H_2O]_{exhaust} - [H_2O]_{residual} \quad \textbf{Eq. (50)}$$

Where: $[H_2O]_{residual}$ concentration of water remaining in the sample after passing through the chiller

$[H_2O]_{exhaust}$ molar fraction of water present in the exhaust.

Note the user manual states that the residual fraction of water in the exhaust sample is a function of chiller temperature, chiller pressure, and efficiency. It also states that the amount of water in the exhaust is determined as a function of fuel properties, ambient humidity, and stoichiometry; which is determined based on the user-defined hydrogen-to-carbon (H/C) ratio of the fuel, ambient humidity measurement, and the exhaust constituent concentrations, without any further reference to a particular method or regulation being used. With the foregoing description of the variables used to determine k_w, it is clear that Eq. (49) is not equivalent to the method specified under §1065.659 [65] unless the fraction of water remaining in the sample after passing through the chiller is equal to zero; in other words, the exhaust sample being analyzed should be completely dry.

3.8 Calculation of Real-time Mass Emissions Rate

If the emissions are sampled continuously from a changing exhaust flow rate, such as sampling from raw exhaust performed by PEMS devices, 40 CFR §1065.650 recommends to time-align, perform dry-to-wet compensation of concentrations, and correct NOx concentrations for intake air humidity and then multiply by the flow rate from which the exhaust was sample to obtain the continuous emissions rate of exhaust constituents. The continuous emission rate is then integrated over the interval of the time during which the total mass of emissions is required. The mass rate of emissions is given by the following equation

$$\dot{m}_{emission}(t) = x_{emission}(t) \cdot M_{emission} \cdot \dot{n}(t) \quad \textbf{Eq. (51)}$$

Where: $x_{emission}(t)$ time-aligned, drift-corrected dry-to-wet compensated, and intake air humidity corrected (if applicable) molar concentration of emission component at time t

$M_{emission}$ molar mass of the emission constituent, $\left[\frac{g}{mol}\right]$

$\dot{n}(t)$ measured exhaust flow rate at time t, $\left[\frac{\text{mol}}{\text{s}}\right]$

A table of molar mass and density at standard conditions for different exhaust constituents as listed in 40 CFR is shown below

Table 10: Molar Mass and Density of Emission Constituents at Standard Conditions

Emission Constituent	Molar Mass: $M_{emission}$ [g/mol]	Density @ Std. Cond.: $\rho_{emission}$ [g/ft^3]
CO_2	44.0095	51.81
CO	28.0101	32.97
NOx	46.0055	54.16
THC	13.8753891	16.331

[1] The effective molar mass and density of THC are defined by an atomic hydrogen-to-carbon ratio, α, of 1.85.

3.8.1 Calculation of Real-Time Emissions Rate of Exhaust Constituents in PEMS A

Real-time mass rate of exhaust emissions are calculated according to the equation shown below using time-aligned, drift corrected, dry-to-wet compensated concentrations and also corrected for intake air humidity (where applicable).

$$\dot{m}_{emission}(t) = x_{emission}(t) \cdot M_{emission} \cdot \dot{Q}_{exh}(t) \cdot \left[\frac{1}{60}\right] \cdot \left[\frac{1}{22.415} \cdot \frac{273.15}{293.15}\right] \qquad \textbf{Eq. (52)}$$

Where: $x_{emission}(t)$ molar concentration of emission constituents at time t, $\left[\frac{mol}{mol}\right]$

$M_{emission}$ molar mass of the respective emission constituent $\left[\frac{g}{mol}\right]$

$\dot{Q}_{exh}(t)$ exhaust flow rate at standard conditions (293.15 K and 101.325 kPa) at time t, $\left[\frac{l}{min}\right]$

$\left[\frac{1}{60}\right]$ factor to convert exhaust flow rate in $\left[\frac{l}{min}\right]$ to $\left[\frac{l}{s}\right]$

$\left[\frac{1}{22.415} \cdot \frac{273.15}{293.15}\right]$ factor to convert exhaust flow rate from $\left[\frac{l}{s}\right]$ to $\left[\frac{mol}{s}\right]$, by using the fact that a mole of ideal gas fills 22.415 liters of volume at 273.15 K and 101.325 kPa

3.8.2 Calculation of Real-Time Mass Emissions Rate in PEMS B

The continuous mass emission rate of exhaust constituents is determined by multiplying the time-aligned, drift-corrected wet gas concentrations with the standard volumetric exhaust flow rate and the standard density for each constituent, as shown in the equation below

$$\dot{m}_{emission}(t) = x_{emission}(t) \cdot \dot{V}_{std}(t) \cdot \rho_{emission,std} \qquad \textbf{Eq. (53)}$$

Where: $x_{emission}(t)$ molar concentration of emission constituent at time t, $\left[\frac{mol}{mol}\right]$

$\dot{V}_{std}(t)$ standard exhaust volumetric flow rate, $\left[\frac{m^3}{s}\right]$

$\rho_{emission,std}$ standard density of the respective emission constituent, $\left[10^3 \frac{g}{m^3}\right]$

3.9 Calculating Total Mass of Emissions

Once the mass rate of emissions constituents are determined based on the steps explained above, the emissions rate is integrated over a given interval time, for example entire duration of the test or the duration of an NTE event or the mass rates can also be integrated until the total emissions are greater than or equal to a set target value as outlined in the emissions based on the averaging work-window method, followed by the European Union in-use emissions regulations.

$$m_{emission} = \sum_{t=1}^{N} \dot{m}_{emissions}(t) \cdot \Delta t \qquad \textbf{Eq. (54)}$$

Where $m_{emission}$ total mass of exhaust constituent measured over a given interval of time

Δt data logging interval

Note that both PEMS devices calculate total mass of emissions as explained in Eq. (54). Also, an in-use emissions regulation requires emissions data to be acquired at a frequency of at least 1 second and report the data to EPA at 1 Hz.

3.10 Calculation of Fuel Consumptions Based on Measured Exhaust Emissions

The chemical balance procedure discussed in §1065.655 [68] also explains how to calculate the exhaust flow based on the measured fuel flow or intake air flow in conjunction with parameters determined using chemical balance. Therefore, it is a general practice to determine the fuel flow based on the chemical balance and the measured exhaust flow in order to check the integrity of emission measurement and calculations. This is performed by evaluating the difference between calculated and measured fuel flow rate, normally broadcasted by the ECU. The other application of chemical balance is to determine the exhaust flow rate using the broadcasted or measured fuel flow rate in the absence of exhaust flow measurement capability. The fuel rate based on chemical balance and measured exhaust rate is given by

$$\dot{m}_{fuel} = \frac{M_C}{w_C} \cdot \frac{x_{Ccombdry}}{\left(1 + x_{H2Oexhdry}\right)} \cdot \dot{n}_{exh} \qquad \textbf{Eq. (55)}$$

Where: $\dot{m}_{fuel}$ fuel flow rate including humidity in intake air $\left[\frac{g}{s}\right]$

$\dot{n}_{exh}$ raw exhaust molar flow rate from which emissions are measured $\left[\frac{mol}{s}\right]$

M_C molecular mass of carbon atom $\left[\frac{g}{mol}\right]$

$x_{Ccombdry}$ amount of carbon from fuel in the exhaust per mole of dry exhaust.

$x_{H2Oexhdry}$ fraction of water in the exhaust per mole of dry exhaust

w_C carbon mass fraction of fuel

$$w_C = \frac{1 \cdot M_C}{1 \cdot M_C + \alpha \cdot M_H + \beta \cdot M_O + \gamma \cdot M_S + \delta \cdot M_N} \qquad \textbf{Eq. (56)}$$

Where: M_{atom} molecular mass of carbon, hydrogen, oxygen, sulfur & nitrogen atoms $\left[\frac{g}{mol}\right]$

$\alpha, \beta, \gamma, \delta$ atomic ratio of hydrogen-to carbon, oxygen-to-carbon, sulfur-to-carbon and nitrogen-to-carbon of the mixture of fuel being combusted, weighted by molar consumption.

The standard setting part of the emission measurement regulation in §86.1342-90 elucidates Eq. (55) in the following equivalent form where fuel flow is presented as total mass of fuel used over a given interval of time

$$M = \frac{\left[\frac{M_C}{(M_C + \alpha \cdot M_H)}\right] \cdot HC_{mass} + \left(\frac{M_C}{M_{CO}}\right) \cdot CO_{mass} + \left(\frac{M_C}{M_{CO2}}\right) \cdot CO_{2mass}}{R_2} \qquad \textbf{Eq. (57)}$$

and

$$R_2 = \left[\frac{M_C}{(M_C + \alpha \cdot M_H)}\right] \qquad \textbf{Eq. (58)}$$

Where: R_2 grams of carbon in the fuel per gram of fuel

Note that Eq. (55) and Eq. (57) are equivalent except for the fact that Eq. (57) is the integrated form of Eq. (55) representing combustion of pure hydrocarbon fuel.

3.10.1 Calculation of Fuel Flow Rate in PEMS A

The real-time fuel consumption rate is calculated by the PEMS A software by following the method outlined in §86.1342-90, which is given by

$$R_{CWF} = \left[\frac{M_C}{(M_C + \alpha \cdot M_H + \beta \cdot M_O)}\right] \qquad \textbf{Eq. (59)}$$

Where: R_{CWF} grams of carbon in the fuel per gram of fuel

$$R_{CWFHC} = \left[\frac{M_C}{(M_C + \alpha_{EX} \cdot M_H)}\right] \qquad \textbf{Eq. (60)}$$

Where: R_{CWFHC} average carbon mass balance of HC in the exhaust gas

α_{EX} average H/C atomic ratio of HC in the exhaust gas

$$\dot{m}_{fuel_{CB}}(t) = \frac{R_{CWFHC} \cdot \dot{m}_{HC_{mass}}(t) + \left(\frac{M_C}{M_{CO}}\right) \cdot \dot{m}_{CO_{mass}}(t) + \left(\frac{M_C}{M_{CO2}}\right) \cdot \dot{m}_{CO_{2mass}}(t)}{R_{CWF}} \quad \textbf{Eq. (61)}$$

Where:

$\dot{m}_{fuel_{CB}}(t)$	real-time fuel flow rate in time t, $\left[\frac{\mathrm{g}}{\mathrm{s}}\right]$
$\dot{m}_{HC_{mass}}(\mathrm{t})$	real-time hydrocarbon emission rate in time t, $\left[\frac{\mathrm{g}}{\mathrm{s}}\right]$
$\dot{m}_{CO_{mass}}(\mathrm{t})$	real-time carbon monoxide emission rate in time t, $\left[\frac{\mathrm{g}}{\mathrm{s}}\right]$
$\dot{m}_{CO_{2mass}}(\mathrm{t})$	real-time carbon dioxide emission rate in time t, $\left[\frac{\mathrm{g}}{\mathrm{s}}\right]$

The fuel economy in terms of distance per unit volume is given by

$$FE(t) = \frac{1}{\dot{m}_{fuel_{CB}}(t)} \cdot \frac{V(t)}{3600} \cdot \rho_{fuel} \cdot 1000 \quad \textbf{Eq. (62)}$$

Where:

$\mathrm{FE(t)}$	fuel economy in time t, $\left[\frac{\mathrm{km}}{\mathrm{l}}\right]$
$\mathrm{V(t)}$	velocity of the vehicle in time t, $\left[\frac{\mathrm{km}}{\mathrm{hr}}\right]$
ρ_{fuel}	density of fuel, $\left[\frac{\mathrm{kg}}{\mathrm{l}}\right]$

3.10.2 Calculation of Fuel Flow Rate in PEMS B

The real-time fuel flow rate is calculated in the PEMS B software based on the method outlined in §1065.655 with the following simplified equation

$$\dot{m}_{fuel} = \left[[CO] + [HC_1] + [CO_2] - [CO_2]_{ambient}\right] \cdot \dot{n}_{exh} \cdot MW_{fuel} \quad \textbf{Eq. (63)}$$

Where:

$\dot{m}_{fuel}$	real-time fuel rate in $\left[\frac{g}{s}\right]$
$[CO, HC, CO_2]$	time-aligned, dry-to-wet compensated concentration of emission constituents containing carbon from fuel per mole of exhaust [ppm].
$\dot{n}_{exh}$	molar flow rate of exhaust

and

$$MW_{fuel} = 1 \cdot M_C + \alpha \cdot M_H + \beta \cdot M_O + \gamma \cdot M_S + \delta \cdot M_N \quad \textbf{Eq. (64)}$$

Where:

$\mathrm{MW_{fuel}}$	molecular weight of fuel, $\left[\frac{\mathrm{g}}{\mathrm{mol}}\right]$
$\mathrm{M_{atom}}$	molecular mass of carbon, hydrogen, oxygen, sulfur & nitrogen atoms $\left[\frac{\mathrm{g}}{\mathrm{mol}}\right]$

$\alpha, \beta, \gamma, \delta$ atomic ratio of hydrogen-to carbon, oxygen-to-carbon, sulfur-to-carbon and nitrogen-to-carbon of the mixture of fuel being combusted, weighted by molar consumption.

Note that fraction of CO_2 contributed by the intake air is reduced from the concentration of combustion products containing carbon from the fuel if the CO_2 analyzer is not zeroed using ambient air.

3.11 Engine Speed and Torque

As the emission standards for heavy-duty diesel engines are set based on brake-specific emission rates, it is imperative to measure or record the engine speed and torque. Engine speed and torque are measured using an engine dynamometer if it is tested in a test cell; whereas in the field, the engine speed and torque are recorded from the ECU as most of the engines that are subjected to in-use emission regulations are modern diesel engines controlled by ECU. The ECU engine speed and torque are broadcasted either via SAE J1939 or J1708 protocols based on the engine MY, post MY 2006 engines follow J1939 protocol.

The speed and torque information broadcasted through J1939 protocol are used to calculate the engine work using different methods based on the mode in which engine torque is broadcasted. Engine torque is determined using a combination of the following parameters based on the available data.

1. Engine Percent Load at Current Speed – a ratio of actual engine percent indicated torque to maximum indicated torque at the given engine speed.
2. Actual Engine Percent Torque – is the indicated torque of the engine transmitted as a percent of the reference torque. Note that the indicated torque will not be less than zero as it includes the torque required to overcome the friction.
3. Nominal Friction Percent Torque – is the torque which represents the friction in the engine. It includes frictional and thermodynamic losses of the engine, pumping torque loss, fuel, oil and coolant pump losses. The frictional torque is also broadcasted as a percentage of reference torque.
4. Engine Reference Torque – is a constant indicated torque value which serves as the 100% reference value for all defined indicated engine torque parameters. This value will not change even when different engine maps such as engine de-rate or thermal management maps become valid.

When engine torque is recorded as engine percent load at current speed, it is used in conjunction with maximum indicated torque curve data over a range of engine speeds that are provided by the manufacturer or inquired through the engine ECU along with curb idle percent torque to calculate the brake torque produced by the engine. The curb idle percent torque is recorded by running the engine from low idle to high idle while the vehicle is parked in order to account for the frictional torque. The brake torque is given by the following equation developed by Gautam et al., [9].

$$T_{Brake} = \left(\frac{Eng.\%load_{@N} - \%load_{noload@N}}{100 - \%load_{noload@N}}\right) \cdot T_{Max\ Eng@N} \qquad \textbf{Eq. (65)}$$

In using the engine percent load at current speed, it has been observed that the representation of percent load is different among heavy-duty engine manufacturers as described by Gautam et al., It is also observed that any deviation or error in percent load at curb idle at lower engine loads influences the actual torque produced by the engine and the error asymptotes to zero at 100 percent engine load. Hence, it is advised to validate the meaning of the term percent load at current speed as broadcasted by the engine ECU in association with the measured torque based on different engine manufacturers.

When the engine torque is broadcasted as actual engine–percent torque, which is an indicated torque represented as a percentage of reference engine torque, it is used in conjunction with nominal friction-percent torque and reference engine torque to calculate the actual engine brake torque using the following equation [69].

$$T_{Brake} = (Act.Eng.\%T - Nom.Fric.\%T) \cdot \frac{1}{100} \cdot T_{Ref\ Eng} \qquad \textbf{Eq. (66)}$$

Note that the engine speed and torque data are required to determine whether the engine is operating in an NTE zone as well.

Once the engine brake torque is determined, the work produced by the engine at a given engine speed is calculated using the following equation.

$$W_{Brake} = \frac{2 \cdot \pi \cdot N \cdot T_{Brake}}{60 \cdot 1000} \cdot \Delta t \cdot \frac{1}{3600} \qquad \textbf{Eq. (67)}$$

Where: W_{Brake}	engine brake work $[kWhr]$
N	engine speed $[rpm]$
T_{Brake}	engine brake torque $[Nm]$
Δt	data logging rate $[s]$

3.11.1 Calculation of Engine Brake Work for PEMS A

The PEMS A data acquisition system uses only the actual engine percent torque in conjunction with the nominal friction percent torque and reference engine torque to calculate the brake work and does not have the option of using the engine percent load at current speed parameters to determine the engine torque. Therefore, the engine brake work is calculated based on Eq. (66) and Eq. (67) shown above. However, the PEMS A provides the option of calculating engine brake work using fuel consumption rate, which is determined based on carbon balance from the measured emissions concentration; and the engine efficiency, in the absence of engine speed and torque values, is given by the following equation.

$$W_{Brake} = LHV_{fuel} \cdot \dot{m}_{fuel\_CB} \cdot \eta_{engine} \cdot \frac{1}{100} \cdot \frac{1}{1000} \cdot \Delta t \cdot \frac{1}{3600} \qquad \textbf{Eq. (68)}$$

Where: LHV_{fuel}	lower heating value of fuel $\left[\frac{kJ}{kg}\right]$
$\dot{m}_{fuel\_CB}$	fuel flow rate based on carbon balance $\left[\frac{g}{s}\right]$
η_{engine}	thermal efficiency of the engine, a user defined value [%]
$\frac{1}{100}$	conversion factor for percentage to fraction
$\frac{1}{1000}$	conversion factor for grams to kilograms
$\Delta t \cdot \frac{1}{3600}$	conversion factor for seconds to hour

3.11.2 Calculation of Engine Brake Work for PEMS B

The PEMS B post-processing software allows for the determination of engine brake torque by the two methods discussed under section 3.11 based on the value of engine torque being recorded from the engine ECU. Note that when using engine percent load at current speed, the user has to input an average curb idle load, which is determined by exercising the engine from low idle to high idle speed while being parked and then averaged over the speed points. Therefore, the engine brake work is calculated by a combination of Eq. (65), Eq. (66), and Eq. (67). It should be noted that PEMS B uses an averaged value of no-load or curb idle percent torque as opposed to curb idle percent torque as a function of speed.

3.12 Calculation of Brake Specific Emissions

After determining the total mass emissions and the total engine brake work for a given interval of time, the brake specific emissions of the vehicle are given by

$$\mathrm{e_{emissions}} = \frac{\sum_{t=1}^{N} \dot{m}_{\mathrm{emissions}}(t) \cdot \Delta t}{\sum_{t=1}^{N} W_{\mathrm{Brake}}(t)} \qquad \textbf{Eq. (69)}$$

Where: $\mathrm{e_{emissions}}$	Brake specific emissions of regulated pollutants $\left[\frac{\mathrm{g}}{\mathrm{kWhr}}\right]$

4 IDENTIFICATION OF FACTORS LEADING TO IN-USE EMISSION DATA POST-PROCESSING ERRORS

4.1 Introduction

This chapter introduces the post-processing of in-use emissions data explaining the basis of in-use regulations and is divided into three major sections listed below:

1. Validation of NTE data point and event.
2. Quantification of NTE event brake-specific emissions.
3. Verification of in-use emission compliance.

The significance of each factor involved in validating a test data point, in quantifying emissions, and in determining in-use emissions compliance of the vehicle are explained in their respective sections.

4.2 Validation of NTE Data Point and Event

The in-use emissions regulation for heavy-duty diesel engines, as mandated by the US EPA, is based on the NTE zone. The engine brake-specific emissions, when operating in this zone, must be lower than the in-use emissions standards, which are determined based on the engine certification standards and the method of in-use emissions measurement. The NTE zone is a region under the engine maximum torque curve (also known as lug curve) whose upper bounds are defined by the maximum torque curve and the lower bound by engine speed, torque, and power. Furthermore, the NTE zone is defined by the US EPA in consensus with the EMA as representing an area under the speed and torque curve where the engine operates the majority of the time and the steady state test modes of a SET, an emission compliance test introduced under the consent decrees. Once the NTE zone is defined for a given engine, a NTE operating point is validated against a set of common exclusions. The exclusions are based upon the ambient conditions in which a vehicle is operating, the technology used in an engine to meet engine certification standards, the amount of time an engine operates in the NTE zone consecutively, and any other engine manufacturer negotiated limited testing regions under the lug curve, including time-weighted limited testing regions (LTRs).

4.2.1 NTE Engine Speed

The engine speed which defines the lower speed boundary of the NTE zone is equal to 15% of the ESC [70], which is given by

$$n_{15} = n_{lo} + 0.15 \cdot (n_{hi} - n_{lo}) \qquad \textbf{Eq. (70)}$$

Where: n_{lo} lowest engine speed at which 50% of the maximum power can be achieved [rpm]

$\mathrm{n_{hi}}$ highest engine speed at which 70% of the maximum power can be achieved [rpm]

The engine speed must be greater than $\mathrm{n_{15}}$ in order to be a valid NTE data point [71].

$$n_{NTE} > n_{15} \qquad \textbf{Eq. (71)}$$

The engine speed data is recorded directly from the engine ECU via J1939 or J1708 protocols. It should be noted that n_{lo} and n_{hi} engine speed, used in defining lower boundary of the NTE zone, does not represent engine low and high idle speeds.

4.2.2 NTE Engine Torque

The engine brake torque must be greater than or equal to 30% of the peak torque for the data point to be a valid NTE point [72].

$$T_{NTE} \geq 0.3 \times T_{max/peak} \qquad \textbf{Eq. (72)}$$

Where: $T_{max/peak}$ maximum or engine peak torque $[\mathrm{Nm\ or\ ft-lb}]$

The engine torque is determined based on the parameter being recorded from the engine ECU via SAE J1939 or J1708 protocols. Post MY2006 engines follow J1939 protocol to broadcast ECU parameters in which engine torque data is transmitted as a percentage of constant reference torque representing indicated torque along with frictional torque, also represented as a fraction of reference torque. The engine brake torque is determined by subtracting the friction torque from indicated torque as defined in Eq. (66).

The engine torque under J1708 communication protocol is represented as a percent load at current speed, which requires maximum engine torque curve data over a range of engine speeds along with the friction torque, known as the curb idle torque. Data is determined by recording the percent load at current speed at no load conditions from low idle to high idle speed. The brake engine torque in engineering units, when recorded using J1708 protocol, is determined as described in Eq. (65).

Incorrect quantification of engine brake torque by using the ECU broadcasted parameters interchangeably as in the case of J1939 protocol, which broadcasts both engine percent torque at current speed as well as normalized engine percent torque will lead to misrepresentation of engine operation in the NTE zone.

4.2.3 NTE Engine Power

The engine power must be greater than or equal to 30% of the rated power in order to be a valid NTE data point [73].

$$P_{NTE} \geq 0.3 \times P_{max} \qquad \textbf{Eq. (73)}$$

Where: P_{max} engine rated power [kW or bhp]

As engine power is a function of engine speed and torque, it is given by

$$P = \frac{2 \cdot \pi \cdot N \cdot T_{Brake}}{60 \cdot 1000} \qquad \textbf{Eq. (74)}$$

Where:		
	N	engine speed in [rpm]
	T_{Brake}	engine brake torque in [Nm]
	$\frac{2 \cdot \pi}{60 \cdot 1000}$	factor used to derive engine power in [kW]

An illustration of the NTE zone definition on the engine speed torque map along with constant power lines for a given maximum torque is shown in Figure 2.

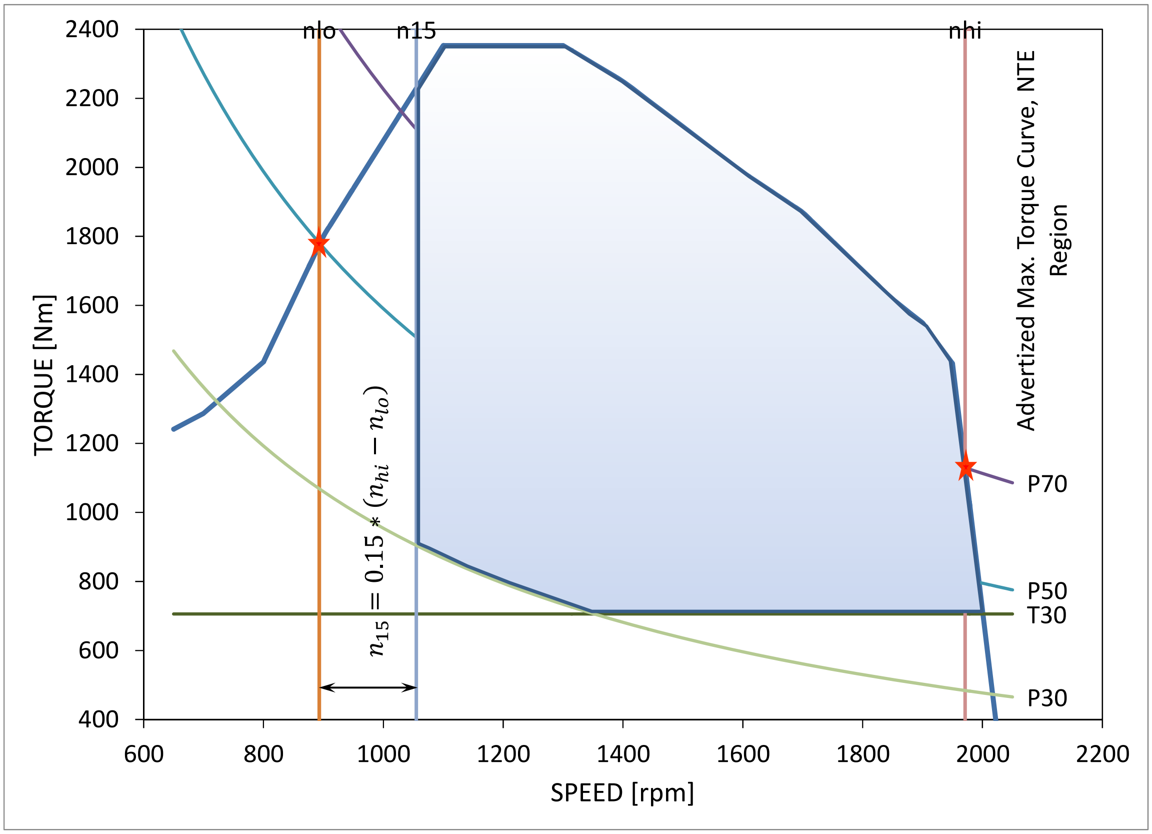


Figure 2: Definition of NTE Zone for a Given Maximum Engine Torque Curve

The maximum torque curve of the engine shown in Figure 2 has a peak torque value of 2353 Nm, rated power of 333 kW at 1654 rpm, and a reference torque of 2561 Nm resulting in n_{lo} and n_{hi} of 893 rpm and 1971 rpm, respectively. From the above engine parameters, the lower bound of the NTE zone for this engine is defined by:

1. $n_{15} = 1055\ rpm$
2. $T_{30} = 705.88\ Nm$
3. $P_{30} = 99.92\ kW$

4.2.4 NTE Altitude

For the engine operating point in the aforementioned NTE zone to be valid, the altitude at which the vehicle is operating must be less than or equal to 5,500 ft above sea level [74]. This condition has been approved by the EPA upon EMA's recommendation that it would be difficult to meet the emission standards at high altitudes due to lower density of the engine intake air and the related ambient conditions requiring the engines to be below 5,500 ft.

$$Alt_{NTE} \leq 5{,}500\ ft \qquad \textbf{Eq. (75)}$$

The altitude at which the test vehicle is operating is determined either by GPS data or the barometric pressure data recorded by PEMS.

4.2.5 NTE Ambient Temperature

The ambient temperature at which the vehicle is operating must be lower than or equal to the temperature given by the altitude of the test location for an NTE operating point to be valid [75]. This is also one of the common exclusions negotiated between EMA and the US EPA to determine in-use emission compliance.

$$T_{amb-NTE} \leq T_{amb-alt} \qquad \textbf{Eq. (76)}$$

Where

$$T_{amb-alt} = -0.00254 \cdot (Alt) + 100 \qquad \textbf{Eq. (77)}$$

Where:		
	$T_{amb-alt}$	ambient temperature limit defined as a function of altitude of test location [°F]
	Alt	altitude of test location in [ft], positive for above sea level.

It should be noted that the aforementioned ambient temperature limit for an engine operating point in the NTE zone to be valid is linear function with a negative slope, which indicates that temperature limit decreases with increase in the altitude. This implies that engines operate with less control over the emission controlling technologies at higher altitudes. Figure 3 shows the ambient temperature limit as a function of altitude from 0 to 5,500 ft. The ambient temperature of the location where the vehicle is being tested is measured by PEMS.

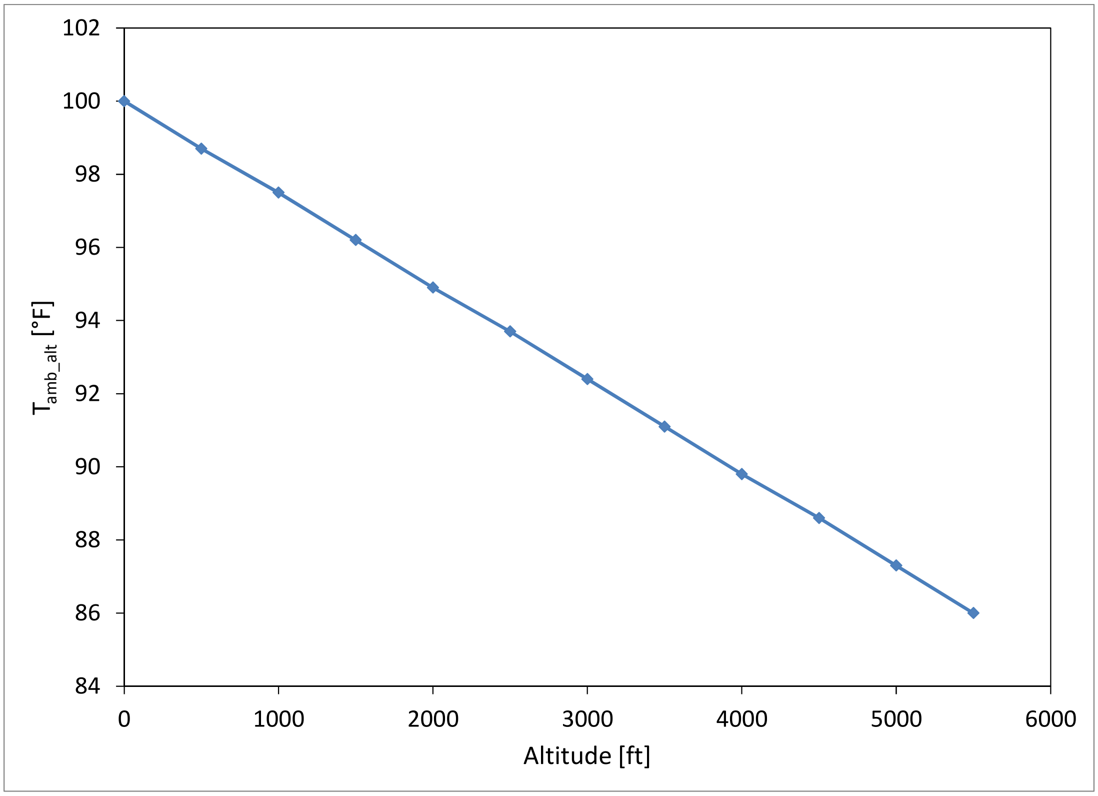


Figure 3: Ambient Temperature Limit for an Engine Operating in NTE Zone [75]

4.2.6 NTE Intake Manifold Temperature

For engines equipped with an exhaust gas recirculation system (EGR) in order to reduce NOx emissions, the intake manifold temperature must be greater than the NTE intake manifold temperature limit, which is defined as a function of absolute intake manifold pressure for an engine operating point in the NTE zone [76].

$$IMT_{NTE} > IMT_{EGR} \qquad \textbf{Eq. (78)}$$

Where

$$IMT_{EGR} = 11.428 \cdot (IMP_{abs}) + 88.571 \qquad \textbf{Eq. (79)}$$

Where: IMT_{EGR} NTE intake manifold temperature limit for engine equipped with EGR [°F]

IMP_{abs} absolute intake manifold pressure [bar]

This condition has been included due to the limitations of operating EGR at cold conditions. The cold operating conditions are defined based on the absolute intake manifold temperature. During these cold operating conditions, the EGR system, which includes EGR cooler, valve, and cross-over tube is closed to protect them from fouling and corrosion due to condensation of exhaust gas laden with un-burnt hydrocarbons, and other inorganic constituents such as sulfur and nitrates at low temperatures [77-80].

4.2.7 NTE Engine Coolant Temperature

For engines fitted with an EGR system to reduce NOx emissions, as their operation is restricted at cold operating conditions, the engine coolant temperature must be greater than NTE engine coolant temperature limit for an engine operating point in the NTE zone to be valid. Both intake manifold temperature and engine coolant temperatures are used to make sure the engine has reached its normal operating conditions to operate the EGR. The NTE engine coolant temperature limits are also defined as a function of absolute intake manifold; pressure given by [81].

$$ECT_{NTE} > ECT_{EGR} \qquad \textbf{Eq. (80)}$$

Where

$$ECT_{EGR} = 12.853 \cdot (IMP_{abs}) + 127.11 \qquad \textbf{Eq. (81)}$$

Where: ECT_{EGR} NTE engine coolant temperature limit for engines fitted with EGR [°F]

$\mathrm{IMP_{abs}}$ absolute intake manifold pressure [bar]

Comparing Eq. (79) and Eq. (81), it can be observed that the slope of the engine coolant temperature limit is 12% higher than that of the intake manifold temperature limit for the same absolute intake manifold temperature, while the offset is 43% higher with respect to the NTE intake manifold temperature limit. This indicates that the engine requires a longer duration to reach optimum operating conditions for EGR to operate, and hence an engine operating point in the NTE zone which satisfies the intake manifold temperature limit would fail for the engine coolant temperature limit resulting in an invalid NTE point. It should also be noted that IMT_{EGR} and ECT_{EGR} definitions have been re-arranged to express them as a function of intake manifold pressure instead of the form it is represented in 40 CFR §86.1370-2007.

Note that both intake manifold and engine coolant temperatures are recorded from the engine ECU using the parameter group number (PGN) and suspect parameter number (SPN) combination that represents the most accurate value. The PGN and SPN are unique identification numbers assigned to the engine parameters and they also provide the details of the order in which the data is received and decoded into their respective engineering units. Similarly, there are several SPNs for intake manifold pressure with varying degrees of accuracy and some even just provide gauge pressure requiring an additional parameter indicating the barometric pressure of the test location in order to arrive at the absolute pressure value.

4.2.8 NTE Exhaust Temperature for Engines with an Aftertreatment Device

In engines employing an oxidation catalyst to reduce NMHC, SCR, or LNT to reduce NOx emissions; the exhaust temperature measured at a distance of up to twelve inches from the outlet of the farthest downstream aftertreatment device with highest flow rate must be greater than 250 °C for the engine operating point in the NTE zone to be a valid NTE point [82].

$$T_{exh\ AT-NTE} > 250°\mathrm{C} \qquad \textbf{Eq. (82)}$$

The exhaust temperature downstream of an aftertreatment device is measured using a thermocouple if it is not broadcasted by the engine ECU. Also, note that regulations are not clear in explaining whether the NTE point would be invalid only for the emission constituent for which the aftertreatment device is used, or the point would become invalid overall. Furthermore, exhaust temperature limit can result in many invalid NTE operating points if the location of the temperature measurement is not followed as prescribed in the regulation.

The above condition is included as it is reported in various studies that the light-off temperatures of commonly used oxidation catalyst, SCR, and LNT aftertreatment systems are near 250 °C [83]. At light-off temperatures, the conversion efficiency of the aftertreatment devices is higher than 50%.

4.2.9 Minimum NTE Event Time

Continuous operation of engines in the NTE zone, while satisfying the aforementioned list of exceptions or exclusions for a minimum duration of thirty seconds, qualifies the engine operation to be a NTE event [84]. Note this minimum NTE event duration is not applicable when an engine equipped with a diesel particulate filter undergoes a regeneration event while operating in the NTE zone.

$$t_{NTE} \geq 30s \qquad \textbf{Eq. (83)}$$

4.2.10 Minimum NTE Event Time During DPF Regeneration

The minimum NTE event time for engines equipped with aftertreatment devices, such as a DPF that requires periodic regeneration to oxidize the collected soot, will be longer than thirty seconds if a regeneration event occurs during an NTE event [85]. This minimum time is determined based on the duration of active regeneration that takes place during a normal NTE candidate event and a factor known as regeneration fraction as follows

$$t_{NTE-regen,min} = \frac{\sum_{i=1}^{N} t_{2,NTE,i}}{RF} \qquad \textbf{Eq. (84)}$$

Where: $t_{2,NTE,i}$	the duration of i-th active regeneration (state 2) time period within the candidate NTE event [s]
RF	Regeneration Fraction

The regeneration fraction is determined based on the number and duration of complete non-regeneration and complete regeneration events over the course of an eight hour shift day of vehicle operation. It is defined as the ratio of the average time spent in active regeneration during the events of complete regenerations to the sum of average time spent in complete non-regeneration event and the average time spent in complete regeneration events. A complete regeneration event includes both duration of active regeneration (state 2) and duration indicating the need for active regeneration also known as active regeneration pending status (state 1).

$$RF = \frac{\frac{\sum_{i=1}^{N_2} t_{2,i}}{N_{12}}}{\frac{\sum_{k=1}^{N_0} t_{0,k}}{N_0} + \frac{\sum_{i=1}^{N_{12}} t_{12,i}}{N_{12}}} \quad \textbf{Eq. (85)}$$

Where: $t_{2,i}$ the duration of active regeneration during the events of complete regeneration in $[s]$

$t_{12,i}$ the duration of complete regeneration events, which includes both active and pending regenerations states in $[s]$

$t_{0,k}$ the duration of complete non-regeneration events

N_2 total number of active regeneration events (state 2)

N_{12} total number of complete regeneration events (state 1 & 2)

N_0 total number of complete non-regeneration events.

Since the ECU signal used to indicate the regeneration status of an aftertreatment device is not standardized, the regeneration status signal is expected to vary among different engine manufacturers. The above example represents the determination of RF and $t_{NTE-regen,min}$ for an engine which broadcasts the following status of aftertreatment states.

1. State 0 no active regeneration
2. State 1 active regeneration pending
3. State 2 active regeneration in progress.

For engines which do not broadcast the regeneration pending status (state 1), Eq. (85) still remains the same except $t_{12,i}$ is replaced by $t_{2,i}$. An illustration of a possible scenario of aftertreatment device regeneration over an eight hour shift day is shown in Figure 4. In this example there are three non-regeneration (state 0) periods, two complete regeneration periods, which in turn consist of three active regeneration (state 2) events and three active regeneration pending (state 1) events. Note that in order to count the number of regeneration and non-regeneration events it should be bracketed by non-regeneration and regeneration events respectively. The total time spent at state 2 is 6300 seconds, total time spent in both state 1 & 2 is 12,600 seconds, while the duration of state 0 is 16,200 seconds resulting in a RF of 0.27.

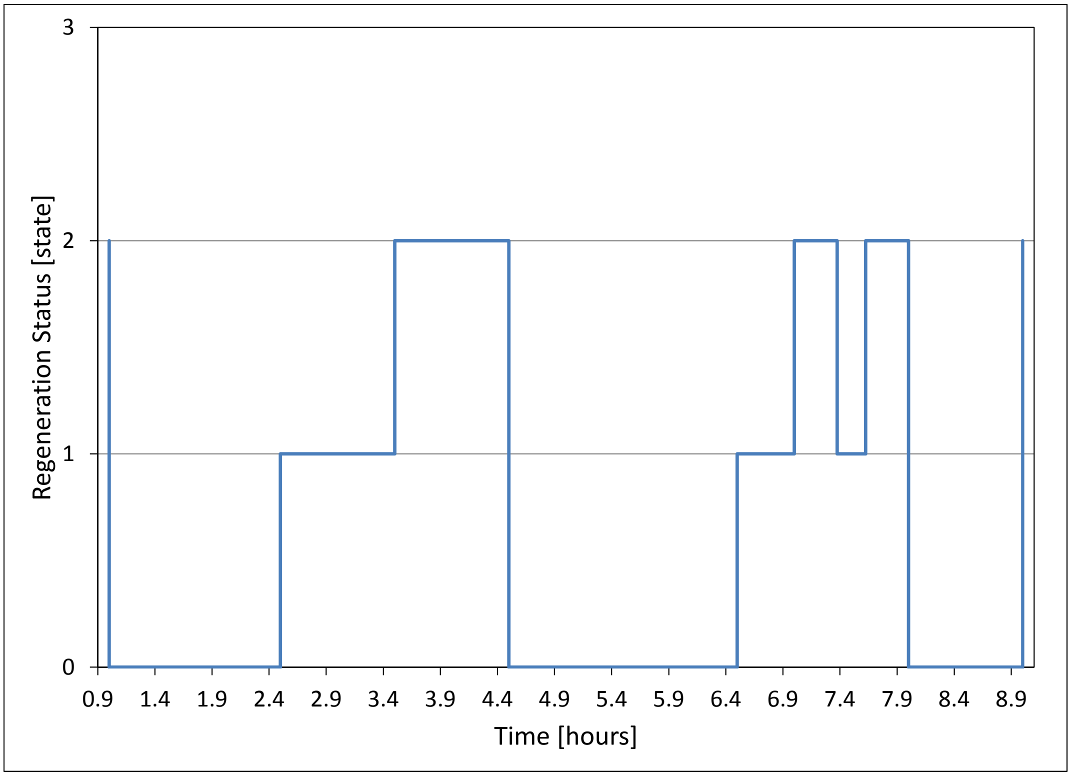


Figure 4: Example Scenario of Aftertreatment Device Regeneration Events Over 8 Hour Shift Day

4.2.11 NTE 5% Time-Weighted Limited Testing Region

A region of engine operation in the NTE zone, generally defined by an elliptical or rectangular shaped area where some portion of its boundaries coincides with the maximum torque curve. This region is defined by the engine manufacturer in approval of US EPA, provided that the engine manufacturer could prove that the engine is not designed to operate in that region for more than five percent of the total engine operating time in a given application [86]. Therefore, an NTE event will be invalid if the engine operates in the time-weighted limited testing region (TWLTR) for more than five percent of the entire NTE event.

$$t_{5\%TWLTR} < 0.05t_{NTE}$$ **Eq. (86)**

An illustration of the NTE zone, along with all the exclusions that need to be satisfied along with the representation of 5% TWLTR for an interval of engine operation in the NTE zone to be a valid NTE event, is shown in Figure 5.

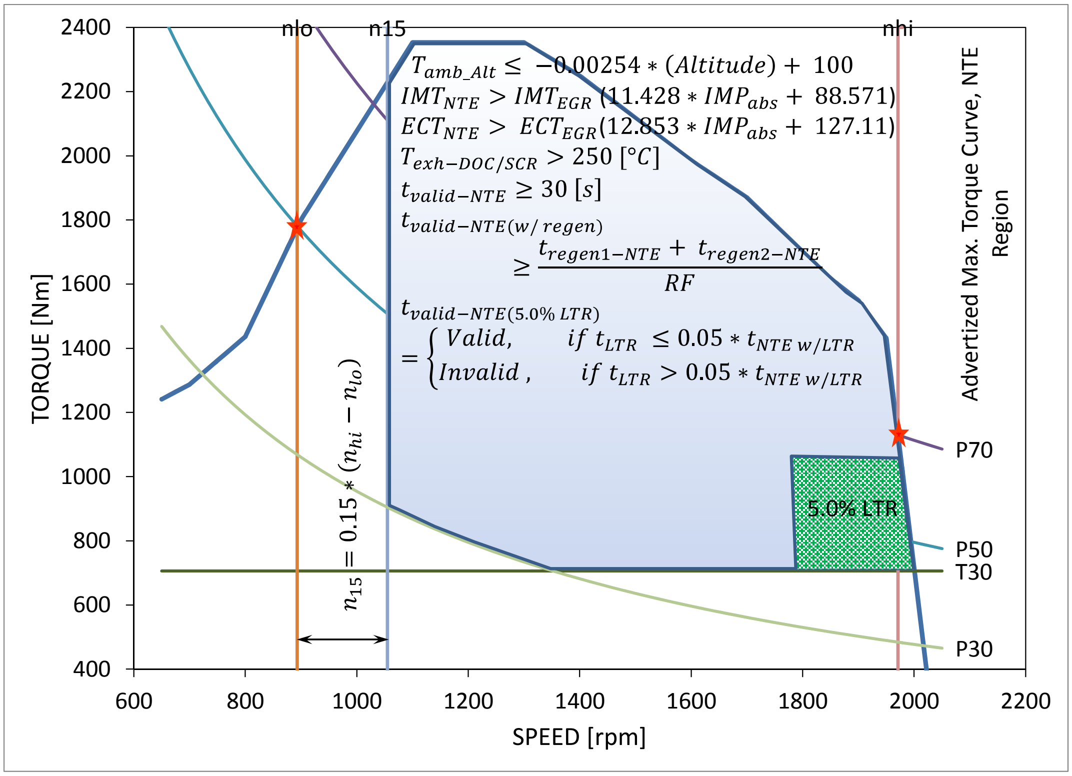


Figure 5: Representation of NTE Zone with Common Exclusions Applicable for Engines Equipped with EGR, DPF, DOC, and SCR

Finally, for an engine operating in the NTE zone to result in an NTE event; it has to meet the aforementioned exclusions depending on the engine technology used in reducing emissions and the ambient conditions at which the vehicle is operating. As the number of exclusions and the conditions to be met increases, the order of complexity in validating an NTE event also increases leading to post-processing errors. Also, any misinterpretation of exclusions could lead to disregarding an NTE event or otherwise. The different conditions to be satisfied in order for an engine operation in the NTE zone to be valid as an NTE event for a modern on-road heavy-duty diesel engine equipped with EGR, DPF and SCR aftertreatment system is shown in the form of a truth table in Table 11.

Table 11: NTE Event Validation Truth Table for On-road Heavy-Duty Diesel Engines Equipped with EGR, DPF and SCR Systems

	n_{NTE}	T_{NTE}	P_{NTE}	Alt_{NTE} [ft]	$T_{amb-NTE}$	IMT_{NTE}	ECT_{NTE}	$T_{exhAT-NTE}$	$t_{min-NTE}$	$t_{NTE,regen,min}$	5% TWLTR	$t_{5\%TWLTR}$	Result	Comment
1	$>n_{NTE}$	0	0	0	0	0	0	0	0	n/a	not defined	n/a	0	non NTE operation
2	$>n_{NTE}$	$\geq T_{NTE}$	0	0	0	0	0	0	0	n/a	not defined	n/a	0	non NTE operation
3	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	0	0	0	0	0	0	n/a	not defined	n/a	0	NTE operation
4	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	0	0	0	0	0	n/a	not defined	n/a	0	NTE operation
5	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	0	0	0	0	n/a	not defined	n/a	0	NTE operation
6	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	0	0	0	n/a	not defined	n/a	0	NTE operation
7	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	0	0	n/a	not defined	n/a	0	NTE operation
8	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	0	n/a	not defined	n/a	0	NTE operation
9	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	≥30s	0	not defined	n/a	0	NTE operation
10	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	≥30s	n/a	defined	0	0	NTE operation
11	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	≥30s	n/a	not defined	n/a	1	NTE event
12	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	≥30s	$\geq t_{NTE,regen,min}$	not defined	n/a	1	NTE event
13	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	≥30s	n/a	defined	$<0.05t_{NTE}$	1	NTE event
14	$>n_{NTE}$	$\geq T_{NTE}$	$\geq P_{NTE}$	≤5,500	$\leq T_{amb-alt}$	$>IMT_{EGR}$	$>ECT_{EGR}$	>250°C	≥30s	$\geq t_{NTE,regen,min}$	defined	$<0.05t_{NTE}$	1	NTE event

4.3 Quantification of NTE Brake-Specific Emissions

The quantification of in-use brake-specific emissions for an NTE event involves following steps listed in the order of execution:

1. Alignment of emission concentration and ECU signal with the exhaust sampling plane.
2. Conversion of measured exhaust flow to standard conditions.
3. Correction of emission concentration for analyzer zero and span drifts.
4. Conversion of emission concentration from dry-to-wet, if measured or reported dry.
5. Correction of NOx emissions for intake air humidity.
6. Addressing negative emissions concentrations.
7. Down sampling of emission measurement data.
8. Integration of emissions mass and brake-specific work over a NTE event.

The influence of the aforementioned in quantifying the emissions mass rate and finally the brake-specific emissions over a valid NTE event will be discussed in the following sections.

4.3.1 Alignment of Emission Concentration and ECU Signal with Exhaust Sampling Plane

Since in-use emission measurement involves recording and measurement of instantaneous engine data, exhaust flow, and emission concentrations; it requires multiple measuring devices and data loggers recording data at that instant. In order to quantify the emissions mass rate and brake-specific emissions from the data collected in the above manner, it is critical to align all the data to a common reference plane; most often the exhaust sampling point is used as the reference plane. As the exhaust flow is measured at the sampling plane normally using a pitot tube, the exhaust flow data serves as reference data to which other signals are shifted, note that there are no prescribed standard to use exhaust flow as a reference signal. The time shift used to align emission signals with exhaust flow measurements include the transportation delay of the exhaust sample from the measuring plane to the analyzer and the response delay of the analyzers; whereas the ECU speed and torque signal are shifted backwards to match the exhaust flow using a correlation between engine torque and exhaust flow. The delay time between the exhaust sampling plane and the emission analyzers are determined by a peak recovery test. The peak recovery test involves flooding the exhaust sampling probe with respective span gases of each analyzer and measuring the time delay to achieve 50% of the span concentration. This test is automated in all PEMS devices and recommended to perform before testing any new vehicle. A study conducted by AVL Inc., one of the PEMS suppliers, has shown that misalignment of emission concentrations with the exhaust flow as one of the significant contributor to error in quantifying emissions mass rate [38, 87].

4.3.2 Conversion of Measured Exhaust Flow to Standard Conditions

The exhaust flow rate is predominantly measured using pitot tube-type devices, which involves measuring differential pressure across the averaging pitot tube in the path of the exhaust flow, static pressure, and the exhaust temperature. The exhaust flow measured in such a manner will result in the flow value for the given pressure and temperature yielding the actual flow values. This actual flow measurement needs to be converted to standard pressure and temperature conditions, which is 101.325 kPa and 20 °C as per EPA standards, in order for the comparison of emissions measured at different ambient conditions. The exhaust flow is further converted into molar flow if the emissions are quantified using the CFR 1065 emissions calculation as the guideline. The methods in which the exhaust flow is quantified in standard conditions are explained in section 3.4. An error in converting the flow rate to the correct standard conditions will lead to error in the final emission results as the emission rates are a function of exhaust flow rate. Also, flow correction to different standard conditions will result in inconsistent emission results reduced by different emission post-processing software for a given dataset.

4.3.3 Correction of Emission Concentration for Analyzer Zero and Span Drifts

It is commonly observed that an emission analyzer can drift while measuring emissions over long durations, even under the controlled environment of a laboratory. So, the drift in emission analyzer is pronounced in PEMS and it is critical to correct the measured concentration for analyzer drift. In order to reduce the effect of drift on emissions, it is mandated by the in-use regulations to zero and span the PEMS emission analyzers for every one hour interval while testing the vehicle over an eight hour shift. PEMS manufacturers follow different methods to correct for analyzer drift as explained in section 3.3 leading to inconsistent results between different PEMS data post-processing software for an identical test dataset.

4.3.4 Conversion of Emission Concentration from Dry-to-Wet, when Measured Dry

As most of the emission analyzers are designed to measure dry samples, it is required to remove water, a product of combustion and also part of intake air, before analyzing the exhaust sample. It is common practice to use electrical chiller to condense water from the exhaust sample before transferring it to the analyzer. As an exception, PEMS A is capable of measuring wet samples which are corrected for water interference by measuring the amount of water, which is used to compensate the measured emissions. The concentration, when measured dry results in higher values an occurrence that is not observed at the sampling plane. Therefore, EPA requires the dry concentration values to be converted back to wet either by using the measured value of water concentration in the sample or by the calculated amount of water in the exhaust by means of the carbon balance method which is explained in section 3.7. It should also be noted that different PEMS manufacturers apply different methods to calculate the amount water in the exhaust, which in turn leads to different results among PEMS data post-processing software for an identical dataset. Any variation in following the method recommended under emission measurement regulations will lead to inconsistent results.

4.3.5 Correction of NOx Emissions for Intake Air Humidity

It has been shown in several studies [56, 88] that the NOx emissions from a heavy-duty diesel engine are influenced by the intake air humidity leading to lower NOx with higher humidity in the intake air, and vice versa. Therefore, in order to normalize the NOx emissions measured from engines operating at different ambient conditions, it is mandated to correct the measured emissions to standard intake air humidity value, which is fixed at 10.71 g H_2O/kg dry air (or 50 grains H_2O/lb dry air) for engines that are tested in a test cell. Whereas, for in-use testing, the NOx emissions have to be corrected to a standard humidity level of 7.14 g H_2O/kg dry air (50 grains H_2O/lb dry air) if the intake air humidity is less than 7.14 g H_2O/kg and to 10.71 g H_2O/kg dry air (75 grains H_2O/lb dry air) if it is greater than 10.71 g H_2O/kg. This results in reporting the measured NOx if the intake air humidity is between 7.14 and 10.71 g H_2O/kg dry air.

The equations used to determine the intake air humidity and the correction factors as presented in the regulations are discussed in section 3.5 along with the equations followed by PEMS post-processing software to correct the NOx emissions. It should be noted that as the method used to determine intake air humidity as well as the correction factors differs between the PEMS devices and the regulation, it could lead to inconsistent results among different post-processing software for an identical dataset.

4.3.6 Addressing Negative Emissions Concentrations

The newer heavy-duty diesel engines, which are subjected to in-use emission compliance, are generally equipped with an advanced exhaust aftertreatment system to reduce all the regulated emissions. It has been observed that when the aftertreatment system has reached the light-off temperatures it reduces the emissions to near-background levels causing the emissions analyzers to operate in its noise range and measuring negative concentrations. Also, analyzer drift could lead to the measurement of negative concentrations which could still result in negative values in spite of zero drift corrections. The regulation mandates any negative concentration to be equated to zero before calculating the mass emissions rate [89]. Therefore, it is imperative to assess how the PEMS data post-processing software handles the negative emission concentrations.

4.3.7 Down Sampling of Emission Measurement Data

The in-use emission compliance regulation requires the engine manufacturer to conduct the in-use emissions test either by themselves or under their supervision and report the results along with the raw emissions and engine ECU data used in arriving at the test results. The raw data submitted to the EPA must be down sampled to one hertz, which is used by EPA to verify the results submitted by the engine manufacturer. In order to reduce the discrepancy in emissions results between manufacturers and the EPA's calculations it is imperative for the manufacturer to calculate the emission results after converting the raw data to one hertz. There are several methods used to down sample high frequency data, the most common are averaging of data between time intervals of high frequency data to low frequency [91] and decimation of data. The decimation of high frequency data to a lower frequency involves disregarding of the data between the time intervals of high frequency when down sampling to low frequency. Therefore, it is essential to assess how the high frequency data is down sampled and the difference in the resulting emissions value.

4.3.8 Integration of Emissions Mass and Brake-Specific Work Over an NTE Event

Once the emission rates and the engine work are determined at a frequency of one hertz, the emissions and the engine work are integrated separately over a given time interval of a valid NTE event and the process is repeated for all the NTE events. The brake-specific emissions rate for a NTE event is calculated as the ratio of total mass of emissions to the total brake-work of the engine over a given NTE time interval, and care should be taken in not integrating the brake-specific emissions calculated at one hertz.

Therefore, a reference dataset should be capable of evaluating the effects of the aforementioned variables in quantifying the final NTE brake-specific emissions. The brake-specific emissions of a valid NTE event are compared against a threshold value representing in-use emission standards to determine if a vehicle passes or fails in-use emissions compliance. The reference dataset, which includes variation of the above factors, will be reduced using post-processing software developed as per the regulations to study the difference in the results of commercial PEMS post-processing software.

4.4 Verification of In-Use Emissions Compliance

Finally, after determining the brake-specific emissions over valid NTE events, they have to be validated against in-use emission standards to conclude whether the vehicle meets or fails the in-use emissions compliance. The verification of in-use emissions compliance of a heavy-duty vehicle involves the following factors:

1. NTE emission threshold.
2. Time weighted vehicle pass ratio.
3. Emission upper limit for all valid NTE events.

The procedure involved in determining the above factors and the possibility of introducing error will be explained in the following sections.

4.4.1 NTE Emission Threshold

The brake-specific emission threshold values of regulated constituents are determined as a function of the following parameters.

1. NTE multiplier
2. Accuracy margin
3. Compliance margin

NTE multiplier is a factor used to multiply the emission certification standards when determining in-use emission threshold value. It depends on the emission constituent and their certification standards, and can have a value of 1.25 or 1.5.

The accuracy margin, an additive factor is used to offset or lower the in-use emission standards to compensate for reduced accuracy of lower grade in-use emissions measurement device in comparison to laboratory grade emission analyzers used for certifying engine in a test cell. The value of accuracy margins is the outcome of the measurement allowance program funded by US EPA and determined by the experiments conducted at SwRI and C-CERT [26]. The value of accuracy margin varies between 0.006 to 0.60 g based on the emissions constituent and the method used to quantify the mass emissions. The accuracy margin is higher for emissions quantified using the exhaust flow measuring device since the accuracy of any flow measuring device used to measure the flow rate of a pulsating exhaust flow is low. The other methods which employ the fueling rate data from the ECU to estimate the exhaust flow have found to be more accurate and as a result it is associated with lower measurement allowance. Furthermore, as PEMS devices have been evolving over time the in-use emissions regulations have fixed the accuracy margin for MY2010 and later engines to be a constant value based on the emissions constituent being measured [92].

Compliance margin is also an additive factor used to account for the deterioration of engine as a function of total miles travelled. The compliance margin is applicable only for NOx and for engines whose certification standards is less than or equal 1.30 g/bhp-hr. The value of compliance margin ranges between 0.10 to 0.20 g/bhp-hr for vehicles whose odometer reading ranges from under 110,000 to over 185,000 miles.

Hence, the NTE emission threshold values are given by

$$NTE_{threshold} = \left(Cert.Std. \times NTE_{multiplier}\right) + Acc.Margin + Comp.Margin \qquad \textbf{Eq. (87)}$$

The interdependency of different factors used in determining emission threshold values are illustrated in Table 12.

Table 12: Variables Used to Determine In-Use Emission Threshold Value.

Pollutant	Engine MY	FTP Standard	FEL with ABT	Certification Standard	NTE Multiplier	Accuracy Margin	Testing Method	Compliance Margin	Odometer Reading
		[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]		[g/bhp-hr]	40 CFR	[g/bhp-hr]	[miles]
NOx (NOx+NMHC)	2007-2009	0.20 (0.20+0.14)	2.00 (2.00+0.14)	>1.50	1.25 *per §86.007-11(a)(4)(i)(B)*	0.50 (0.50+0.17)	§86.1930	Not eligible *per §86.007-11(h)(1)*	NA
						0.45 (0.45+0.02)	1065.650(a)(1)		
						0.15 (0.15+0.01)	1065.650(a)(3) & 1065.915(d)(5)(iv)		
				1.30 < Certification Standard < 1.50	1.5 *per §86.007-11(a)(4)(i)(A)*	0.50 (0.50+0.17)	§86.1930	Not eligible *per §86.007-11(h)(1)*	NA
						0.45 (0.45+0.02)	1065.650(a)(1)		
						0.15 (0.15+0.01)	1065.650(a)(3) & 1065.915(d)(5)(iv)		
				≤ 1.30	1.5 *per §86.007-11(a)(4)(i)(A)*	0.50 (0.50+0.17)	§86.1930	0.10 *per §86.007-11(h)(2)(i)*	<110,000
								0.15 *per §86.007-11(h)(2)(ii)*	>110,000 & <185,000
								0.20 *per §86.007-11(h)(2)(iii)*	>185,000
						0.45 (0.45+0.02)	1065.650(a)(1)	0.10 *per §86.007-11(h)(2)(i)*	<110,000
								0.15 *per §86.007-11(h)(2)(ii)*	>110,000 & <185,000
								0.20 *per §86.007-11(h)(2)(iii)*	>185,000
						0.15 (0.15+0.01)	1065.650(a)(3) & 1065.915(d)(5)(iv)	0.10 *per §86.007-11(h)(2)(i)*	<110,000
								0.15 *per §86.007-11(h)(2)(ii)*	>110,000 & <185,000
								0.20 *per §86.007-11(h)(2)(iii)*	>185,000

Pollutant	Engine MY	FTP Standard	FEL with ABT	Certification Standard	NTE Multiplier	Accuracy Margin	Testing Method	Compliance Margin	Odometer Reading
		[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]		[g/bhp-hr]	40 CFR	[g/bhp-hr]	[miles]
	2010 and later	0.20	0.50		1.5 *per §86.007-11(a)(4)(i)(A)*	0.50 (0.50+0.17)	§86.1930	0.10 *per §86.007-11(h)(2)(i)*	<110,000
								0.15 *per §86.007-11(h)(2)(ii)*	>110,000 & <185,000
								0.20 *per §86.007-11(h)(2)(iii)*	>185,000
						0.45 (0.45+0.02)	1065.650(a)(1)	0.10 *per §86.007-11(h)(2)(i)*	<110,000
								0.15 *per §86.007-11(h)(2)(ii)*	>110,000 & <185,000
								0.20 *per §86.007-11(h)(2)(iii)*	>185,000
						0.15 (0.15+0.01)	1065.650(a)(3) & 1065.915(d)(5)(iv)	0.10 *per §86.007-11(h)(2)(i)*	<110,000
								0.15 *per §86.007-11(h)(2)(ii)*	>110,000 & <185,000
								0.20 *per §86.007-11(h)(2)(iii)*	>185,000
PM	2007 and later	0.01	0.02		1.5 *per §86.007-11(a)(4)(i)(C)*	0.1	§86.1930	0.01 *per §86.007-11(h)(3)*	na
						0.006	40 CFR 1065	0.01 *per §86.007-11(h)(3)*	na
CO	2007 and later	15.5	na		1.25 *per §86.007-11(a)(4)(i)(D)*	0.6	§86.1930	na	na
						0.5	1065.650(a)(1)	na	na
						0.25	1065.650(a)(3) & 1065.915(d)(5)(iv)	na	na

4.4.2 Time Weighted Vehicle Pass Ratio

The vehicle pass ratio for in-use emission compliance is defined as the ratio of total duration of valid NTE events whose emissions are at or below the threshold value of the respective pollutant to the total duration of all valid NTE events. In order for a vehicle to be compliant with in-use emission regulation, the pass ratio must be at least 90%. The pass ratio is given by [93]

$$R_{pass} = \frac{\sum_{m=1}^{n_{pass}} t_m}{\sum_{k=1}^{n_{total}} t_k} \qquad \textbf{Eq. (88)}$$

Where: t_m duration of a valid NTE event at or below emission threshold

t_k duration of a valid NTE event

n_{pass} total number of valid NTE events that meets emissions threshold

n_{total} total number all the valid NTE events

There are also restrictions applied on the duration of a valid NTE event used to calculate vehicle pass ratio. NTE events which are longer than ten times the shortest NTE event or longer than 600 seconds are shortened to the shortest of the above two conditions when used to calculate the vehicle pass ratio. This is implemented in order to reduce the significance given for a longer NTE event since the majority of NTE events are of short duration. An illustration of the restriction on NTE event duration used in evaluating vehicle pass ratio is shown in Table 13. Therefore, it is required to evaluate the PEMS data post-processing software for its ability to incorporate the restriction on NTE event duration in determining the vehicle pass ratio.

Table 13: Restriction on NTE Event Duration to Evaluate Vehicle Pass Ratio [94]

NTE sample	NTE sample duration [s]	Duration limit applied?	R_{pass} duration [s]
1	45	No	45
2	168	No	168
3	500	Yes, 10 times shortest valid NTE	450
4	605	Yes, 10 times shortest valid NTE	450
5	65	No	65

4.4.3 Emission Upper Limit for All Valid NTE Events

Finally, in order for the engine that satisfies the 90% emissions pass ratio to be certified as compliant to in-use emission standards, the emissions measured over the NTE events that fail to meet the threshold must meet the following criteria based on the engine MY and the emission constituent:

1. For MY 2007 to 2009 engines emissions for valid NTE events that fail to meet the in-use threshold standards must be less than two times the threshold value except for NOx.

2. The NOx emissions for engines certified to family emission limit (FEL) at or below 0.50 g/bhp-hr for NTE events failing to meet NTE threshold must be lower than two times the NTE threshold or 2.0 g/bhp-hr, whichever is greater.

The above additional criteria is incorporated to discourage gross increase of emissions over the rest of the 10% of the NTE events for engines that meet the 90% pass ratio, and encourage the early adopters of NOx reducing technologies by providing an extra margin with an upper limit of 2.0 g/bhp-hr for NOx. For example, the second criteria allows an additional margin of up to 1.10 g/bhp-hr for 10% of the NTE events when the engine is certified at 0.2 g/bhp-hr with less than 110,000 miles and when their emissions are quantified using a method that correlates with lowest allowance to accuracy margin, when compared to using 2.0 times of maximum NTE threshold [95].

Therefore, any PEMS data post-processing software's ability to qualify the test vehicle to meet in-use emissions compliance has to be evaluated as a function of the aforementioned criteria and is given by

$$Veh_{pass} = f\begin{cases} NTE\ emission\ Threshold \\ Time\ weighted\ vehicle\ pass\ ratio \\ Emission\ upper\ limit\ for\ valid\ NTE\ events \end{cases} \quad \textbf{Eq. (89)}$$

5 EXPERIMENTAL METHODOLOGY

5.1 Introduction

This chapter gives a detailed explanation of how the reference dataset is developed based on the factors that influence the determination of valid NTE events, quantification of emissions rates, quantification of engine brake work, calculation of brake-specific emissions over NTE events, determination of NTE emission threshold, evaluation of vehicle pass ratio, and ultimately compliance of the vehicle for in-use emissions standards. The expected outcome for the reference dataset, when reduced using a given in-use emissions post-processor, will be presented as well. Furthermore, the reference dataset is developed based on the template in which the engine manufacturers are required to submit the in-use emissions compliance test results as well as the raw data at 1 Hz.

The development of the reference dataset is explained in the following three sections. The reference dataset developed in this manner is compiled into a single dataset which is compatible with the post-processing software in order to evaluate the data post-processing software. The three sections are as follows:

1. Dataset to verify NTE event validation.
2. Dataset to verify quantification of emissions rates.
3. Dataset to verify in-use emissions compliance.

The reference dataset discussed in this chapter is developed based on the robustness technique for black-box testing [96 - 98]. In the robustness technique, unlike the boundary value analysis method, the factors which influence an outcome are tested near the boundary, both inside and outside, as well as in middle of the domain. This type of testing will result in more test cases than boundary value analyses. For example, in the case of an engine operating point to be a valid NTE point, engine speed must be greater than 15% of ESC speed; engine torque must be greater than or equal to 30% of peak torque, and engine power must be greater than or equal to 30% of rated power. In order to test the outcome of in-use emissions post-processor data for the above scenario under boundary value analysis, it requires five test cases that satisfy boundary conditions. Conversely, under the robustness technique; more test cases are designed, which both satisfies and fails the boundary conditions including a test case that tests at the middle range of values [99]. Therefore, for the aforementioned scenario under the robustness technique, four test cases are designed to test each engine speed, engine torque, and engine power resulting in a total of twelve test cases to ensure an overall verification of the data post-processing software. The development of test cases involving each factor that are required for NTE event validation, quantification of emissions rates, and verification of in-use compliance will be discussed in the following sections.

5.2 Development of Dataset to Verify NTE Event Validation

As discussed in section 4.2, validation of a NTE data point and an event can be defined as a function of different factors, which is given by:

$$NTE_{valid} = f\begin{pmatrix} n_{15}, T_{30}, P_{30}, \text{Alt}, T_{amb\_Alt}, IMT_{EGR}, ECT_{EGR}, \\ T_{exhAT}, t_{NTE}, t_{NTE-regen,min} \end{pmatrix} \quad \textbf{Eq. (90)}$$

It must be noted that for a NTE event to be valid, it has to satisfy all the conditions of the variables listed in Eq. (90). Therefore, the NTE event validation process can be visualized as a large AND gate wherein all inputs must be true for the output to be true.

As the definition of a NTE zone is characterized using the maximum torque of an engine, the reference dataset has been developed using the advertised maximum torque curve of a heavy-duty diesel engine manufactured by Mack. The engine details are listed in Table 1 and the torque curve is shown in Figure 9.

Table 14: Test Engine Specification Used for Developing the Reference Dataset [100]

Manufacturer	Mack
Model	MP8-445C
Engine MY	2011
Configuration	6 cylinders, Inline
PM Aftertreatment	DPF + Diesel Oxidation Catalyst (DOC)
NOx Aftertreatment	Urea-SCR System
Peak Torque	1735 ft-lbs@1100 (2352 N-m)
Rated Power	445 bhp@1500 (332kW)
Displacement	12.8 L (781.1 in^3)
NOx Certification Standard	0.20 g/bhp-hr
PM Certification Standard	0.01 g/bhp-hr

The NTE zone is outlined using the torque curve with a resolution of one rpm derived by linear interpolation from the advertised torque curve. After characterizing the NTE zone, the reference dataset is designed in a manner that allows for all the factors required for satisfying an interval of engine operation to be a NTE event, save for one factor whose values are varied at its boundary conditions to result in a NTE event; or possibly nothing at all. An example of this can be seen while testing the in-use emissions data post-processor or reduction code for accurate interpretation of the NTE engine speed, is tested by creating an NTE event of minimum duration that satisfies all the conditions for an NTE event, but for the engine speed. The engine speed is varied in such a way that it results in a NTE event, or nothing at all. This failure can occur by having the engine speed lower than the NTE engine speed by as little as one rpm, the exact same event is repeated now with a value of engine speed equal to NTE engine speed; the last event being at an engine speed higher than the NTE engine speed by one rpm. The aforementioned sequence of data with varying engine speed should result in exactly one NTE event since the engine speed must be always greater than NTE engine speed. It should be noted that after each event of 30 seconds, a one second data with engine speed and torque values lower than the NTE limits are included to deliberately break the continuity of a NTE event while testing for each factor. The NTE torque and power limits are tested by adjusting the engine percent torque, which is represented as a percent of a constant reference torque value along with nominal friction percent torque in such a way that the absolute torque values are lower or greater than the NTE torque and power limits. It is worth mentioning that the conditions of engine torque and power being equal to NTE limits are difficult to achieve since the engine torque is expressed as a percent of a reference torque with a resolution restricted to 0.1 percent and the resolution of the NTE limits being 1 Nm and 0.01 kW. Therefore, it is difficult to result in both engine torque and engine power values to be exactly equal to NTE limits for the given combination of maximum torque curve and the reference torque values. The guide describing the format in which in-use emissions test results, along with 1 Hz emissions data required by the EPA for each vehicle after completion of in-use compliance testing conducted by the engine manufacturer, is used in fixing the resolution of all the factors used in determining the NTE event and in quantifying NTE brake-specific emissions.

The order in which the reference dataset is developed to verify data post-processing software for the validation of NTE events based on the engine operating conditions will be explained one factor at a time in the following sections.

5.2.1 Verification of NTE Engine Speed

The engine speed must be greater than 15% of the ESC speed for an engine to be in the NTE zone provided all other factors meet the NTE operating conditions and exclusion criterion. In order to verify this specific condition, all the engine operating conditions are set to satisfy the NTE conditions and exclusions except for the engine speed. In the first 30 seconds, the engine speed is set to be lower than the NTE speed by one rpm to ensure that the data post-processor could recognize and fail the event for engine speed being lower than the NTE speed. The first 30 second data sequence is deliberately terminated with a one second data point by having the engine speed and torque lower than the NTE limits. The second interval of 30 seconds is tested with engine speed being equal to NTE engine speed which should also result in a non-NTE event due to engine speed not meeting the NTE speed limit. The second interval of data sequence is terminated with a one second data point which fails to meet NTE zone operating conditions. In the third 30 second interval, the engine speed is set to one rpm higher than the NTE speed limit, which should result in a NTE event. The data trace of the first 93 seconds in which NTE engine speed is varied to verify the data post-processing software is shown in Figure 6 along with engine torque and engine power.

5.2.2 Verification of NTE Engine Torque

In the next 93 seconds of data, which begins from 94 seconds and ends at 186 seconds, NTE engine torque is varied by having the first NTE event of 30 seconds fail due to the engine torque being lower than 30% of peak torque. The second interval of 30 seconds is designed in such a way that the engine torque is exactly equal to NTE engine torque limit resulting in an NTE event. Finally, in the last 30 second event, the engine torque is set to a value greater than NTE torque limit to result in an NTE event. It should be noted that the second set of data comprised of 93 seconds is designed to meet all conditions to result in an NTE event, except for the engine torque. The data trace of NTE torque validation data is shown in Figure 7.

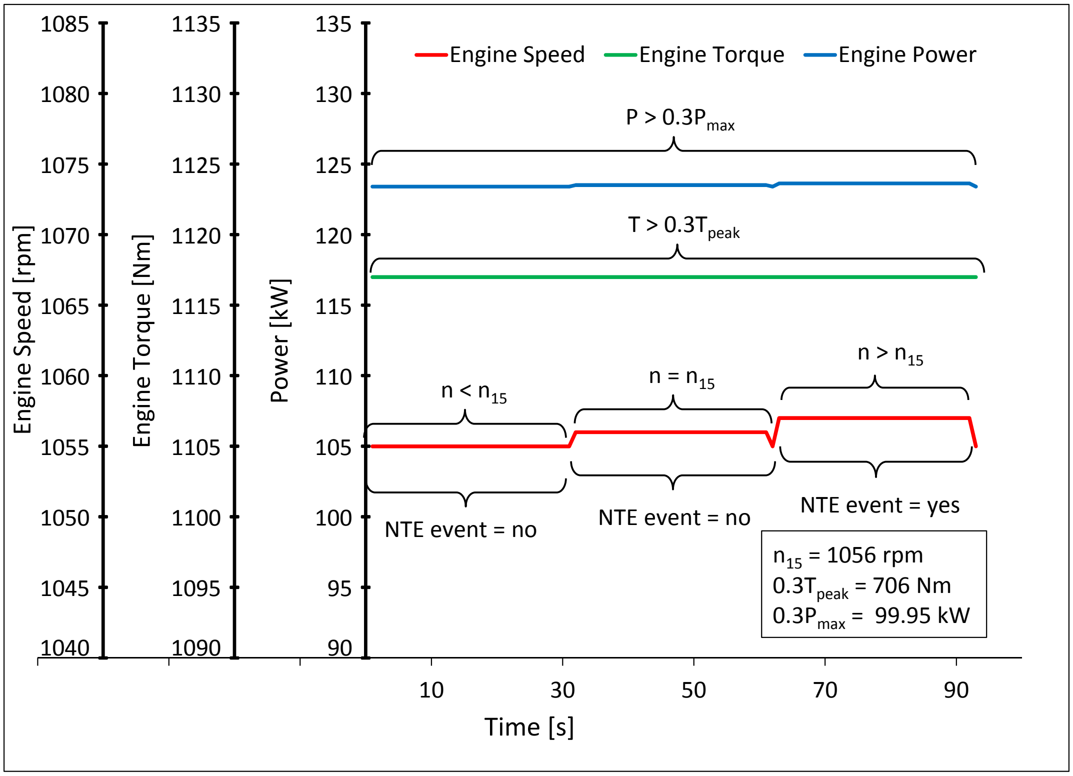


Figure 6: Time Trace of NTE Engine Speed Verification Data

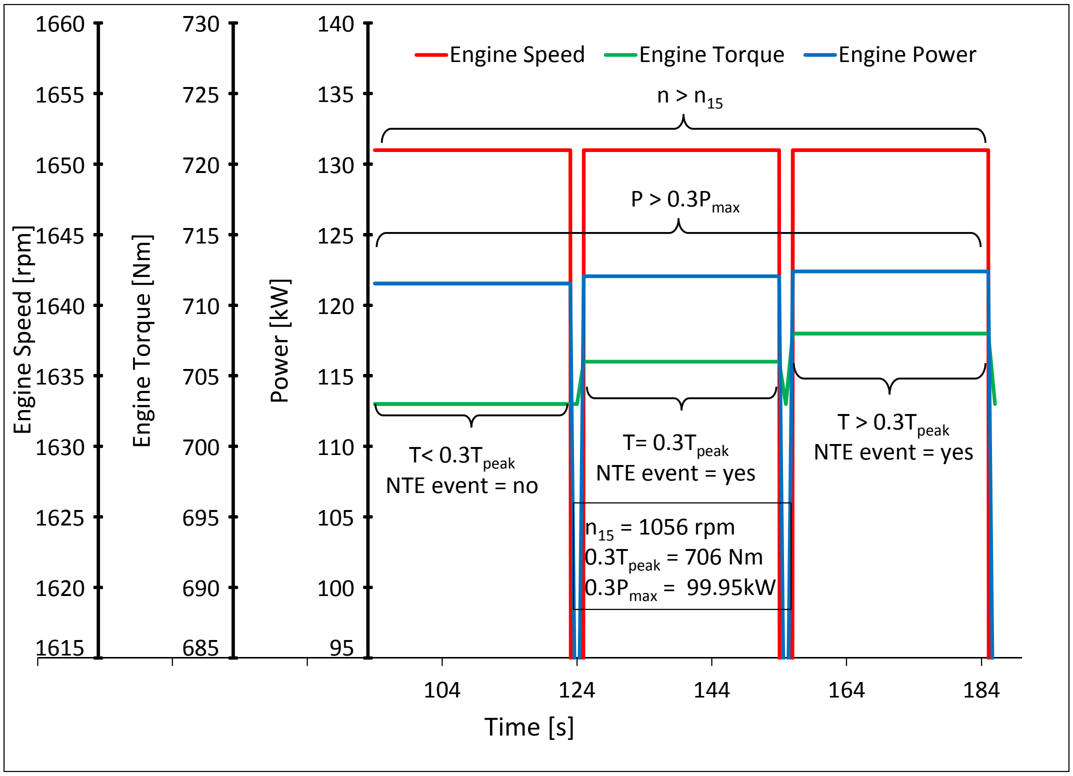


Figure 7: Time Trace of NTE Engine Torque Verification Data

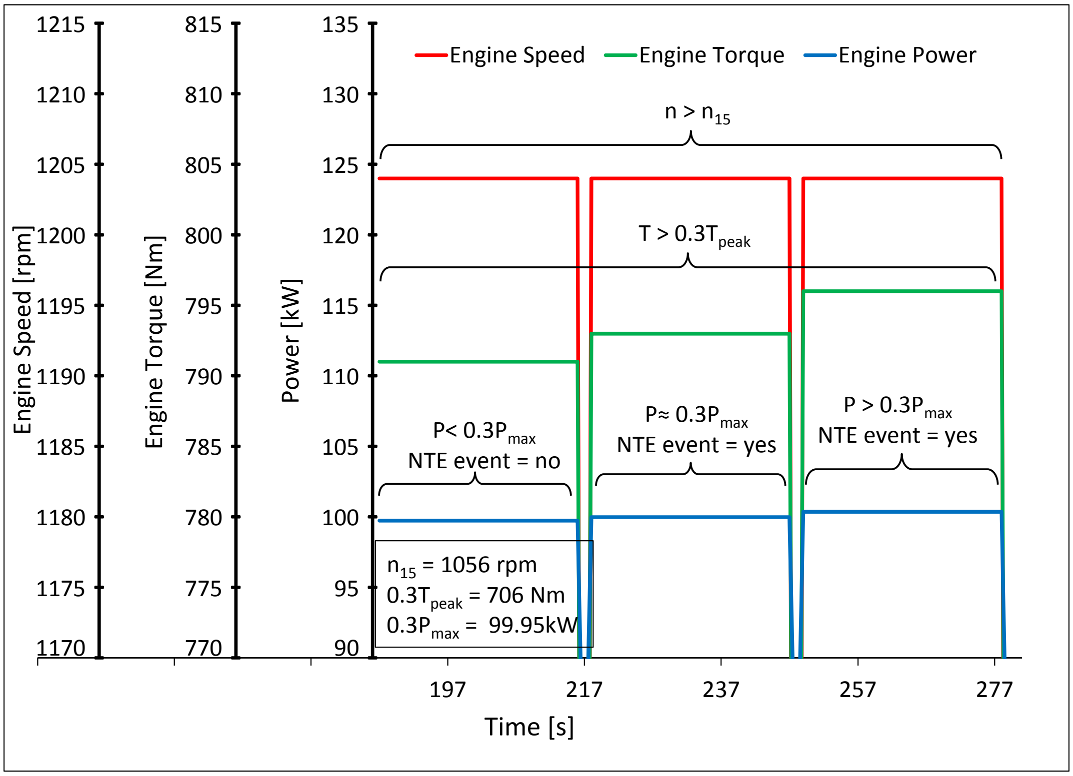


Figure 8: Time Trace of NTE Engine Power Verification Data

5.2.3 Verification of NTE Engine Power

The NTE engine power validation is tested between the time intervals of 188 seconds to 280 seconds wherein the first 30 second interval is designed to fail an NTE event due to engine power being lower than 30 percent of peak power. The second event of 30 seconds is set such that the engine power is approximately equal to NTE engine power limit so that it results in an NTE event. The last 30 seconds event is made to result in an NTE event by satisfying the NTE engine power limit where the engine power is greater than the limit. The data trace of the NTE engine power verification data is illustrated in Figure 8. An illustration of the engine operation regions where the NTE engine speed, torque, and power are validated is shown in Figure 9.

5.2.4 Verification of NTE Altitude

After validating the NTE zone definition, the reference dataset is further expanded to test the common exclusion that results in the exclusion of a NTE event. The common exclusions are based on ambient conditions in which the engine operates such as altitude and temperature, cold operating conditions of an engine, which are equipped with EGR, cold operating conditions of exhaust aftertreatment systems including regeneration of aftertreatment systems.

The altitude at which an engine operates is one factor the reference dataset is designed to test in NTE altitude testing. This testing is performed by rendering the first 30 seconds of engine operation to yield in a non-NTE event by making the test altitude higher than the NTE limit by one foot. The next 30 second engine operating event is rendered to yield into a NTE event by having the test altitude equal to the NTE limit of 5,500 feet. The test altitude, which is lower than the NTE limit by one foot, is tested in the last 30 seconds resulting in a NTE event. The data trace of the reference dataset validating the NTE altitude is shown in Figure 10. Note that the figure also includes the trace of NTE ambient temperature limit, which is a function of the test altitude along with the actual ambient temperature satisfying the NTE exclusion by being lower than the NTE limit for the entire test section validating the NTE altitude.

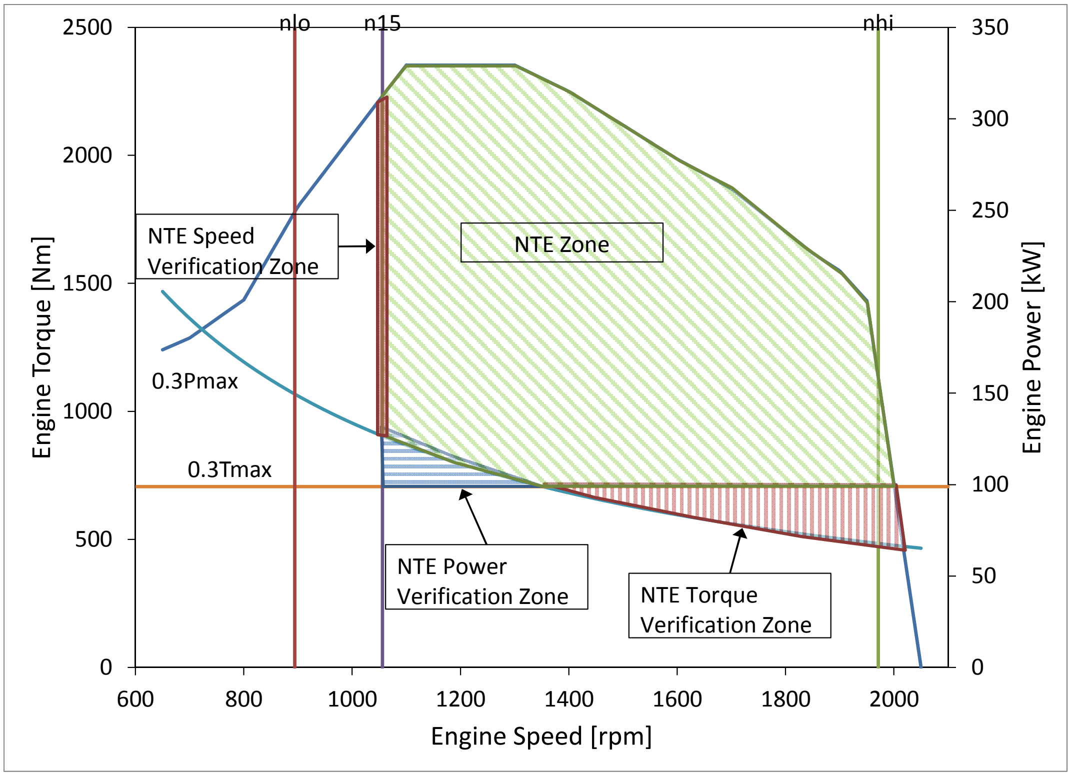


Figure 9: Regions of NTE Zone Validation to Result in an NTE Event

5.2.5 Verification of NTE Ambient Temperature

The ambient temperature exclusion, a function of engine test altitude, is tested between 373 and 465 seconds. The trace of the data verifying NTE ambient temperature is illustrated in Figure 11. It can be seen in the figure that for the first 30 seconds ambient temperature is higher than the NTE limit resulting in that event to be excluded as an NTE event. In the second interval of 30 seconds, the ambient temperature is exactly equal to the NTE limit resulting in a NTE event. In the last 30 seconds, the ambient temperature is set to be lower than the NTE limit by 1 °F to result in a NTE event. It should be noted that the ambient temperature is set to a constant value greater, equal, and lower than the limit only while testing NTE ambient temperature limit and allowed to vary sinusoidally with 3 °C amplitude, and reference value of 27 °C at a frequency of 0.13 Hz for rest of the test.

5.2.6 Verification of Engine Coolant Temperature

The verification of in-use emissions data post-processor for conditions that exclude a NTE event for engines equipped with emissions reduction technologies that are restricted to operate at cold operating conditions is tested between 466 and 651 seconds. The NTE limit for engine coolant temperature, which is a function of the absolute intake manifold pressure for an engine equipped with exhaust gas recirculation technology, is tested between 466 and 558 seconds. The first event of 30 seconds is set such that the NTE event will be excluded because the engine coolant temperature is below the NTE limit. In the second 30 seconds event, the actual engine coolant temperature is set to be exactly equal to the NTE event exclusion limit; which should result in a non-NTE event. Finally, in the last 30 seconds of the data, engine coolant temperature is set to be higher than the limit by 1 °F leading to an NTE event. The data trace to verify the engine coolant temperature exclusion in the NTE zone is shown in Figure 12.

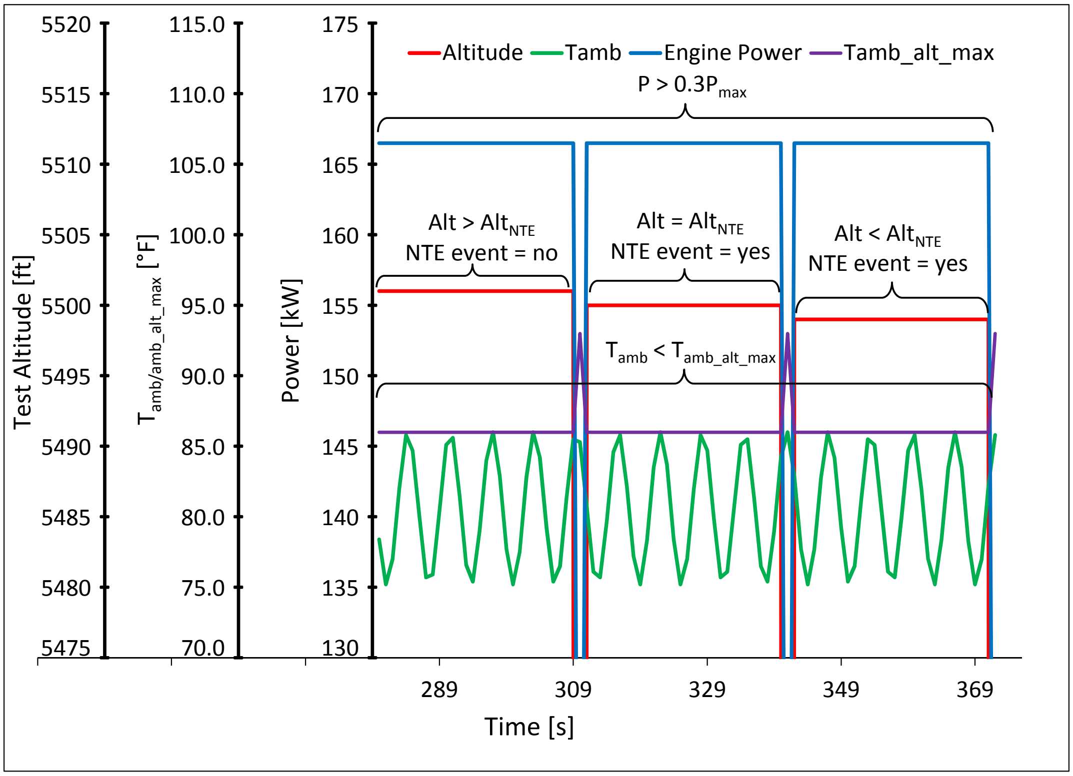


Figure 10: Time Trace of NTE Altitude Verification Data

5.2.7 Verification of NTE Intake Manifold Temperature

The time trace of the data used to verify the validation of NTE limits for intake manifold temperature for engines equipped with an EGR system is shown in Figure 13. As illustrated in the first 30 seconds, the actual intake manifold temperature (IMT) is set to a value lower than the NTE limit by 1 °F so that the interval of engine data results in a non-NTE event due to intake manifold temperature exclusion. The second interval of 30 seconds is set such that the IMT is equal to the NTE exclusion limit resulting in non-NTE event. The final 30 second interval the actual IMT value is set to be greater than the NTE limit by 1 °F, which should result in NTE event.

5.2.8 Verification of NTE Light-Off Temperature of Aftertreatment System

The NTE limit for the light-off temperature of aftertreatment devices used to reduce NOx and hydrocarbons is set to be greater than 250 °C when measured within 12 inches of the aftertreatment device with the highest exhaust flow. The reference dataset is designed to test this condition between 652 and 744 seconds where the first event of 30 seconds is made to fail for NTE aftertreatment device light-off temperature by setting the exhaust temperature to be lower than 250 °C by 1 °C. The next 30 second exhaust temperature is set exactly equal to 250 °C failing the event to be an NTE event. Finally, for the last 30 seconds, the exhaust temperature is set at 1 °C higher than the limit resulting in a NTE event. The time trace of the reference dataset testing the validation of exhaust temperature at the outlet of an aftertreatment device is shown in Figure 14.

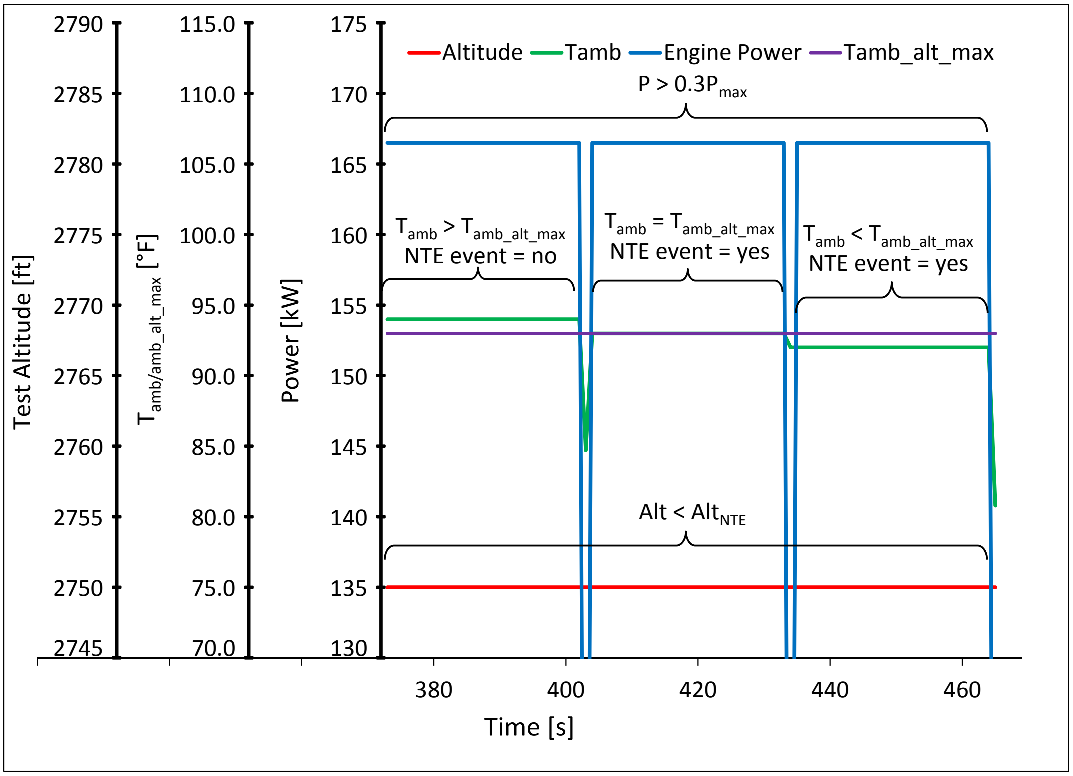


Figure 11: Time Trace of NTE Ambient Temperature Limit Verification Data

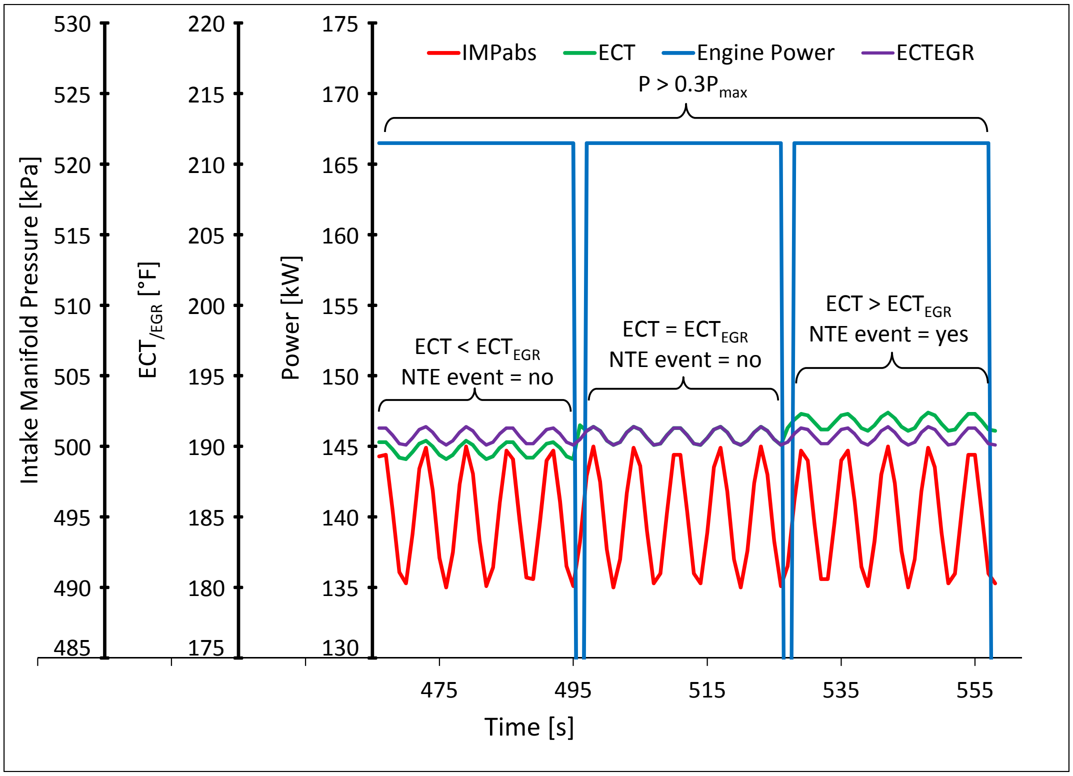


Figure 12: Time Trace of NTE Engine Coolant Temperature Limit Verification Data

5.2.9 Verification of Minimum Time Required for an NTE Event

If an engine operates continuously in a NTE zone while satisfying all the common exclusions discussed above for at least 30 seconds, and if there are no regeneration events of an aftertreatment device, then that event is considered to be a valid NTE event. This condition of minimum time for a NTE event is tested using the reference dataset by making the first event of engine operation to endure in the NTE zone for 29 seconds thereby failing the event from becoming a NTE event. The next interval of engine operation is set to operate in the NTE zone for 30 seconds resulting in a NTE event. The last interval of engine operation in the NTE zone is set to 31 seconds, which should also result in a NTE event. The time trace of the reference dataset used to evaluate minimum time required to be a NTE event is shown in Figure 15.

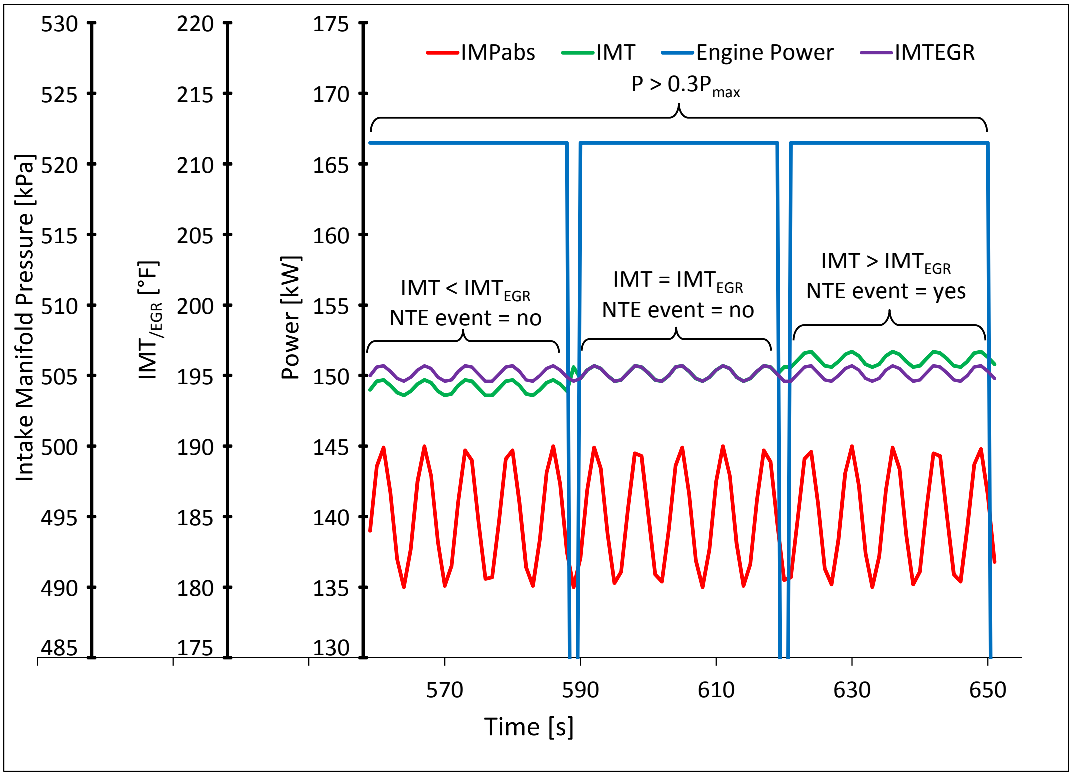


Figure 13: Time Trace of NTE Intake Manifold Temperature Limit Verification Data

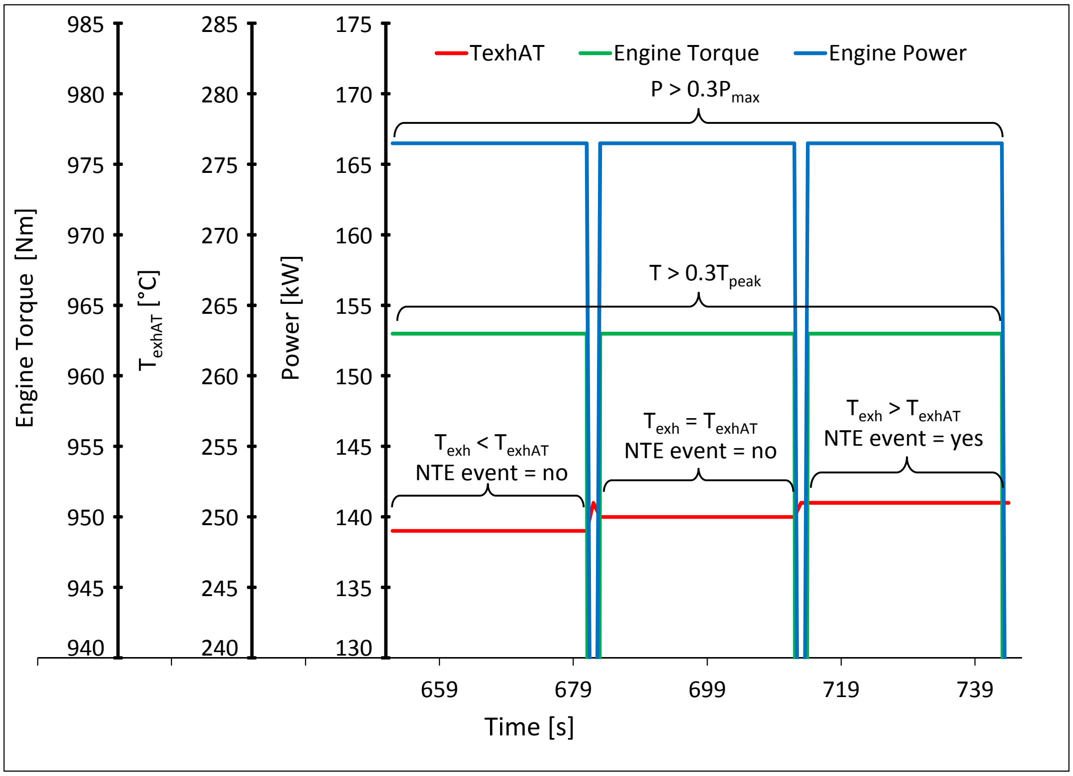


Figure 14: Time Trace of NTE Exhaust Temperature Limit Verification Data for Aftertreatment System

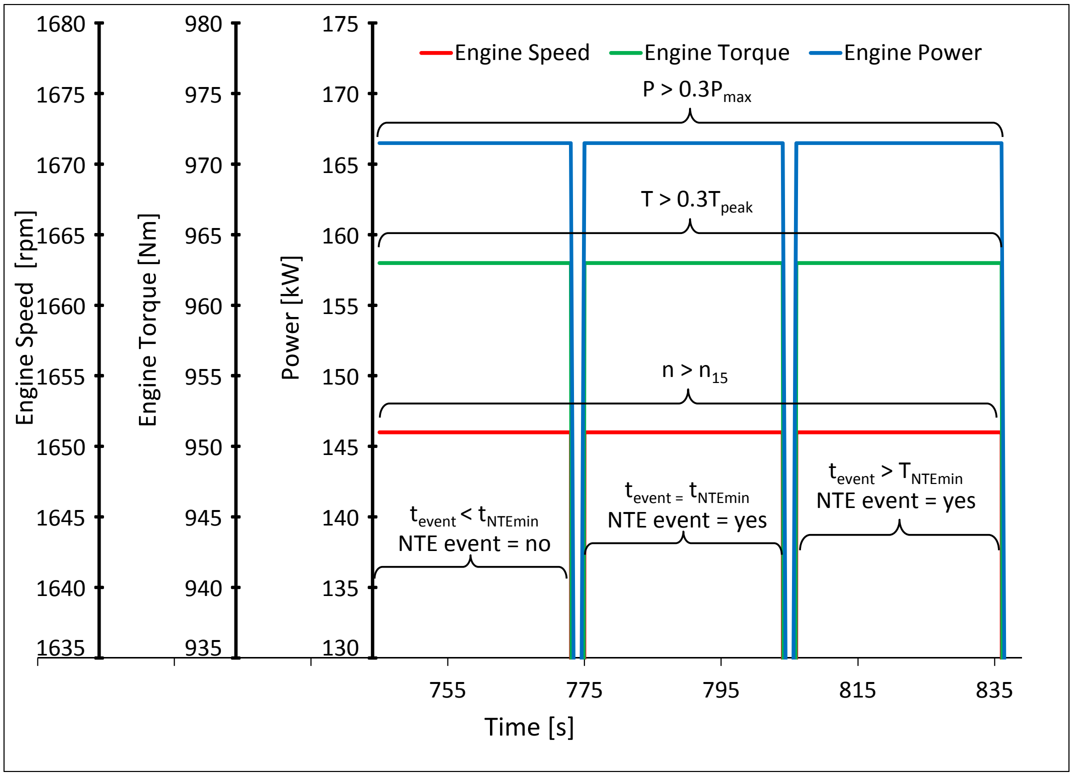


Figure 15: Time Trace of Minimum NTE Event Time

5.2.10 Representation of Data Collected Over Eight Hour Shift Day in the Reference Dataset

It is required to collect in-use emissions data from a heavy-duty diesel vehicle over a period of eight hours representing a full shift work day using PEMS device while performing its intended activity. Therefore, in order to represent data collected over an eight hour shift day the reference dataset is divided into two major intervals of four hours each and they are further divided into smaller intervals of one hour each. The first and second four hour intervals are similar in engine operating points. The four hour interval is further divided into two hour intervals wherein the first and second hour of engine operation data is exactly same; the third and fourth intervals are similar as well. The first hour of engine operations data comprises NTE event validation data from the beginning to 836 seconds, which is followed by a steady state operation at peak torque speed and 50% load for 300 seconds, and then terminated with a one second non NTE engine operation point. The steady state operation of 300 seconds is followed immediately by a ramp modal cycle supplemental emissions test (RMCSET) without the warm idle mode in the beginning which is shown in Table 15.

Table 15: RMCSET Engine Operation Modes

RMC Mode		MY 2010 & later		
		Time [s]	Speed	Torque [%]
2a	Steady-state	173	A	100
2b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
3a	Steady-state	219	B	50
3b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
4a	Steady-state	217	B	75
4b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
5a	Steady-state	103	A	50
5b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
6a	Steady-state	100	A	75
6b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
7a	Steady-state	103	A	25
7b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
8a	Steady-state	194	B	100
8b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
9a	Steady-state	218	B	25
9b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
10a	Steady-state	171	C	100
10b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
11a	Steady-state	102	C	25
11b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
12a	Steady-state	100	C	75
12b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
13a	Steady-state	102	C	50
13b	Transition	1	$< n_{15}$	$< 0.3\ T_{peak}$
14	Steady-state	168	Warm idle	0

$A = n_{lo} + 0.25*(n_{hi}-n_{lo})$, $B = n_{lo} + 0.50*(n_{hi}-n_{lo})$, and $C = n_{lo} + 0.75*(n_{hi}-n_{lo})$.

The RMCSET cycle results in nine NTE events out of 14 test modes. The RMCSET engine operation points are further followed by another steady state engine operation at rated speed and 50% load for 478 seconds. The main difference between the first two hours and the following two of engine operation is the steady state operation at the end NTE event validation set is extended to 600 seconds, while the last steady state operation after the RMCSET data points is reduced to 178 seconds. Every hour of the engine operation should yield 25 NTE events if the engine is not equipped with an aftertreatment system that requires regeneration. All post-2007 MY heavy-duty diesel engines are equipped with DPFs to meet the PM standards and these filters have to undergo regenerations in order to clean the filter from soot deposition. Therefore, the reference dataset is designed to include regeneration events represented by the Boolean variable called aftertreatment regeneration (AT Regen) where Y denotes aftertreatment device regeneration. The sequence of regeneration events and the calculation of regeneration fraction (RF) are explained in the next section.

5.2.11 Validation of RF and Minimum NTE Event Time in the Event of AT Regen

As the in-use emissions reference dataset is designed to represent emissions measured from post-MY 2007 engines, which are equipped with a DPF that requires periodic active regeneration, it is imperative to include aftertreatment regeneration signals in order to calculate RF. The RF is used in calculating the new minimum NTE event time when an engine encounters regeneration events while operating in the NTE zone. There are three active regeneration events in the reference dataset, two of those events last for 1800 seconds and the last event lasts for 60 seconds, as illustrated in Figure 16. Therefore, the RF for the reference dataset should yield a value of 0.16, whose calculation is shown below:

$$RF = \frac{\frac{\sum_{i=1}^{N_{regen}} t_{regen,i}}{N_{regen}}}{\frac{\sum_{k=1}^{N_0} t_{0,k}}{N_0} + \frac{\sum_{i=1}^{N_{regen}} t_{regen,i}}{N_{regen}}}$$ **Eq. (91)**

Where:

$t_{regen,i}$	$t_{0,k}$	N_{regen}	N_0
[s]	[s]	[#]	[#]
1800	10800	3	4
1800	9000		
60	3117		
	2223		

$$RF = \frac{\frac{1800 + 1800 + 60}{3}}{\frac{10800 + 9000 + 3117 + 2223}{4} + \frac{1800 + 1800 + 60}{3}} = 0.16$$

The 60 second regeneration event is included in the reference dataset in a manner such that it coincides with the steady state operation of the engine in the last hour of the test where the engine is running at peak torque speed and 50% load over a period of 600 seconds. Therefore, the minimum NTE event time for this event to be valid NTE event is given by:

$$t_{NTE-regen,min} = \frac{\sum_{i=1}^{N} t_{regen,NTE,i}}{RF} \qquad \textbf{Eq. (92)}$$

Where:

$$t_{NTE-regen,min} = \frac{60}{0.16} = 375\ s$$

Hence, the aforementioned interval of engine operation should result in a valid NTE event as it is longer than 375 seconds. Where there is a regeneration event of 1,800 seconds long, the short duration NTE events will be invalidated for not satisfying the minimum duration of NTE operation during regeneration event.

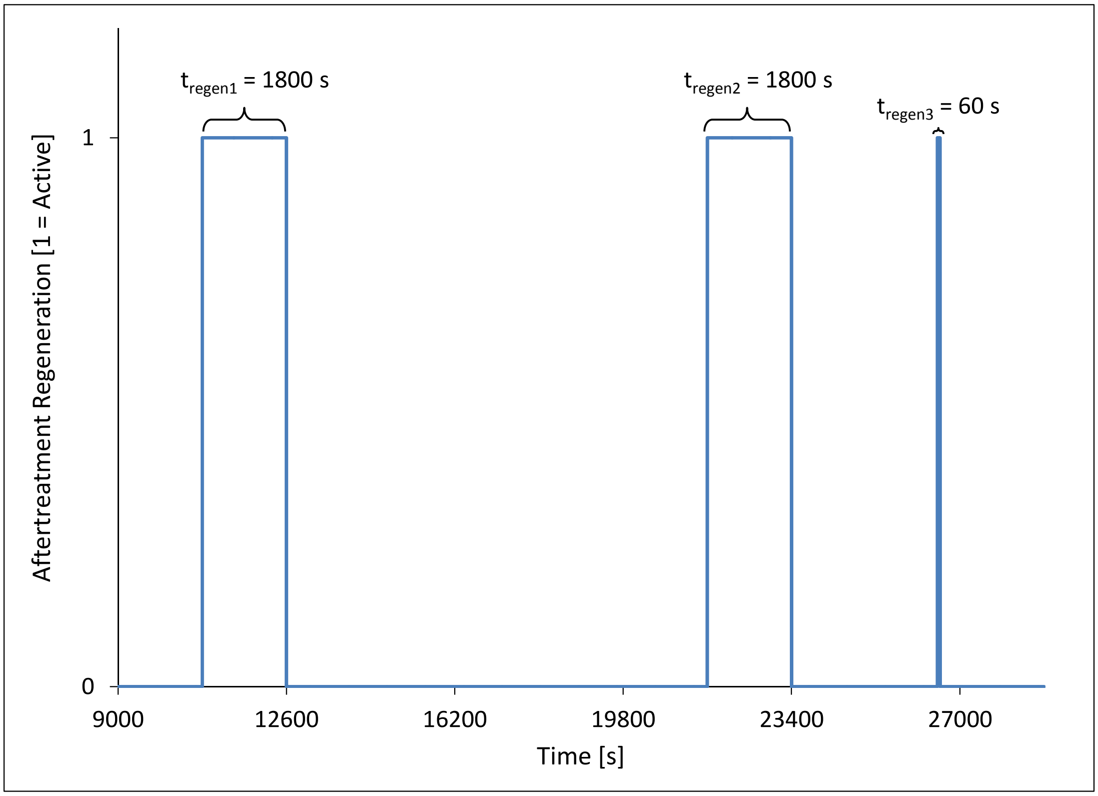


Figure 16: Time Trace of Aftertreatment Regeneration Signal Over 8 Hour Shift Day

5.3 Development of Dataset to Verify Quantification of Emissions Rates

As discussed in section 4.3, Quantification of NTE Brake-specific Emissions, the determination of emissions rate can be defined as a function of various factors based on the method of emissions measurement, which is given by:

$$\dot{m}_{emissions} = f\begin{pmatrix} \text{Allign concentrations, ECU signals to flow measurement,} \\ \text{Conversion of actual exhaust flow to standard conditions,} \\ \text{Correct concentrations for analyzer drift} \\ \text{Convert concentrations from dry to wet,} \\ \text{Correct NOx emissions for intake air humidity,} \\ \text{Addressing negative emissions concentrations,} \\ \text{Down sampling of emissions measurement data,} \\ \text{Integration of emissions, brake work over each NTE event} \end{pmatrix} \quad \textbf{Eq. (93)}$$

The quantification of emissions rate as discussed in chapter 3, Fundamental of Emissions Calculations, provides details about the difference between the methods followed by two different commercial PEMS manufacturers in comparison to the method specified under 40 CFR part 1065. Therefore, the reference dataset developed to verify the quantification of NTE brake-specific emissions and emission rates will include all the variables that are required to verify the difference in quantification of emissions based on 40 CFR part 1065; in comparison to PEMS manufacturers preferred methods. The discussion of the development of the emissions quantification dataset is divided into a list of factors stated in Eq. (93) and is discussed in detail in the following sections.

The dataset developed to quantify the emissions rates follows a sinusoidal wave form whose frequency is linked to the frequency at which the data is acquired; the amplitude and the reference value can be adjusted by the user in order to result in emissions rates that could lead to final brake-specific emissions of a NTE event to either satisfy or fail NTE threshold values. There are several ways to achieve the above criteria of passing or failing a NTE event, one of which being the adjustment of emissions concentration values.

5.3.1 Validation of Emissions Concentrations and ECU Signals Alignment with the Exhaust Sampling Plane.

Horiba, Inc. and SwRI found that the alignment of ECU signals and emissions concentrations to exhaust flow values [87] is the most critical step in quantifying the emission rates and determining the NTE brake-specific emissions. It has been shown that a misalignment of ± 1 second between emissions concentrations and exhaust flow could lead to an error of up to ten percent for a single NTE event and about five percent average error for all NTE events. Furthermore, among different methods used to align the emissions concentration signals to exhaust flow values, it has been found that the application of the average of rise and delay time (T_r & T_d) of an emissions analyzer at a constant sampling rate is the most accurate method to align emissions signals with exhaust flow values. Therefore, the modern PEMS devices include the feature of determining the average analyzer rise and delay time to reach 90 percent response of the span gas values and use the same to align the emissions signals with exhaust flow values. Some PEMS devices also allow the user to adjust the time alignment of the signals by a value given by the user.

5.3.2 Validation of Converting Measured Exhaust Flow to Standard Conditions.

As discussed in section 3.4 the exhaust flow measurement is one of the primary variables required in quantifying emissions mass rates. There are several methods used to determine the exhaust flow rate, of which the most prevalent method is to measure exhaust flow directly using an averaging pitot tube. Therefore, the reference dataset represents exhaust flow values as measured by averaging the pitot tube and is recorded in terms of actual exhaust flow in m^3/min along with exhaust temperature and pressure values at the point of exhaust flow measurement. The actual exhaust flow is further converted to a standard temperature and pressure of 20 °C and 101.325 kPa as mandated by USEPA for emissions quantification purposes.

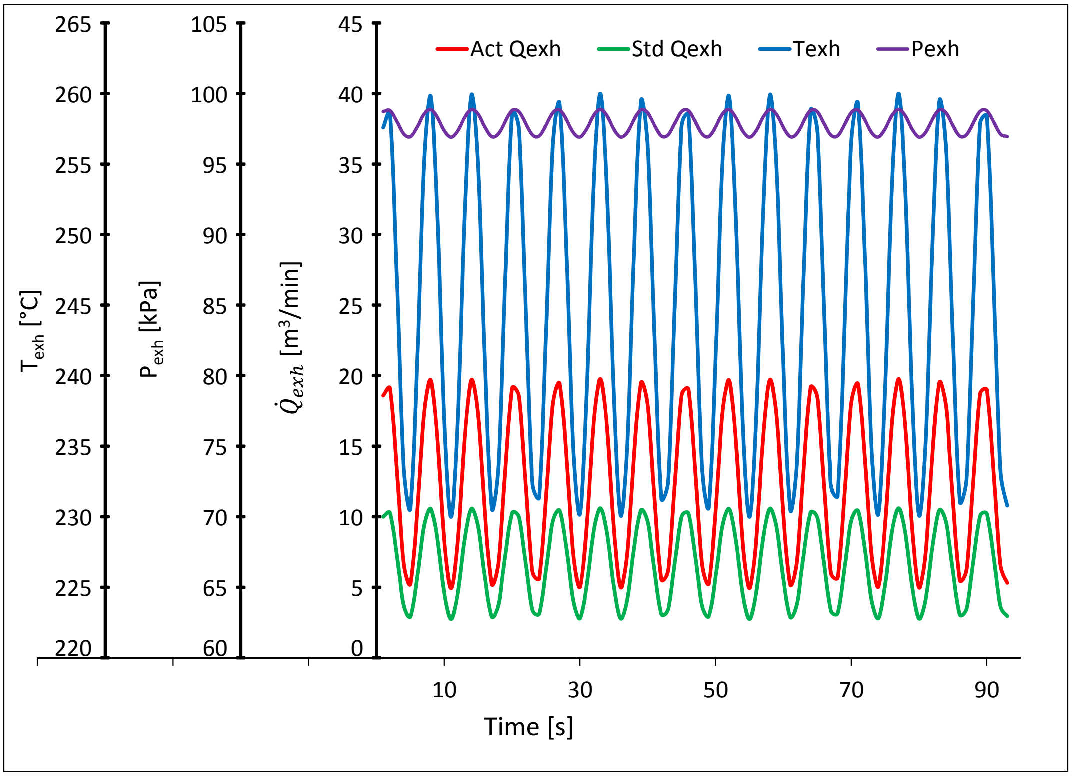


Figure 17: Time Trace of Standard Exhaust Flow Along with Actual Exhaust Flow and Actual Exhaust Temperature and Pressure

The actual exhaust flow, exhaust temperature, and pressure are varied sinusoidally over a given range and average values as depicted in Figure 17. The equation used to generate the exhaust flow, temperature, and pressure signal is given in Eq.(94), along with the amplitude, range, and average values of each signal in Table 16. The actual exhaust flow is then converted to standard exhaust flow using Eq. (95):

$$x = Amplitude \times \sin t + Average \qquad \textbf{Eq. (94)}$$

$$Std.Q_{exh} = Act.Q_{exh}\left(\frac{P_{exh}}{P_{std}}\right)\left(\frac{T_{std}}{T_{exh}}\right) \qquad \textbf{Eq. (95)}$$

It should be noted that the amplitude and average values used to set the exhaust flow, pressure, and temperature as shown in Table 16 are just an example and these values can be varied for each hour of testing or even within an hour of testing in order to yield emission mass rates to either pass or fail an NTE event.

Table 16: Parameters of Exhaust Flow Variables

x	Amplitude	Average
Actual Exhaust Flow Q_{exh} [m^3/min]	7.5	12.5
Exhaust Pressure P_{exh} [kPa]	0.9899	97.8999
Exhaust Temperature T_{exh} [°C]	15	245

5.3.3 Validation of Correcting Emissions Concentrations Due to Analyzer Drift.

As discussed in section 3.3 a PEMS device is required to record the response of its analyzers before beginning the test for zero and span gases after the analyzers are zero spanned with respective gases of known concentrations. These response values are known as pre-test zero/span values. Similarly, the response values of the analyzers for zero/span gases have to be recorded after the test and before zero/spanning the analyzers. These response values are known as post-test zero/span values. Note that the pre-test zero/span values normally refer to the exact zero and span responses since they are recorded right after zero/spanning the analyzers, whereas the post-test zero/span are going to be different as some drift is expected. Furthermore, if the test duration exceeds more than one hour, the in-use emissions measurement regulations require the analyzers to be zeroed for every hour after recording the post-zero response after every hour.

The reference data-set is designed to span over an eight hour shift day, therefore it includes user defined zero drift values for every one hour and for each analyzer. It also includes the reference zero and span values along with pre- and post-test zero/span values recorded in the beginning of zeroth and the end of eighth hour of the test. The reference span value is set to be 10% higher than the set maximum value of emissions measurement for each analyzer, while reference zero is set at zero. An illustration of the measured and analyzer drift corrected dry emissions concentrations time trace for the first hour is shown in Figure 18. The measured emissions concentrations are given by the flowing equation:

$$x_{conc\_dry} = \left(Ampx_{conc\_dry} \times \sin t\right) + Avgx_{conc\_dry}$$ **Eq. (96)**

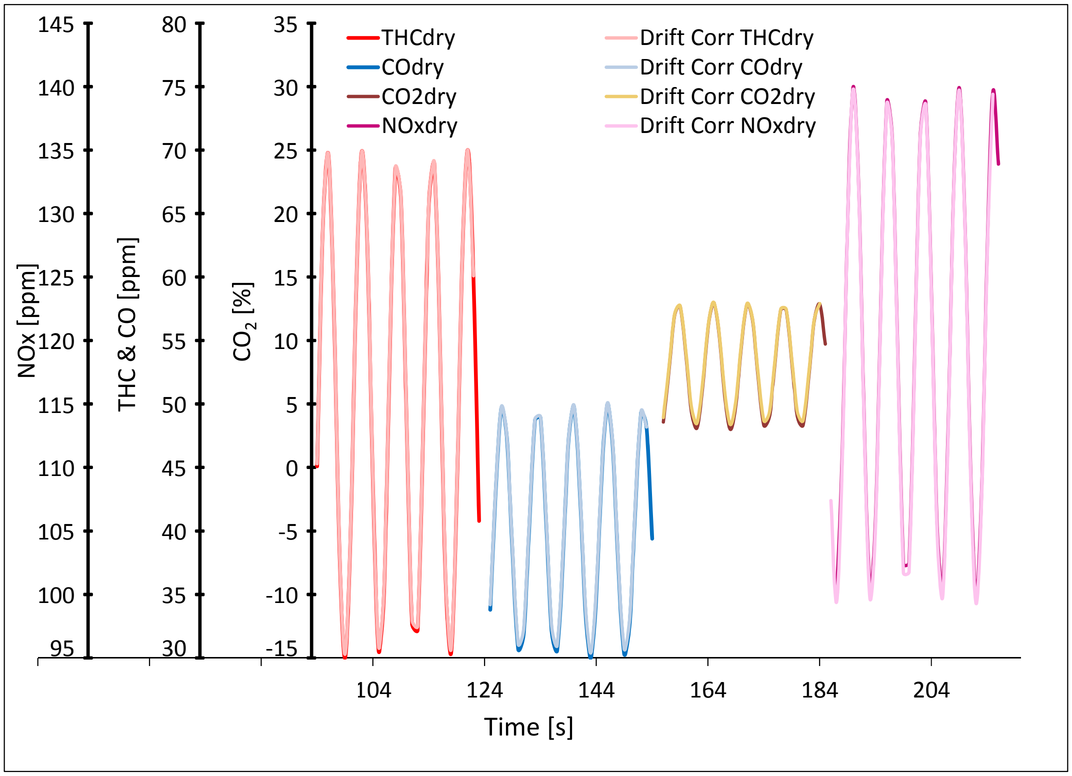


Figure 18: Time Trace of Measured and Analyzer Drift Corrected Emissions Concentrations

The amplitude and average values used for the measured dry emissions concentrations are given in Table 17. Note that the parameters used to define the emissions concentrations can be changed over each hour of the test or within the hour leading to pass/failure of a NTE event.

Table 17: Parameters of Exhaust Emissions Concentrations

x_{conc_dry}	$Ampx_{conc\_dry}$	$Avgx_{conc\_dry}$	$Avgx_{conc\_dry}$
THC [ppmC]	20	50	70
CO [ppm]	10	40	50
CO_2 [%]	5	8	13
NOx [ppm]	20	120	140

The zero/span drift checks parameters along with zero drift values for each analyzer over an interval of one hour used in correcting the measured emissions concentrations for drift is shown in Table 18 and Table 19.

From the zero drift data at the end of the first hour, it is clear that all other analyzers save for the NOx analyzer have drifted in the negative direction causing the drift corrected emissions concentrations, shown in a lighter shade of the raw emissions concentrations in Figure 13, to be higher than the measurement concentrations. The drift corrected concentration, calculated in accordance with CFR 40 Part 1065, will be compared to the value resulting from commercial in-use emissions data post-processor.

Table 18: Zero/Span Drift Check Parameters of Emissions Analyzers

x_{conc_dry}	z_ck_BT	span_ck_BT	z_ck_AT	span_ck_AT	ref_zero	ref_span
THC [ppmC]	0	77	-1	70	0	77
CO [ppm]	0	55	-2	53	0	55
CO_2 [%]	0	14	-0.11	13.89	0	14
NOx [ppm]	0	154	4	158	0	154

Table 19: Zero Drift Value of Different Analyzers at the End of Each Hour

Hour	$THC_{z\_ck\_perh}$	$CO_{z\_ck\_perh}$	$CO_{2z\_ck\_perh}$	$NOx_{z\_ck\_perh}$
[ ]	[ppmC]	[ppm]	[%]	[ppm]
1	-1	-2	-1	4

5.3.4 Validation of Dry-to-Wet Compensation of Emissions Concentrations Measured in Dry Mode.

The dry-to-wet compensation of measured emissions concentrations that are time aligned and drift-corrected are performed in several ways as discussed in section 3.3. The data shown in Figure 19 is corrected for dry-to-wet compensation using the iterative method discussed in section 3.7 as per CFR 40 part 1065.655. From the illustration shown in Figure 19, it can be observed that drift-corrected wet concentrations are lower than measured dry concentrations in agreement to the fact that the total volume increases when the fraction of water is considered. Also, the trace of dry-to-wet compensation factor k_w, which is a function of the fraction of water present in the exhaust due to combustion, is out of phase with measured concentrations signifying that the higher fraction of water in exhaust will reduce the measured dry concentration of emissions.

The drift-corrected and dry-to-wet compensated emissions concentrations resulting from the given reference dataset by using the method described in section will be compared with values that are produced from commercial PEMS post-processing software for the same reference dataset if they are available.

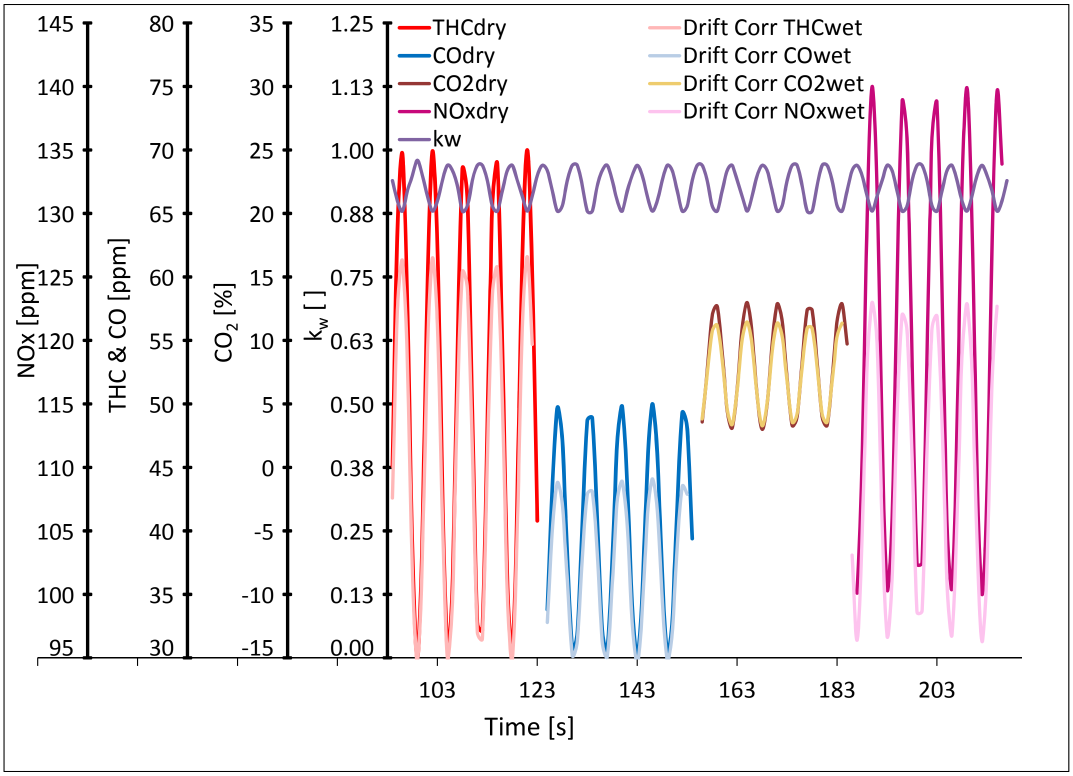


Figure 19: Time Trace of Dry and Drift Corrected & Dry-to-Wet Compensated Emissions Concentrations Along with Dry-to-Wet Compensation Factor k_w

5.3.5 Validation of NOx Emission Corrections Due to Variation in Intake Air Humidity.

Measured NOx emissions are corrected for ambient humidity as it has been found that that higher the intake air humidity, lower the NOx is emitted by the engine. Therefore, in order to normalize the measured emissions for different intake air conditions with varying humidity values, the measured and dry-to-wet compensated NOx values are corrected with a factor known as k_h as discussed section 3.6. Figure 20 illustrates the measured dry concentrations of NOx, drift corrected NOx, dry-to-wet compensated concentrations of NOx, and humidity corrected NOx concentrations along with variation in intake air humidity and the associated humidity correction factor k_h.

It should be noted that for in-use emissions measurement, the NOx concentrations are corrected to 10.71 and 7.14 g of H_2O/kg dry air when the measured intake air humidity is higher or lower than the specified values. It can be observed in Figure 20 that the value of k_h is greater than one when the intake air humidity is above 10.71 g/kg dry air in order to compensate for measured lower NOx emissions. Similarly, the k_h value is lower than one when intake air humidity is below 7.14 g/kg dry air to compensate for measured higher NOx concentrations. Furthermore, the value of k_h is set to one for intake air humidity varying between 10.71 to 7.14 g/kg dry air. The commercial PEMS data post-processing software employs different methods to correct measured NOx emissions for intake air humidity as discussed in section 3.6. The results from commercial PEMS post-processors will be compared with the expected humidity corrected NOx concentrations calculated in accordance with CFR 40 part 1065 for the given reference dataset.

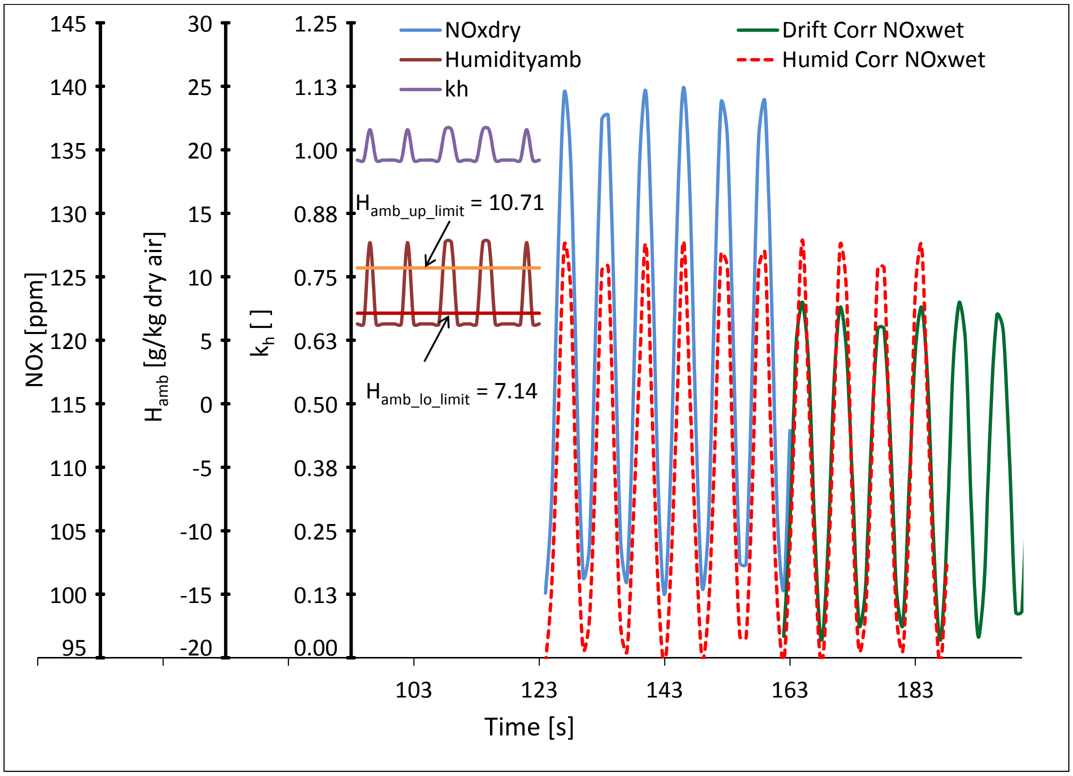


Figure 20: Time Trace of Dry, Drift Corrected Wet and Intake Air Humidity Corrected NOx Concentration Along with Ambient Humidity and Humidity Correction Factor k_h

5.3.6 Validation of Method Used to Address Negative Emissions Concentrations

In order to verify the method used to address negative emissions concentrations, a one hour long emissions reference dataset is developed as a subset of the eight hour long reference dataset. In this hour long dataset, the measured raw emissions concentrations are allowed to vary between a positive and negative range with an average value equal to zero, as shown in Figure 21. These raw emissions concentrations are corrected for drift and then filtered for negative values by setting the resulting negative concentration to zero as per in-use emissions regulations [89] and illustrated in Figure 21, which is subjected to further manipulations as usual to obtain the mass rates of emissions. The commercial PEMS post-processing software should be capable of filtering the negative emissions concentrations after drift corrections as shown in Figure 16, if the data reduction code is designed as per in-use emissions data reduction regulations.

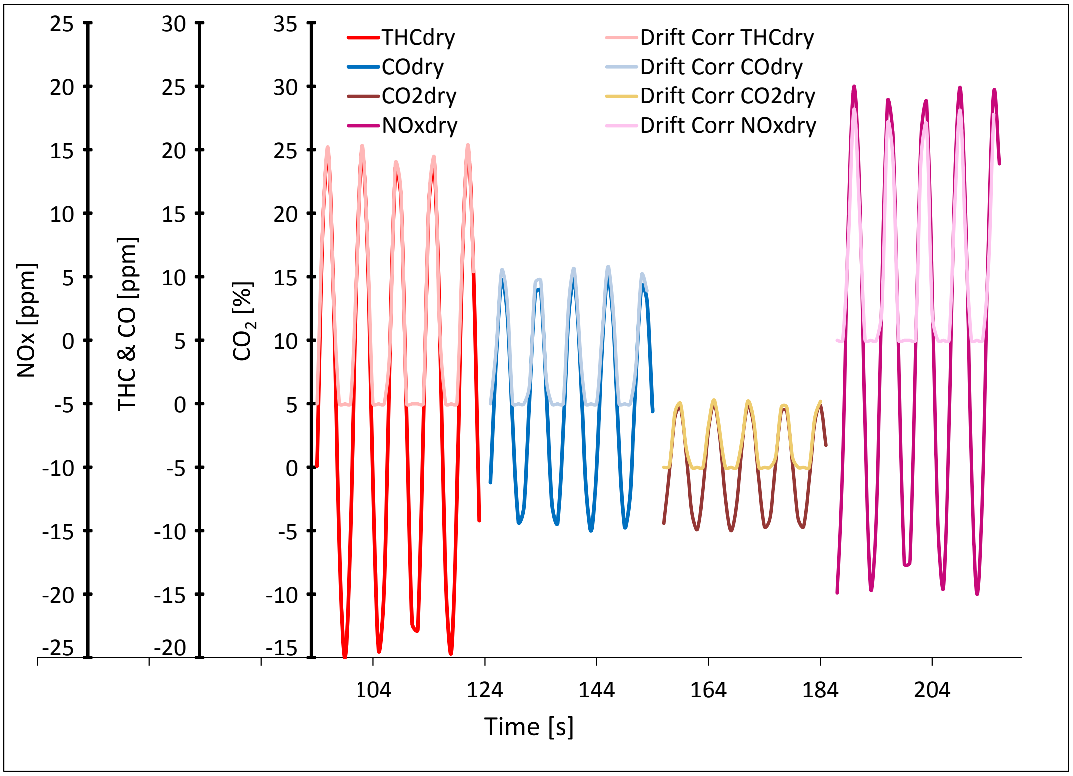


Figure 21: Time Trace of Measured Emissions Concentrations with Negative Values and Drift Corrected Concentrations After Filtering Negative Values

The validation of the commercial PEMS in-use emissions post-processing software is conducted with just a hour long dataset which consists of negative concentration values separately instead of as a part of 8 hour long master reference dataset.

5.3.7 Validation of Down Sampling Emissions Measurement Data

The validation of emissions data down sampling is verified using a one hour long reference dataset, which is a subset of the eight hour long master reference dataset. This hour long reference dataset is designed in such a way that the measured engine operating parameters, emissions concentrations, exhaust flow values, and ambient conditions are allowed to vary about a mean value sinusoidally so that when the data is down sampled to one hertz by averaging the high frequency data (eg. 10Hz) to one hertz, as recommended by in-use emissions regulations [90], it should result in the designed average value for each parameter. If any other method is employed to down sample the data as explained in section 4.3.7, it will result in different emissions results that can be observed in the final one hertz result produced by the commercial PEMS data post-processor.

5.3.8 Validation of Integrating Emissions Mass and Brake-Specific Work Over an NTE Event

In order to determine the brake-specific emissions over a NTE event, it should be noted that the total emissions mass must be divided by the total engine work measured over that NTE event and not just an integration of the brake-specific emissions determined at one hertz. The reference dataset is designed to evaluate the commercial PEMS post-processing software for the above error by knowing the brake-specific emissions for an NTE event quantified by the above methods *a priori*.

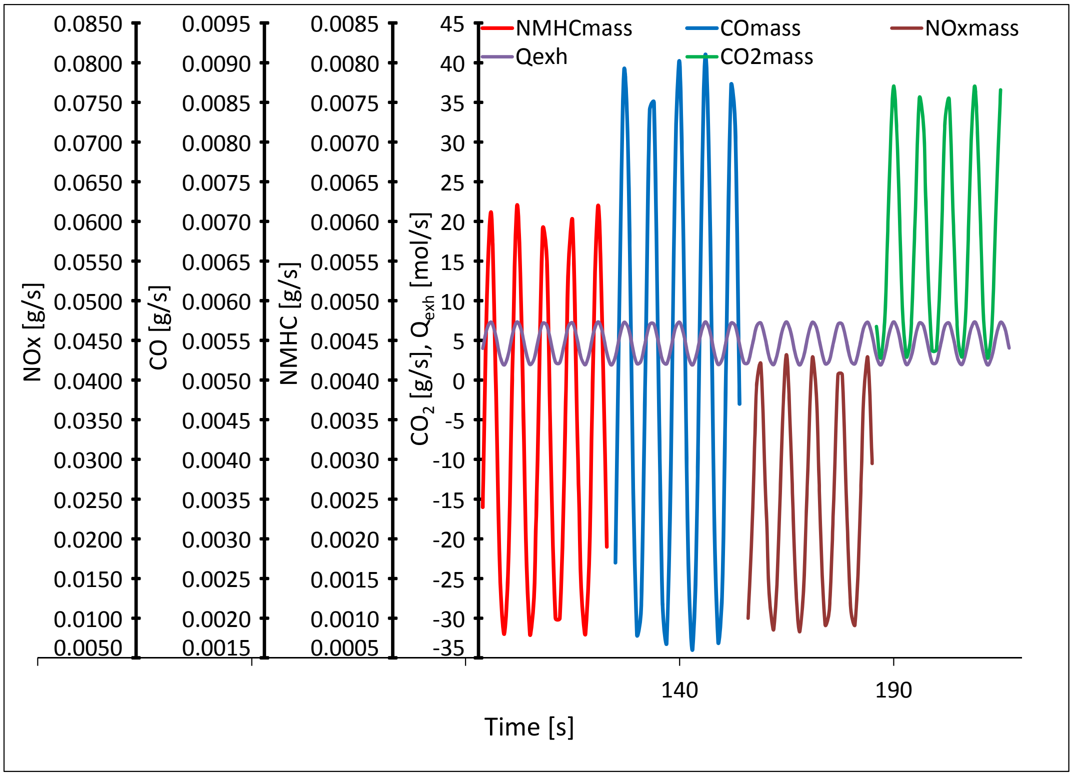


Figure 22: Time Trace of Emissions Rates and Exhaust Flow

The illustration in Figure 22 shows the range of emissions mass rates of different regulated emission constituents along with the molar exhaust flow.

5.4 Development of a Dataset to Verify In-Use Emissions Compliance

The development of a reference dataset to verify in-use emissions compliance is divided into three different datasets, which are supplementary to the original eight hour long reference dataset. The supplementary reference datasets are created by varying the last hour of the original reference dataset to meet or fail the criteria required to pass in-use emissions compliance. The in-use emissions compliance can be defined as a function given by:

$$Veh_{pass} = \begin{pmatrix} NTE\ Emissions\ Threshold \\ Time\ Weighted\ Vehicle\ Pass\ Ratio \\ Emissions\ Upper\ Limit\ for\ Valid\ NTE\ Events \end{pmatrix} \quad \textbf{Eq. (97)}$$

The reference dataset used to verify the above criteria is developed for a post-MY2010 engine whose NOx FTP standard is 0.2g/bhphr. The development of the dataset will be explained in terms of the master reference dataset that satisfies all the criteria for a heavy-duty diesel on-road vehicle to comply with in-use emissions compliance and the other two supplementary reference datasets that fail to meet in-use emissions compliance for time-weighted vehicle pass ratio and emissions upper limit criteria for valid NTE events.

5.4.1 Master Reference Dataset that Satisfies all In-Use Emissions Compliance Criteria

As discussed in section 5.2, the eight hour long master reference dataset engine operating points are fixed in such a way that it yields a total of 166 NTE events over a period of eight hours. Additionally, as discussed in section 5.3, the exhaust flow values and emissions concentrations of the regulated pollutants are fixed to result in brake-specific emissions for the above 166 NTE events to satisfy the in-use emissions threshold values. Note that the emissions threshold values for regulated emissions are calculated as they apply to post-MY2010 engines whose FTP standards along with NTE multipliers, accuracy margins, and compliance margins are used to arrive at the NTE threshold shown in Table 20.

Table 20: FTP Standard and NTE Emissions Threshold of Post-MY2010 Heavy-duty Diesel Engines.

Regulated Pollutant	MY2010 FTP Standards [g/bhp-hr]	NTE Multiplier	Accuracy Margin [g/bhp-hr]	Compliance Margin [g/bhp-hr]	NTE Threshold [g/bhp-hr]
NOx	0.20	1.5	0.15	0.1*	0.55
NMHC	0.14	1.5	0.01	n/a	0.22
CO	15.5	1.25	0.25	n/a	19.6
NOx+NMHC	0.34	1.5	0.16	0.1	0.77

** For odometer reading of less than 110,000 miles*

The master reference dataset should result in valid NTE events of a total duration of 275 minutes when post-processed in accordance to in-use emissions regulations. Additionally, the valid NTE events which fail to meet the emissions threshold satisfy the condition of emissions upper limit which is set at two times the emissions threshold or 2.0 g/bhp-hr NOx for engines certified at 0.20 g/bhp-hr NOx.

5.4.2 Supplementary Reference Dataset Used to Verify the Validation of Emissions Upper Limit for Valid NTE Events

The last hour of the master reference dataset is replaced by a supplementary hourly emissions dataset to verify the validation of emissions upper limit for valid NTE events. The emissions concentrations for this hour long dataset are adjusted such that the brake-specific emissions rate for the valid NTE events, which do not meet the in-use emissions threshold, will fail for the emissions upper limit. The emissions upper limit criteria for valid NTE events are set at two times the in-use emissions threshold values for MY2007 through MY2009 and 2.00 g/bhp-hr NOx limit for engines certified at the

MY2010 NOx emissions standard of 0.20 g/bhp-hr [95]. The vehicle is pronounced as compliant with in-use emissions regulations if it meets both the time-weighted vehicle pass ratio and upper limit of emissions for valid NTE events.

The emissions concentration parameters for the hour long supplementary dataset used to verify the validation of upper limit of emissions for valid NTE events is shown in Table 21. Note that the emissions concentrations are offset to higher concentrations for the last 1800 seconds in order to yield emissions results that satisfies vehicle pass ratio but fails for not meeting the upper limit criteria for NOx emissions.

5.4.3 Supplementary Reference Dataset Used to Verify the Validation of Time-Weighted Vehicle Pass Ratio

The commercial PEMS in-use emissions data post-processing software is validated for failure in identifying the vehicle that does not meet the vehicle pass ratio criteria by replacing the eighth hour data in the master reference dataset with a supplementary hour long dataset. The supplementary dataset is designed to fail the NTE emissions threshold values by fixing emissions concentration and exhaust flow values to result in brake-specific emissions of the valid NTE events to be greater than threshold values. The average emissions concentration and their range along with the exhaust flow are shown in Table 21.

Table 21: Exhaust Flow Parameters of Different Datasets

Exhaust Parameter	Master Dataset	Rfail Dataset	ULfail Dataset
ExhFlow_Avg [m^3/min]	12.5	12.5	12.5
CO_Avg [ppm]	40	80	80
CO_2_Avg [%]	8	8	8
THC_Avg [ppmC]	50	100	100
NOx_Avg [ppm]	120	2000	1000
Exhflow_Amp [m^3/min]	7.5	7.5	7.5
CO_Amp [ppm]	10	40	40
CO_2_Amp [%]	5	5	5
THC_Amp [ppmC]	20	50	50
NOx_Amp [ppm]	20	300	300

6 RESULTS AND DISCUSSION

6.1 Introduction

This chapter will discuss the difference between the expected and actual in-use emissions results, also known as NTE emissions, from emissions data post-processing software that are included with PEMS devices and from independent applications developed in-house for reducing in-use emissions data based on a reference input dataset. The reference dataset is synthesized to represent the possible scenarios that can be encountered during an actual in-use emissions test. The possible scenarios are developed based on the NTE emissions exclusions that are negotiated between EPA and EMA under the code of CFR 40 Part 86. Furthermore, the emissions results of the reference dataset are obtained based on emissions calculations as recommended by CFR 40 Part 86 and 1065 regulations so that the results are known *a priori* in order to compare with the actual emissions results obtained from commercial PEMS data post-processing software, as well as independent data post-processing applications. It should be noted that it has been a challenge to procure only the post-processing software without owning the respective PEMS device resulting in being unable to test such post-processing applications. Furthermore, one of the PEMS device manufacturers was not supportive in their post-processing software being evaluated independently using synthesized data. The manufacturer claims that such an exercise is not required as their device and post-processing software has evolved over several years into a mature product from customer feedback resulting in minimal to no errors in emissions measurement as well as NTE emissions calculations.

The available in-use emissions post-processing software will be tested using the reference dataset, which is developed as explained in previous chapters to execute specified NTE exclusion conditions, NTE emissions corrections and calculations, and the criteria used to determine pass/fail results of the vehicle based on the calculated NTE emissions. Therefore, results of the PEMS post-processing software will be discussed in the following three sections:

1. NTE event validation results
2. In-use emissions quantification results
3. In-use emissions compliance results

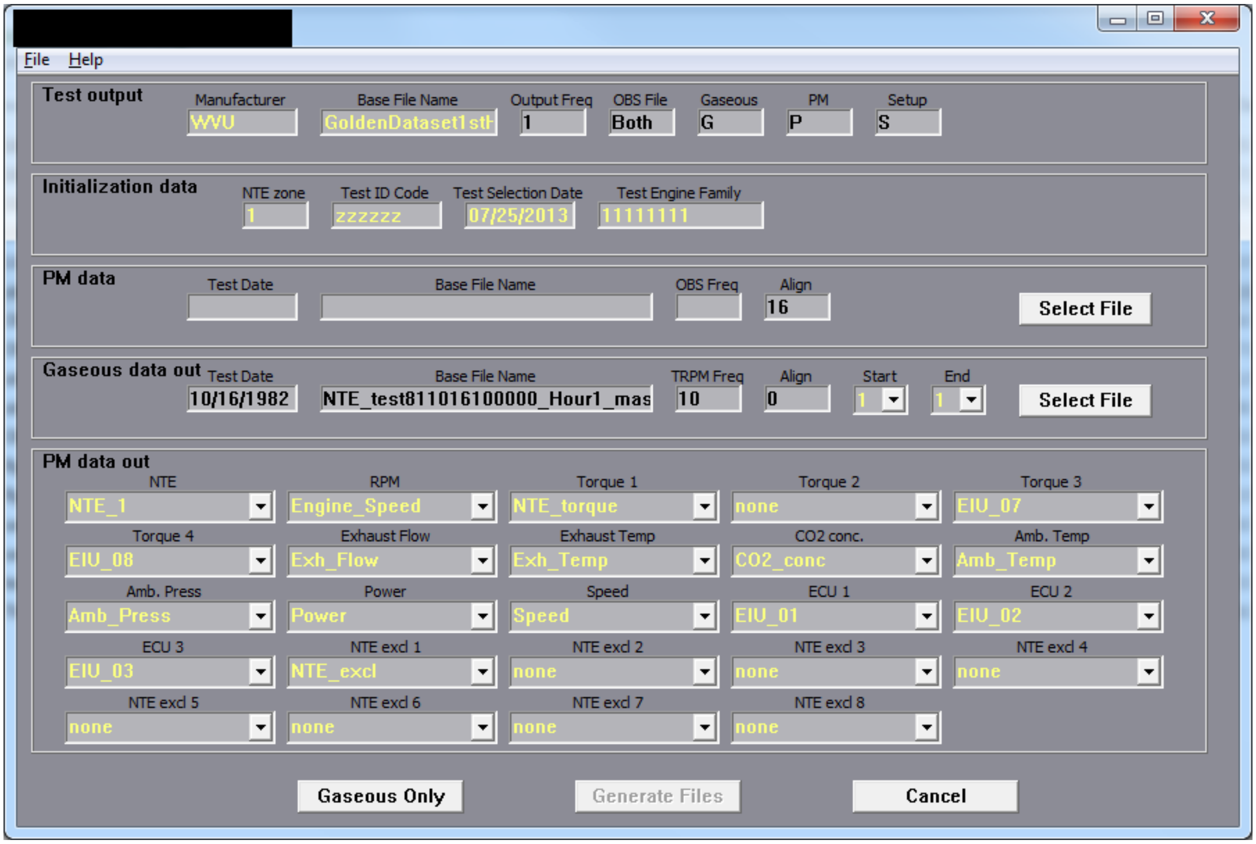
It should be noted that the PEMS data post-processing software will be evaluated for the above mentioned categories using an hour long data. Some of the NTE event validation criteria, however, require a minimum of eight hour long data. The summary section will also discuss the results produced by different post-processing software for the eight hour long reference dataset, which is the minimum time a vehicle is required to be tested for in-use emissions compliance, by comparing the actual emissions results with the expected results that are known *a priori*.

6.2 Description of In-Use Emissions Post-Processing Software

This section describes an overview of two commercial in-use emissions data post-processing software provided along with the PEMS device and an in-house post-processing software developed based on in-use emissions regulations, and the one hertz data that needs to be submitted to the EPA as per the heavy-duty in-use test data template [51]. The in-house post-processing software is developed based on the open source programming language Python.

6.2.1 PEMS A In-Use Emissions Post-Processing Software

The PEMS A processes in-use emissions data in two different stages, one while data is being acquired and the rest after completion of the test. The data acquisition software produces two different test files for every hour of the test; one of them consists of data that are not drift corrected and the other being drift corrected data. The data post-processing software consists of two different applications; one of them is used to produce one Hz of all required emissions data along with ambient conditions, engine operating conditions, which includes parameters used to determine NTE event exclusions along with their NTE exclusion limits. The user interface of the first post-processing application, known as PEMS A Data Analysis, is shown in Figure 23. The parameters that are mandated to be submitted along with NTE emissions compliance reports are given in reference [51]. The data used to populate different sections of the PEMS A data analysis application is provided through an initialization file called “PEMS A_DA.INI”. The PEMS A data analysis software uses both raw and drift corrected files produced by the data acquisition system along with “sample.txt” file to produce one Hz data required by EPA. The sample.txt file consists of all the equation used to manipulate the input file and produce the required data. The sample.txt file can be modified by the user giving the flexibility of updating the equations as prescribed by the CFR at the same time it can be leading to application of incorrect equations based on user interpretation of the regulations. This increases the burden felt by regulators to verify the equations being used to obtain the reported results.


[redacted]

Test output

Manufacturer: WVU
Base File Name: GoldenDataset1stH
Output Freq: 1
OBS File: Both
Gaseous: G
PM: P
Setup: S

Initialization data

NTE zone: 1
Test ID Code: zzzzzz
Test Selection Date: 07/25/2013
Test Engine Family: 11111111

PM data

Test Date:
Base File Name:
OBS Freq:
Align: 16

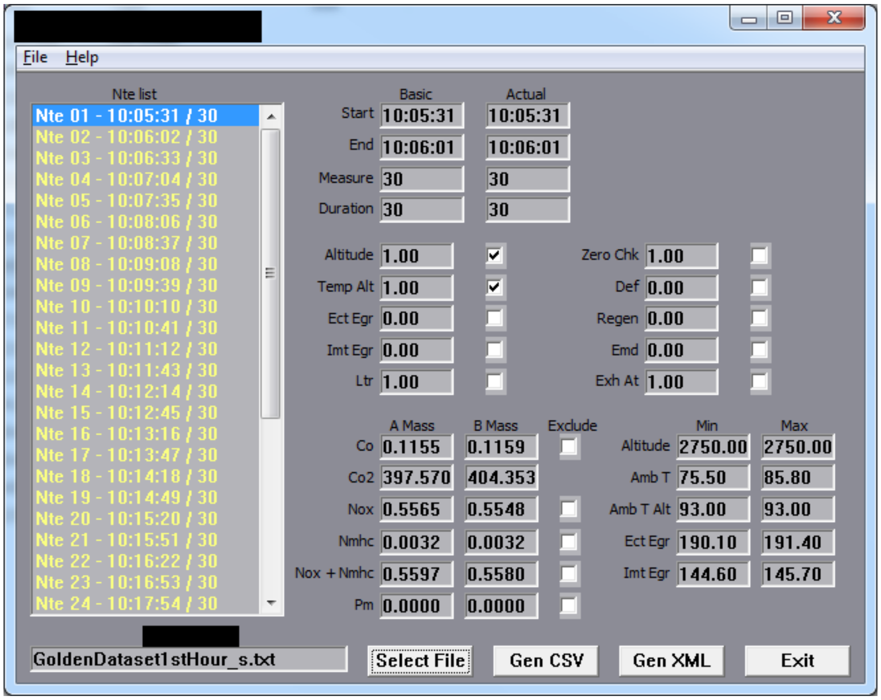
Gaseous data out

Test Date: 10/16/1982
Base File Name: NTE_test811016100000_Hour1_mas
TRPM Freq: 10
Align: 0
Start: 1
End: 1

PM data out

NTE: NTE_1
RPM: Engine_Speed
Torque 1: NTE_torque
Torque 2: none
Torque 3: EIU_07
Torque 4: EIU_08
Exhaust Flow: Exh_Flow
Exhaust Temp: Exh_Temp
CO2 conc.: CO2_conc
Amb. Temp: Amb_Temp
Amb. Press: Amb_Press
Power: Power
Speed: Speed
ECU 1: EIU_01
ECU 2: EIU_02
ECU 3: EIU_03
NTE excl 1: NTE_excl
NTE excl 2: none
NTE excl 3: none
NTE excl 4: none
NTE excl 5: none
NTE excl 6: none
NTE excl 7: none
NTE excl 8: none

Figure 23: User Interface of PEMS A Data Analysis Software


[redacted]

Nte list
- Nte 01 - 10:05:31 / 30
- Nte 02 - 10:06:02 / 30
- Nte 03 - 10:06:33 / 30
- Nte 04 - 10:07:04 / 30
- Nte 05 - 10:07:35 / 30
- Nte 06 - 10:08:06 / 30
- Nte 07 - 10:08:37 / 30
- Nte 08 - 10:09:08 / 30
- Nte 09 - 10:09:39 / 30
- Nte 10 - 10:10:10 / 30
- Nte 11 - 10:10:41 / 30
- Nte 12 - 10:11:12 / 30
- Nte 13 - 10:11:43 / 30
- Nte 14 - 10:12:14 / 30
- Nte 15 - 10:12:45 / 30
- Nte 16 - 10:13:16 / 30
- Nte 17 - 10:13:47 / 30
- Nte 18 - 10:14:18 / 30
- Nte 19 - 10:14:49 / 30
- Nte 20 - 10:15:20 / 30
- Nte 21 - 10:15:51 / 30
- Nte 22 - 10:16:22 / 30
- Nte 23 - 10:16:53 / 30
- Nte 24 - 10:17:54 / 30

	Basic	Actual
Start	10:05:31	10:05:31
End	10:06:01	10:06:01
Measure	30	30
Duration	30	30

Altitude	1.00	☑	Zero Chk	1.00	☐
Temp Alt	1.00	☑	Def	0.00	☐
Ect Egr	0.00	☐	Regen	0.00	☐
Imt Egr	0.00	☐	Emd	0.00	☐
Ltr	1.00	☐	Exh At	1.00	☐

	A Mass	B Mass	Exclude		Min	Max
Co	0.1155	0.1159	☐	Altitude	2750.00	2750.00
Co2	397.570	404.353		Amb T	75.50	85.80
Nox	0.5565	0.5548	☐	Amb T Alt	93.00	93.00
Nmhc	0.0032	0.0032	☐	Ect Egr	190.10	191.40
Nox + Nmhc	0.5597	0.5580	☐	Imt Egr	144.60	145.70
Pm	0.0000	0.0000	☐			

[redacted]

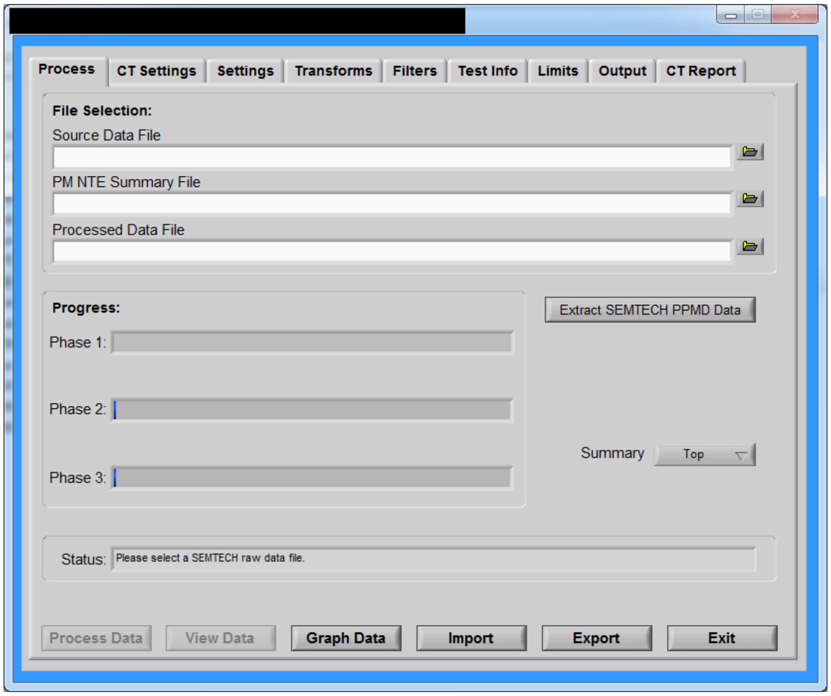
GoldenDataset1stHour_s.txt

Figure 24: User Interface of PEMS A XML Report Generating Software

The second post-processing application is the report generating software, known as the PEMS A XML report. The PEMS A XML report application makes use of the one Hz data file produced by PEMS A Data Analysis application along with maximum torque curve of the test engine, supplied through a file named LUG_TBL.csv to quantify the number of NTE events and their emissions. The user interface of the PEMS A XML report generating software is shown in Figure 24. The PEMS A report generating software lists all the NTE events based only on the minimum amount of time an engine should operate in the NTE zone. The user is allowed to apply different exclusions as required based on the engine technology, aftertreatment devices used to reduce emissions, the ambient conditions in which the vehicle is operating and other deficiencies and limited testing region exclusions as negotiated with the EPA.

6.2.2 PEMS B In-Use Emissions Post-Processing Software

The in-use emissions data collected using PEMS B is post-processed using stand-alone software, which has a tab-driven user interface providing flexibility to the user to choose different calculation methods in determining the brake-specific emissions as well as to choose different NTE exclusions as applicable to the test engine. The user interface of the Sensors post-processing software is shown in Figure 25. The compliance test (CT) “settings tab” allows the user to set emissions standards for different pollutants along with the NTE multiplier, accuracy and compliance margins. Under the CT setting tab, the exclusions tab allows the user to activate different exclusions as they are applied to the engine based on the respective emissions control strategies. The settings tab allows the user to set delay time for different analyzers to compensate for the delay in transportation of exhaust from the sampling plane to the analyzer. Note these are normally set to zero as the device compensates for the transportation delay during data acquisition and is used to override that value when there is any rectification to be made. The “calculation control section” under the setting tab allows the user to choose different calculation methods to determine the final brake-specific emissions. The maximum torque curve of the test engine is entered through the lug curve editor which shows the NTE zone speed and torque boundaries instantly. The lug curve editor is also used to input the engine manufacturer-negotiated limited testing region co-ordinates under the lug curve. The user interface of the “CT settings,” “Settings” and the “Lug Curve Editor” are shown in Figure 25 through Figure 28.



[redacted]

Source Data File

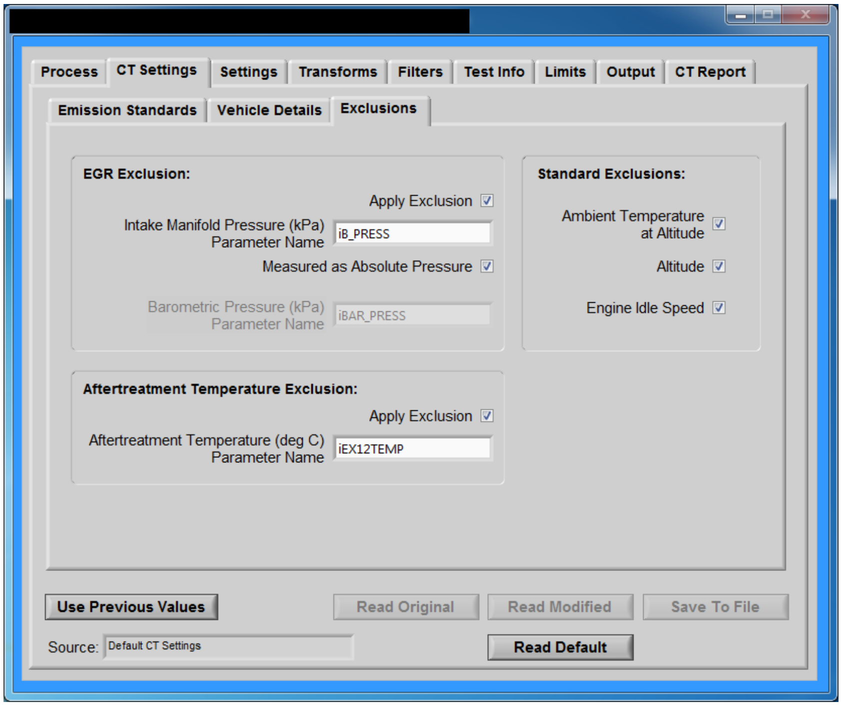
PM NTE Summary File

Processed Data File

Summary: Top

Status: Please select a SEMTECH raw data file.

Figure 25: User Interface of PEMS B Post-Processing Software



[redacted]

Apply Exclusion ☑

Intake Manifold Pressure (kPa) Parameter Name: iB_PRESS

Measured as Absolute Pressure ☑

Barometric Pressure (kPa) Parameter Name: iBAR_PRESS

Ambient Temperature at Altitude ☑

Altitude ☑

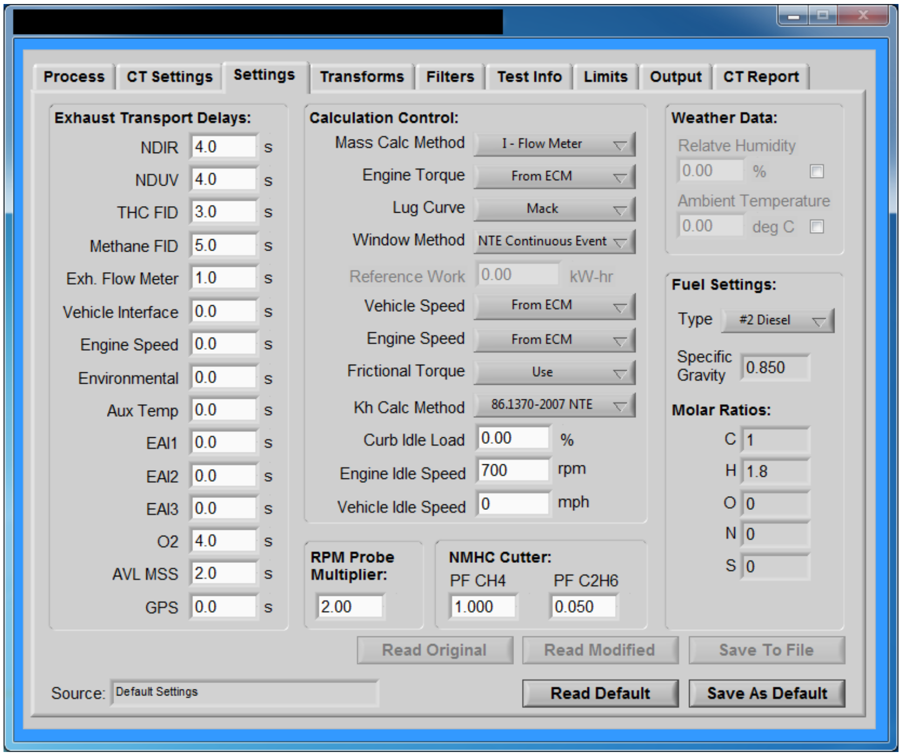
Engine Idle Speed ☑

Apply Exclusion ☑

Aftertreatment Temperature (deg C) Parameter Name: iEX12TEMP

Source: Default CT Settings

Figure 26: PEMS B Compliance Test Settings User Interface



Exhaust Transport Delays:

NDIR 4.0 s
NDUV 4.0 s
THC FID 3.0 s
Methane FID 5.0 s
Exh. Flow Meter 1.0 s
Vehicle Interface 0.0 s
Engine Speed 0.0 s
Environmental 0.0 s
Aux Temp 0.0 s
EAI1 0.0 s
EAI2 0.0 s
EAI3 0.0 s
O2 4.0 s
AVL MSS 2.0 s
GPS 0.0 s

Calculation Control:

Mass Calc Method I - Flow Meter
Engine Torque From ECM
Lug Curve Mack
Window Method NTE Continuous Event
Reference Work 0.00 kW-hr
Vehicle Speed From ECM
Engine Speed From ECM
Frictional Torque Use
Kh Calc Method 86.1370-2007 NTE
Curb Idle Load 0.00 %
Engine Idle Speed 700 rpm
Vehicle Idle Speed 0 mph

RPM Probe Multiplier: 2.00

NMHC Cutter:

PF CH4 1.000
PF C2H6 0.050

Weather Data:

Relatve Humidity 0.00 % ☐
Ambient Temperature 0.00 deg C ☐

Fuel Settings:

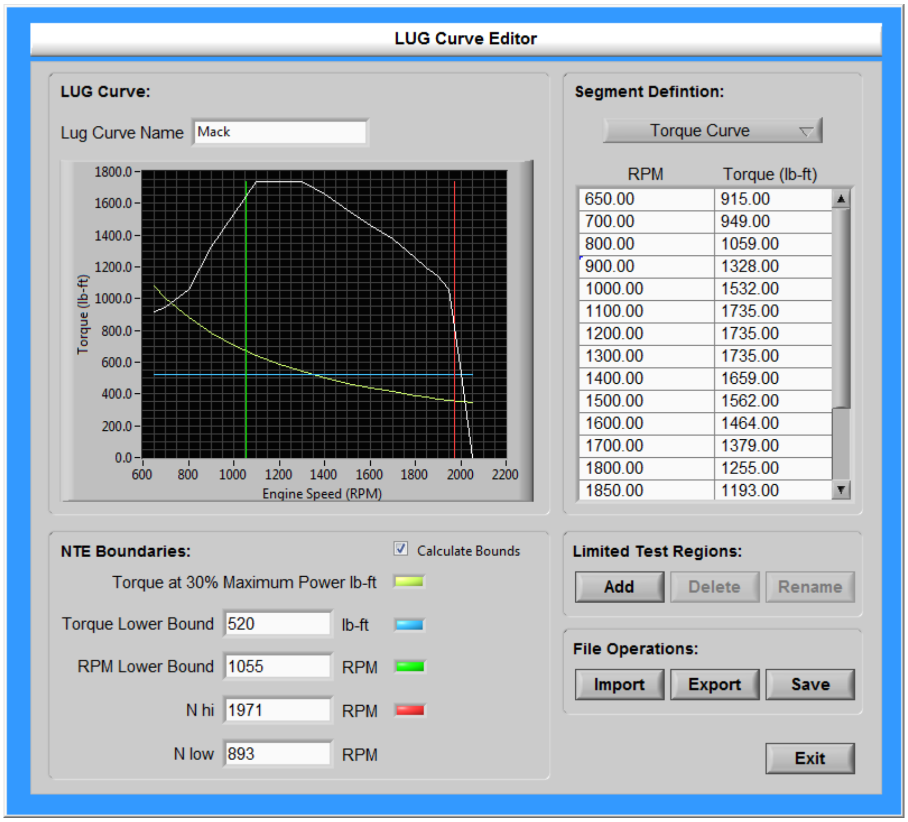
Type #2 Diesel
Specific Gravity 0.850

Molar Ratios:

C 1
H 1.8
O 0
N 0
S 0

Source: Default Settings

Figure 27: PEMS B Settings User Interface



LUG Curve:

Lug Curve Name Mack

Segment Defintion: Torque Curve

RPM	Torque (lb-ft)
650.00	915.00
700.00	949.00
800.00	1059.00
900.00	1328.00
1000.00	1532.00
1100.00	1735.00
1200.00	1735.00
1300.00	1735.00
1400.00	1659.00
1500.00	1562.00
1600.00	1464.00
1700.00	1379.00
1800.00	1255.00
1850.00	1193.00

NTE Boundaries: ☑ Calculate Bounds

Torque at 30% Maximum Power lb-ft 🟨
Torque Lower Bound 520 lb-ft 🟦
RPM Lower Bound 1055 RPM 🟩
N hi 1971 RPM 🟥
N low 893 RPM

Limited Test Regions:

File Operations:

Figure 28: PEMS B Lug Curve Editor User Interface

The post-processing software also includes in-use emissions compliance report generating functionality where the user can enter the information required as per HDIUT data reporting template given in the reference [51].

6.2.3 In-House In-Use Emissions Post-Processing Software

The in-house emissions data reduction software is developed using an open source coding language known as Python. The software consists of a user interface which plots the time trace of all the data channels acquired during data acquisition as shown in the Figure 29. The data reduction software has the functionality reducing in-use emissions data independent of the data acquisition system, but the version that is used here is built based upon PEMS A data structure. Therefore, the input data for in-house software is provided in the PEMS A data format. The software has been built to be stand-alone reduction code that can be used to reduce data acquired in different setting, from test cell to locomotive testing, complying with different emissions regulations.

The software produces a spreadsheet of the calculated channels and the brake-specific emissions results for all the valid NTE events using the export function in addition to the NTE emissions results in PDF format.

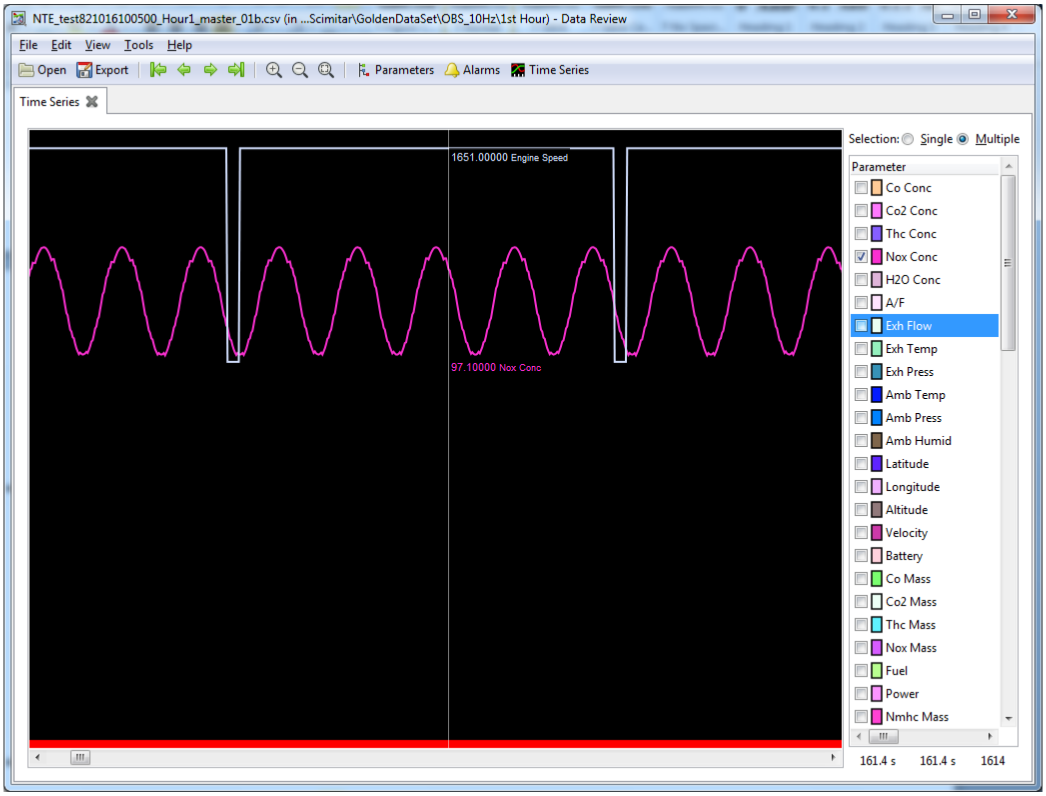
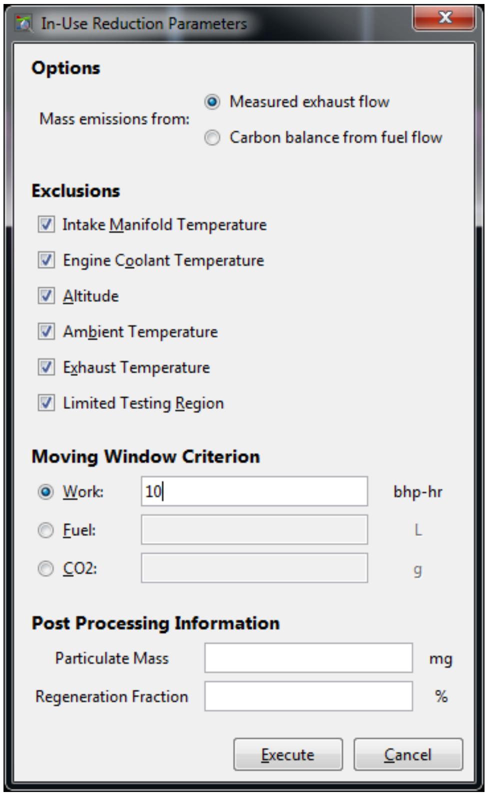


Figure 29: Input Data User Interface of In-House Data Reduction Software


In-Use Reduction Parameters

Options

Mass emissions from: ● Measured exhaust flow ○ Carbon balance from fuel flow

Exclusions

☑ Intake Manifold Temperature
☑ Engine Coolant Temperature
☑ Altitude
☑ Ambient Temperature
☑ Exhaust Temperature
☑ Limited Testing Region

Moving Window Criterion

● Work: 10 bhp-hr
○ Fuel: L
○ CO2: g

Post Processing Information

Particulate Mass mg
Regeneration Fraction %

Figure 30: User Interface to Choose In-Use Emissions Exclusions

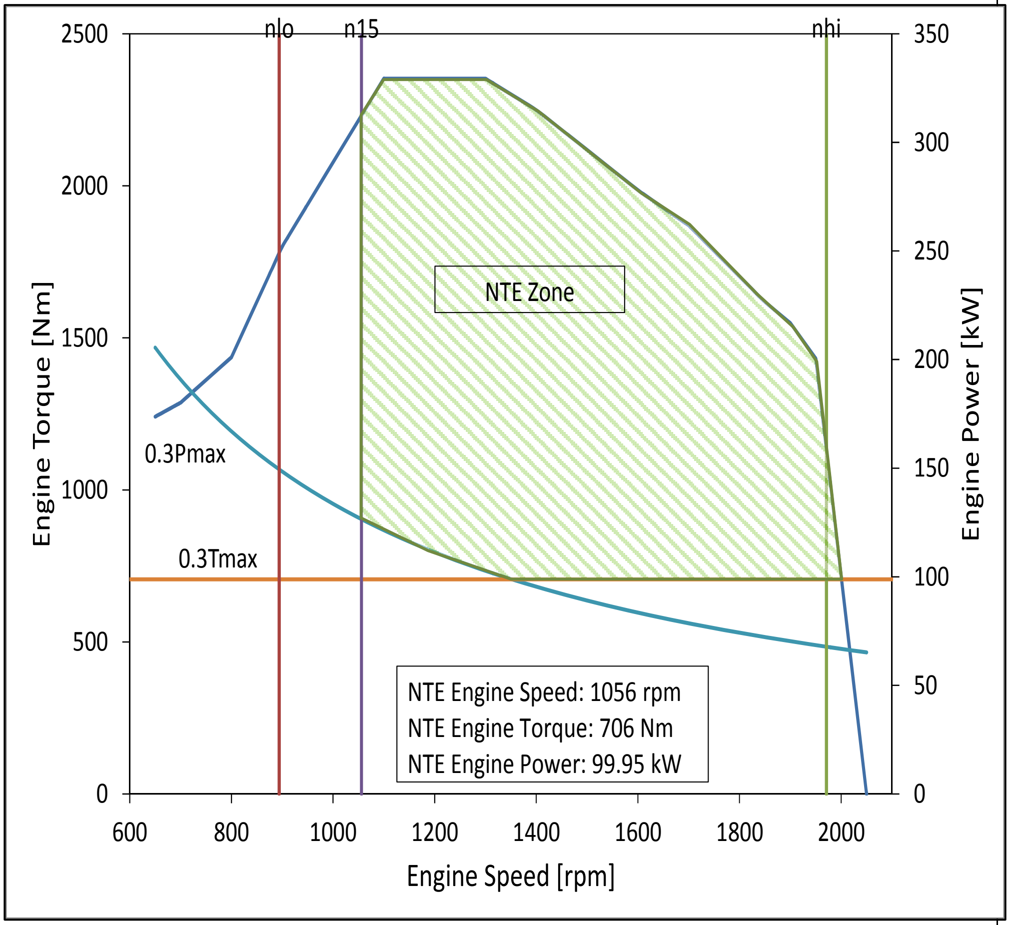
6.3 NTE Event Validation Results

As described in section 5.2, the reference dataset developed to verify the accuracy in qualifying an engine operation into an NTE event, or lack thereof, is applied to test different PEMS post-processing software, which includes commercial as well as in-house applications in this section. The dataset is grouped to test each exclusion parameter such that it meets as well as fails the boundary condition along with an additional test condition in which the variable being tested is in the middle of the domain satisfying the robustness test criteria for software testing. It should be noted that an hour long reference dataset used for NTE event validation consists of all the parameters required by EPA that have to be reported along with in-use emissions results, but the software test findings are discussed in three aforementioned sub-sections for the purpose of clarity.

6.3.1 NTE Zone Definition Results

As described in earlier chapters, the NTE zone is defined by three parameters namely engine speed, torque and power. An engine is considered to be operating in the NTE zone provided the engine speed is greater than NTE engine speed, which is 15% of the ESC speed, engine torque is greater or equal to NTE engine torque, which 30% of the peak engine torque, and the engine brake power is greater or equal to 30% of maximum rated power. Therefore, for the maximum torque curve being used to synthesize the reference dataset, the NTE zone definition, along with the maximum torque values, are shown in the Table 22.

Table 22: Definition of NTE Zone for the Given Maximum Engine Torque Curve

Speed	Torque	
[rpm]	[Nm]	
650	1240.74	
700	1286.84	
800	1436.00	
900	1800.77	
1000	2077.39	
1100	2352.66	
1200	2352.66	
1300	2352.66	
1400	2249.60	
1500	2118.07	
1600	1985.18	
1700	1869.92	
1800	1701.78	
1850	1617.71	
1900	1548.55	
1950	1431.94	
2000	715.97	
2050	0	

The reference dataset based upon the above engine map, which also includes all the other required data channels such as the ambient temperature, and pressure, emissions concentrations, exhaust flow values, engine ECU information required to exclude certain NTE points as well as determine brake-specific NTE emissions is used as an input to test four different NTE emissions post-processing software. The software includes two commercially available packages as part of the PEMS devices namely PEMS A, and PEMS B along with a package developed in-house at WVU based on the open programming language Python. Since some of the post-processing software does not report the engine operating points that defines the NTE zone, results will be discussed based on the number of NTE events produced against the expected number of events while testing each engine operating parameter exclusively for conditions that meet or fail the criteria to be an NTE event.

6.3.2 NTE Engine Speed Validation Results

As discussed in section 5.2.1, the reference dataset consists of the first ninety-three seconds of engine operation data which comprises of first thirty seconds of steady-state operation at an engine speed being less than NTE engine speed by one rpm. This operation is followed by another thirty seconds of steady-state operation where the engine speed is equal to NTE engine speed, and in the final thirty seconds the engine speed is maintained at a value greater than the NTE engine speed by one rpm. Note that each thirty second steady-state operation is followed by one second of engine operation where the engine speed is less than NTE engine speed by one rpm. This is included to separate the events based on minimum duration of NTE event, which is thirty seconds. The results illustrated in Table 23, show that PEMS A post-processing software resulted in two NTE events; PEMS B produced one NTE event, and the in-house post-processing software resulted in two NTE events. The PEMS A post-processor considers the engine operation as an NTE operating point when the engine speed is equal to n_{15} leading to an error by counting an extra NTE event. Contrary to the above explanation the PEMS A post-processor could have resulted with n_{15} equal to 1055 rpm and counting the two NTE events where engine speed is greater than 1055 rpm since PEMS A post-processor does not list the NTE zone boundary values.

The PEMS B data reduction software definition of NTE speed is lower than the expected value by one rpm and also the definition of engine speed exclusion is such that the operation at engine speed equal to n_{15} is considered as valid NTE point hence counting the entire first ninety-three seconds of data as one NTE event.

The in-house data reduction software also resulted with lower limit of engine speed to be one rpm lower than the expected value. However, the condition used to qualify an event based on engine speed was proven to be correct as it counted the duration of engine operation only when the engine speed is greater than n_{15} as valid NTE event.

Table 23: NTE Engine Speed Validation Results

Test Condition	Event Start	Event End	Engine Speed	Expected Results	PEMS A	PEMS B	In-house
NTE Engine Speed > n_{15}	1	30	1055	Not NTE event	TRUE	FALSE	TRUE
	32	61	1056	Not NTE event	FALSE	FALSE	FALSE
n_{15} = 1056 rpm	63	92	1057	NTE event	TRUE	TRUE	TRUE
Total NTE events				1	2	1	2

6.3.3 NTE Engine Torque Validation Results

The next set of ninety-three seconds that follows NTE engine speed validation data is arranged such that a thirty second-long, continuous event would result in an NTE event if not for the engine torque being lower than 30% of maximum torque. A condition required for a thirty second-long, continuous event to result in an NTE event. Each thirty seconds event is terminated using one second of engine operation data with engine speed being lower than n_{15} speed.

Table 24: NTE Engine Torque Validation Results

Test Condition	Event Start	Event End	Engine Torque	Expected Results	PEMS A	PEMS B	In-house
NTE Engine Torque ≥ $0.3T_{max}$ $0.3T_{max}$ = 706 Nm	94	123	704	Not NTE event	FALSE	TRUE	TRUE
	125	154	706	NTE event	TRUE	TRUE	TRUE
	156	185	709	NTE event	TRUE	TRUE*	TRUE
Total NTE events				2	3	2	2

** indicates the length of NTE duration does not match*

The results shown in Table 24 confirm that the NTE engine torque of 706 Nm is agreed by two of the post-processing software resulting in two NTE events except for PEMS A. The two NTE events are produced when the broadcasted or measured engine torque is equal to or greater than NTE engine torque.

The PEMS B data reduction software clearly identifies the value of the torque and validates against the NTE torque limits, but the last event where the engine torque is greater than the limit by 3 Nm it counts one extra second and makes it a 31 second-long event. This is because the PEMS B data acquisition system records the signal from different analytical devices/sensors as and when they are received resulting in inconsistent time stamps at the resolution of milliseconds scale. The post-processing software further fixes a consistent millisecond resolution while producing the one Hz output, note that this can range anywhere between 0 to 999 milliseconds. Therefore, based on the time stamp of recorded signal and the output time stamp, the values are interpolated linearly producing the results observed above. Note that the reference dataset is developed with one second resolution with an interval of integer seconds, but while producing the PEMS B output file an actual file produced by the PEMS B data acquisitions system is modified by inserting the reference dataset values to their respective variable names at the native time stamp.

6.3.4 NTE Engine Power Validation Results

The values shown in the Table 25 illustrate results of the ninety-three second, continuous engine operation data used to validate thirty seconds-long, steady-state operation to be a NTE event based on engine brake power. The engine brake power must be greater than or equal to 30% of maximum engine power for thirty seconds or long for an operation to be considered to be an NTE event. The results indicate that all the data post-processing software results in correct number of events based on the above condition.

Note that the engine power is a function of engine speed and torque. Since engine torque is broadcasted as a percentage value of the reference torque value whose resolution is limited to one decimal place as mandated by the heavy-duty in-use emissions test data submission requirements, it will be impossible for synthesizing both engine torque and power to be exactly equal to 30% of the maximum torque and power using a maximum torque curve of a production engine.

Table 25: NTE Engine Power Validation Results

Test Condition	Event Start	Event End	Engine Power	Expected Results	PEMS A	PEMS B	In-house
NTE Engine Power ≥ 0.3Pmax 0.3Pmax=99.95 kW	187	216	99.73	Not NTE event	FALSE	TRUE	TRUE
	218	247	100.11	NTE event	TRUE	TRUE	TRUE
	249	278	100.36	NTE event	TRUE	FALSE	TRUE
Total NTE events				2	3	1	2

Results show that PEMS A post-processing software definition of NTE zone power boundary is different from the expected value leading to count a non-NTE event when the engine power is lower than 30% of the maximum power. The results of PEMS B agree with the NTE zone power, but the length of NTE events does not match with the expected result because of the variation in the time stamp of the acquired data. In-house data post-processor results in exactly two NTE events of expected duration and at the expected point in time.

6.3.5 NTE Test Altitude Validation Results

As per NTE in-use emissions regulations when the vehicle is operating at an altitude of greater than 5,500 ft, then any NTE event or engine operation in the NTE zone are excluded from emissions compliance due to the fact that the engine is operating in protection mode because of reduced density of intake air at high altitudes. The limit of 5,500 ft was negotiated between EMA and EPA for in-use emission regulation. The NTE altitude validation test results illustrated in Table 26 show that both PEMS A and in-house post-processing software produces two NTE events when the test altitude is equal to less than 5,500 ft. The PEMS B data reduction software does not count the event to be an NTE event if the test altitude is equal to 5,500 ft hence producing only one event. Furthermore, the time stamp of the events does not match with that of the expected results because of un-even time stamp interval of the input dataset.

Table 26: NTE Test Altitude Validation Results

Test Condition	Event Start	Event End	Test Alt.	Expected Results	PEMS A	PEMS B	In-house
NTE Test Altitude ≤ 5,500 ft	280	309	5,501	Not NTE event	TRUE	TRUE	TRUE
	311	340	5,500	NTE event	TRUE	FALSE	TRUE
	342	371	5,499	NTE event	TRUE	TRUE	TRUE
Total NTE events				2	2	1	2

6.3.6 NTE Ambient Temperature Validation Results

An NTE engine operating point, or an NTE event, is excluded if the ambient temperature in which the vehicle is operated is greater than a certain value, which is given as a function of the altitude at which the vehicle is tested. Hence the reference dataset from 373 seconds to 465 seconds is set to test the result of the post-processing software for ambient temperature being greater, equal and lower than the limit, respectively. Note that the limit is set based on the test altitude of 2,750 ft. The test results illustrated in Table 27 show that all post-processing applications agree with the expected number of NTE events and for the aforementioned conditions except for PEMS B because the variables used for validating the conditions are not produced in the output file.

Table 27: NTE Ambient Temperature Validation Results

Test Condition	Event Start	Event End	Ambient Temp.	Expected Results	PEMS A	PEMS B	In-house
NTE Amb. Temp. ≤ $T_{amb-alt} = -0.00254 \cdot (Alt) + 100$ 93 °F	373	402	94	Not NTE event	TRUE	Not Tested	TRUE
	404	433	93	NTE event	TRUE		TRUE
	435	464	92	NTE event	TRUE		TRUE
Total NTE events				2	2	NT	2

6.3.7 NTE Engine Coolant Temperature Validation Results

The NTE exclusion conditions applied for cold operating conditions of the engine is tested followed by the ambient condition exclusions. The cold operating conditions are represented by engine coolant and intake air manifold temperatures. The limit for both temperatures is defined as a function of intake air manifold pressure. An event, or NTE operating point, is excluded if the measured or ECU broadcasted engine coolant temperature is less than or equal to temperature set based on the intake manifold pressure. Furthermore, the aforementioned exclusion applies only for engines that are equipped with an EGR system to meet the emissions standards. Note that the engine coolant temperatures are set such that it is exactly one degree F lower, exactly equal to the limit and a degree F higher than the limit respectively to result in one NTE event. The intake manifold pressure is allowed to vary sinusoidally between 490 and 500 kPa absolute. The results from different post-processing software are illustrated in Table 28.

The results from PEMS A post-processing software are complimentary to the expected values concluding a non-NTE event to be an NTE event and vice versa. Note that the PEMS A post-processing software provides the user an option to turn the exclusions ON/OFF independently. Therefore, if the ECT exclusion were to be turned ON for the entire test it would have resulted with one NTE event over an hour long reference dataset when engine coolant temperature is lower than the ECT limit.

Table 28: NTE Engine Coolant Temperature Validation Results

Test Condition	Event Start	Event End	ECT	Expected Results	PEMS A	PEMS B	In-house
NTE ECT > $ECT_{EGR} = 12.853 \cdot (IMP_{abs}) + 127.11$ °F	466	495	ECT_{EGR} - 1	Not NTE event	FALSE	FALSE	TRUE
	497	526	ECT_{EGR}	Not NTE event	FALSE	FALSE	TRUE
	528	557	ECT_{EGR}+ 1	NTE event	FALSE	FALSE	TRUE
Total NTE events				1	2	0	1

PEMS B data reduction software resulted in zero NTE events when the ECT exclusion was turned on. It was difficult to validate the results of the post-processing software because the output did not include the engine coolant temperature limit against which the input ECT values are compared to determine the validity of an NTE event. The in-house post-processing software was able to identify the NTE events based on the ECT exclusions.

6.3.8 NTE Intake Manifold Temperature Validation Results

The intake manifold temperature exclusion for EGR-equipped engines is tested following the engine coolant temperature validation. The dataset is set such that the first thirty seconds of data represents the IMT values broadcasted by engine ECU is lower than the IMT_{EGR} limit by one degree F, which is a function of absolute intake manifold pressure. This event is followed by another thirty second event where the IMT is equal to IMT_{EGR}, followed by another thirty seconds event with IMT greater than IMT_{EGR} by one degree F. Note that each thirty second event is separated by a one second data point representing non-NTE zone engine operation. The test results are illustrated in Table 29 showing that PEMS A post-processing software results are complimentary to the expected outcome for the given dataset. The PEMS B output was similar to ECT validation results resulting in zero NTE events when intake IMT exclusion was turned on. The in-house post-processing software was able to identify the IMT exclusions and produce one NTE event accordingly.

Table 29: NTE Intake Manifold Temperature Validation Results

Test Condition	Event Start	Event End	IMT	Expected Results	PEMS A	PEMS B	In-house
NTE IMT > $IMT_{EGR} = 11.428 \cdot (IMP_{abs}) + 88.571$ °F	559	588	IMT_{EGR} - 1	Not NTE event	FALSE	FALSE	TRUE
	590	619	IMT_{EGR}	Not NTE event	TRUE	FALSE	TRUE
	621	650	IMT_{EGR}+ 1	NTE event	FALSE	FALSE	TRUE
Total NTE events				1	1	0	1

6.3.9 NTE Aftertreatment Device Light-Off Temperature Validation Results

In order for an NTE event generated from a heavy-duty vehicle equipped with aftertreatment devices such as oxidation catalyst and SCR system to be valid the exhaust temperature, measured or broadcasted by ECU, within 12” downstream of the last aftertreatment device must be greater than 250 °C. The validation of this exclusion is performed between 652 and 744 seconds by setting the first thirty second NTE event to have an exhaust temperature of 249 °C, followed by exhaust temperature of 250 and 251 °C respectively for the next two different thirty second events. The validation results are shown in Table 30.

Table 30: NTE Aftertreatment Device Light-Off Temperature Validation Results

Test Condition	Event Start	Event End	T_{exhAT}	Expected Results	PEMS A	PEMS B	In-house
NTE T_{exhAT} > 250 °C	652	681	249	Not NTE event	FALSE	FALSE	TRUE
	683	712	250	Not NTE event	FALSE	FALSE	FALSE
	714	743	251	NTE event	TRUE	TRUE	TRUE
Total NTE events				1	3	3	2

From the results, it is evident that PEMS A post-processing software does not exclude NTE events based on exhaust temperature, downstream of an oxidation-type catalyst, used to identify the catalyst has reached its light-off temperature, a condition required for the catalyst to reduce emissions. PEMS B data reduction software also falls short in recognizing an NTE event exclusion based on exhaust aftertreatment temperature measured 12” downstream of the last oxidation type catalyst. The in-house emissions reduction software considers exhaust temperature downstream of an oxidation-type catalyst to be equal to greater than or equal to 250 °C as the condition of exclusion hence counts an invalid NTE event as a valid event.

6.3.10 Minimum NTE Event Time Validation Results

For an engine operating in NTE zone to become an NTE event, the engine operation must last for at least thirty seconds or more. However, the duration of NTE events are shortened to either ten times the shortest NTE event or six hundred seconds when determining the vehicle pass ratio used to determine the in-use emissions compliance. The minimum NTE event duration requirement is tested by fixing the reference dataset to represent engine operation in NTE zone continuously for twenty-nine, thirty and thirty-one seconds respectively in order to produce two NTE events. The post-processing software generated exactly two NTE events at the correct point in time as expected, the results are illustrated in the Table 31.

This aspect of NTE event validation could not be validated for PEMS B post-processing software due to the reason that the NTE zone definition is different from the expected values for engine speed and also the random time interval of data acquisition leads to interpolation of data points in the output data interval, which consists of a fixed-time interval determined internally by the post-processing software.

The in-house data reduction software was able to recognize the events and resulted in expected number of NTE events at the correct point in time.

Table 31: Minimum NTE Event Time Validation Results.

Test Condition	Event Start	Event End	NTE Event t	Expected Results	PEMS A	PEMS B	In-house
NTE Event t ≥ 30 s	745	773	29	Not NTE event	TRUE	FALSE	TRUE
	775	804	30	NTE event	TRUE	FALSE	TRUE
	806	836	31	NTE event	TRUE	FALSE	TRUE
Total NTE events				2	2	0	2

6.3.11 Minimum NTE Event Time Validation During the Event of DPF Regeneration

The in-use emissions regulations allows NTE events to be longer than the minimum event time of thirty seconds if there are any instances of DPF regeneration while the engine is operating in the NTE zone for thirty seconds or longer counting towards a normal NTE event. The validation of this scenario is performed by using an eight hour long dataset that consists of signals indicating active regeneration of DPF using a binary value with zero signifying normal operation and one representing active regeneration of the DPF. The DPF regeneration signal is used in calculating the RF, a value which is used to determine a new value for minimum NTE event time, based on the duration of active regeneration in a valid NTE event. The reference dataset used here yields a value of 0.16 for RF based on the DPF regeneration events embedded into the reference dataset as illustrated in Figure 31. Several short regular NTE events are invalidated due to the presence of two 1800s long active DPF regeneration episodes except for a 60s long short regeneration event that occurs at the end of 600s long NTE event. The combination of 600s long NTE event with a 60s long DPF regeneration episode and a RF of 0.16 results in the event being a valid event since the minimum event time is equal to 375s. The test results of different data post-processors are illustrated in Table 32. It should be noted that one of the 600s NTE event is set to be invalid because the DPF was regenerating the entire duration of that particular NTE event.

None of the in-use data reduction software was capable of resolving RF out of the 8-hour data including in-house post processing software. However, the in-house post-processing software is designed to receive user input for RF and evaluate the minimum NTE event duration if there is any DPF regeneration taking place during a valid NTE event. But, upon verification it was found that the in-house data post-processor did not invalidate any NTE event based on the minimum event time with DPF regeneration criteria.

Table 32: Minimum NTE Event Time with DPF Regeneration Validation Results

Test Condition	Event Start	Event End	NTE Event t	Expected Results	PEMS A	PEMS B	In-house
NTE Event with DPF Regeneration $t_{NTE_{DPF}} \geq \frac{t_{DPFregen}}{RF}$	21163	21692	30	Not NTE event	n/a	n/a	FALSE
	22438	23037	600	Not NTE event	n/a	n/a	FALSE
	26038	26637	600	NTE event	n/a	n/a	FALSE
Total NTE events				1	n/a	n/a	3

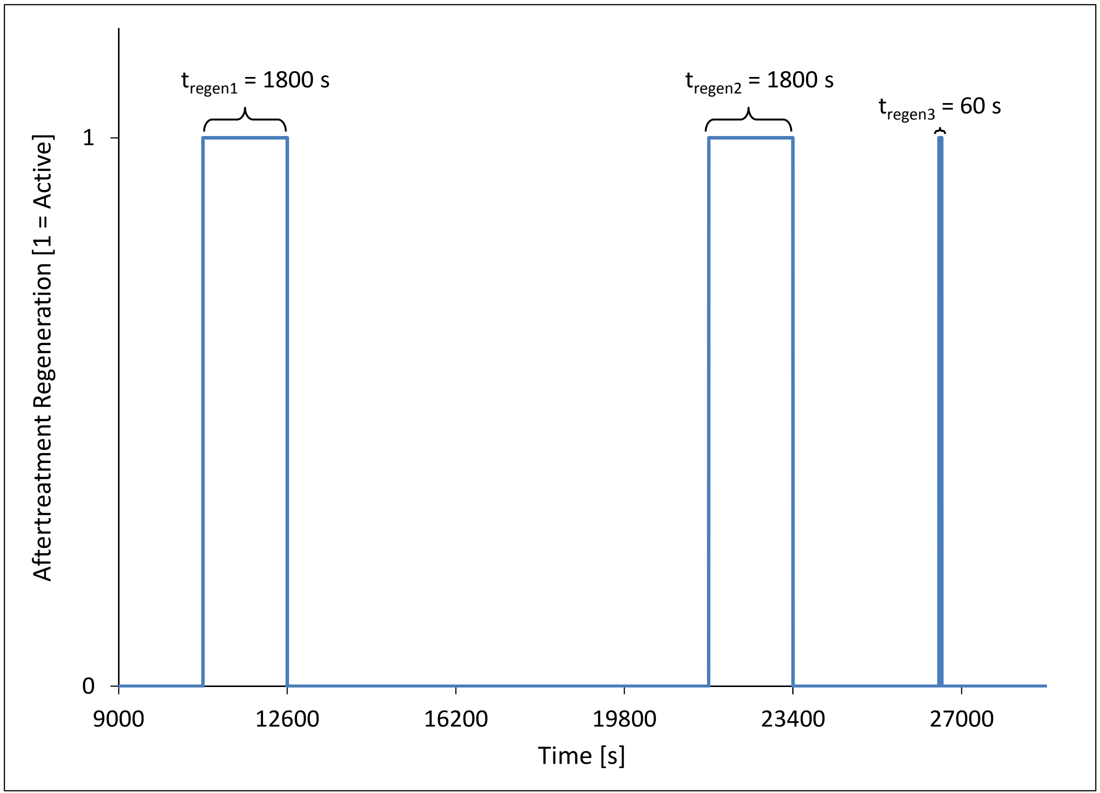


Figure 31: Illustration of Active DPF Regeneration Events Over Eight Hour Long In-Use Emissions Test

6.4 In-Use Emissions Quantification Results

The validation of in-use emissions quantification is performed based on one Hz data that is required to be reported to EPA after in-use compliance test. These data include ambient humidity, ambient dewpoint temperature, exhaust temperature, raw exhaust flow rate, standardized exhaust flow rate, raw emissions concentrations of measured exhaust constituents, instantaneous mass of emissions constituents reported in wet basis and corrected for zero drift, NOx emissions rate corrected for ambient humidity, calculated brake horsepower, and brake-specific emissions rate of emissions constituents. Finally, in-use brake-specific emissions over different NTE events will be validated by comparing the expected results with actual results of different PEMS in-use emissions post-processor using event start and end time, event duration, brake-specific emissions of regulated pollutants over each event. Note that the validation results described in the following sections are based on the first hour of reference emissions data including special cases of one hour emissions data used to validate the handling of negative emissions concentrations, and cases that lead to failure of in-use emissions test.

6.4.1 Conversion of Measured Actual Exhaust Flow to Standard Conditions Validation Results

The measured actual exhaust flow rate in the reference dataset is set to be a sinusoidal signal ranging from 5 - 20 m^3/min, along with exhaust pressure and temperature varying sinusoidally between 96.91 - 98.8898 kPa, and 230 - 260 °C respectively at the point of flow measurement. The actual flow values must be standardized to 101.325 kPa and 20 °C as per EPA standard conditions, and the standard flow must be reported in the units of standard ft^3/min (scfm). The standard exhaust flow results from different post-processing software are shown along with the expected flow rates for the given input value in Figure 32 for a time period of 60 seconds.

The PEMS A post-processing software down samples 10 Hz emissions data into one Hz by averaging over a window of 10 data points. It can be observed that the peaks of down sampled PEMS A exhaust flow values are shifted by 0.5 seconds relative to the expected flow rate values due to forward averaging used by PEMS A data post-processor. Note that CFR 40 part 1065 does not specify a specific averaging method for down sampling data from higher frequency to lower [91], but they offer averaging as one of the methods to down sample. Furthermore, the flow values shown under expected results are calculated based on one Hz synthesized data as discussed under Experimental Methodology chapter while post-processor results are down sampled from 10 Hz continuous data.

The PEMS B exhaust flow measuring device reports exhaust flow in terms of mass rate based on the density of the exhaust gas whose value is calculated using the molecular weight of constituent exhaust fractions as measured by the emissions analyzer with the major fraction being nitrogen. The equations used in calculating exhaust mass rate for PEMS B are discussed under section 3.4.1. The exhaust flow results in terms of standard cubic feet per minute (scfm) plotted against reference data in Figure 32 shows that the method used to calculate volumetric exhaust flow rate agrees with the method described in the manual. However, the actual flow values are significantly different than the expected values as illustrated in Figure 32

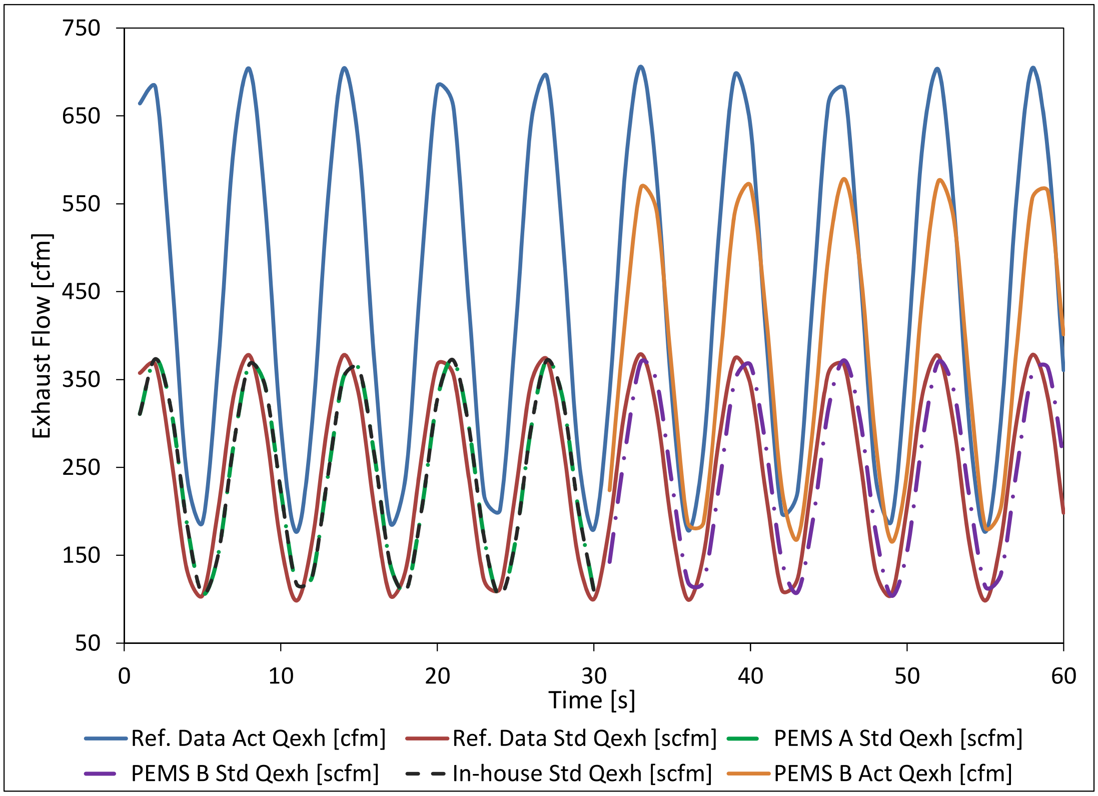


Figure 32: Comparison between Expected and PEMS Post-Processor Exhaust Flow Values

The in-house emissions data reduction software also uses forward averaging to down sample 10 Hz data to 1 Hz, and the standard exhaust flow rate results plotted against the expected values show that the peaks are shifted by 0.5 seconds similar to PEMS A post-processor results. As the flow values exactly correspond to the PEMS A results, the exhaust flow value of in-house post-processing software is plotted in a black dotted line as shown in Figure 32.

6.4.2 Corrected Emissions Concentrations for Analyzer Drift Validation Results

The in-use emissions regulation requires the analyzers to be zeroed at the end of each hour during an eight hour in-use emissions compliance test so that the analyzer can be adjusted for drift and the measured concentration over the previous hour can be corrected for drift, if there is any. Therefore, the reference dataset is split into eight hourly tests with a common set of zero drift values for different analyzers over each hour as discussed under section 5.3.3. It should be noted that since in-use emissions regulation does not require span check at the end of each hour, the zero span drift correction equation prescribed under CFR part 1065.672 has been modified to exclude span drift values as discussed in section 3.3. Therefore, expected emissions concentration corrected for zero drift reflects the modified zero drift correction factor.

In the case of PEMS A, the data acquisition is set to perform analyzer zero every hour. The data collected during the process of analyzer zeroing is used by the data acquisition system to perform zero drift correction and create two data files one representing raw data, referred to as “a” file while the other one called as “b” file representing drift corrected concentrations. Since drift correction procedure is performed while collecting the data, it cannot be tested under post-processor verification. Therefore, the validation of zero drift correction is performed using data collected over an actual test. The results are shown in Figure 33 and Figure 34 including span values and zero drift values for NOx and CO analyzers as recorded during testing. From the results, it is clear that PEMS A zero drift correction values are higher compared to values derived using modified zero drift correction factor. Note the direction of the drift correction would change based on the direction in which the analyzer would drift.

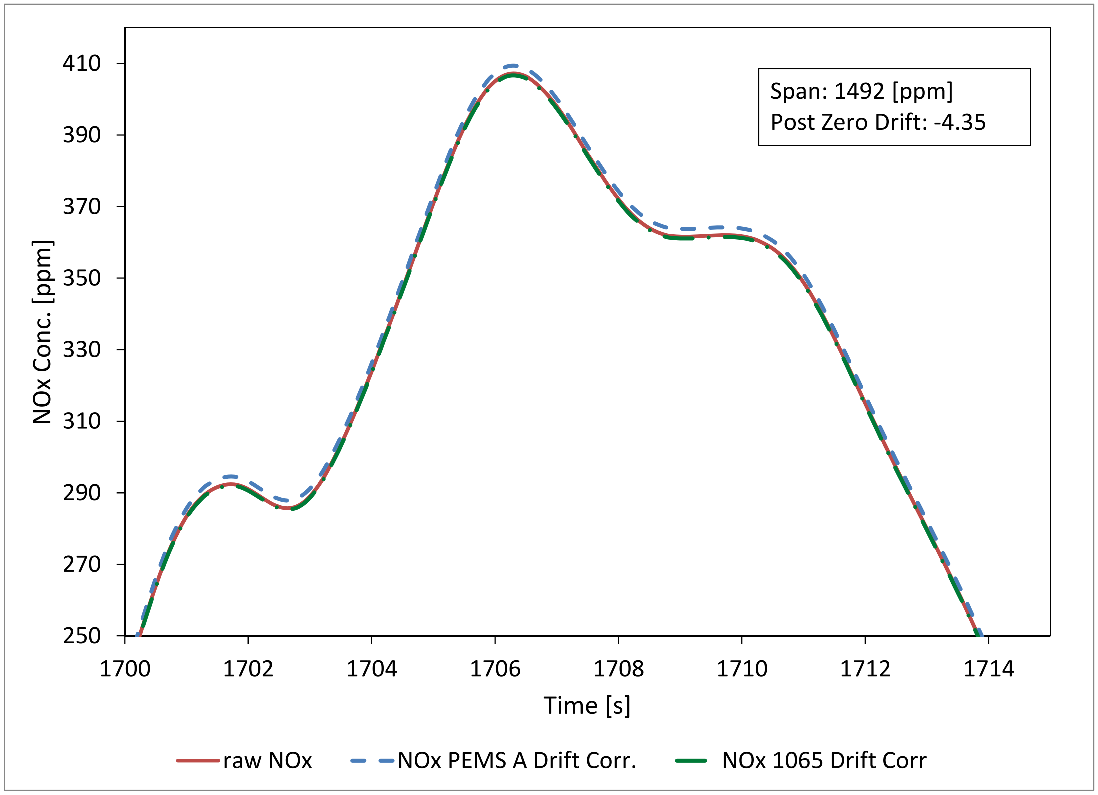


Figure 33: Comparison between 1065 and PEMS A Drift Correction Method for NOx

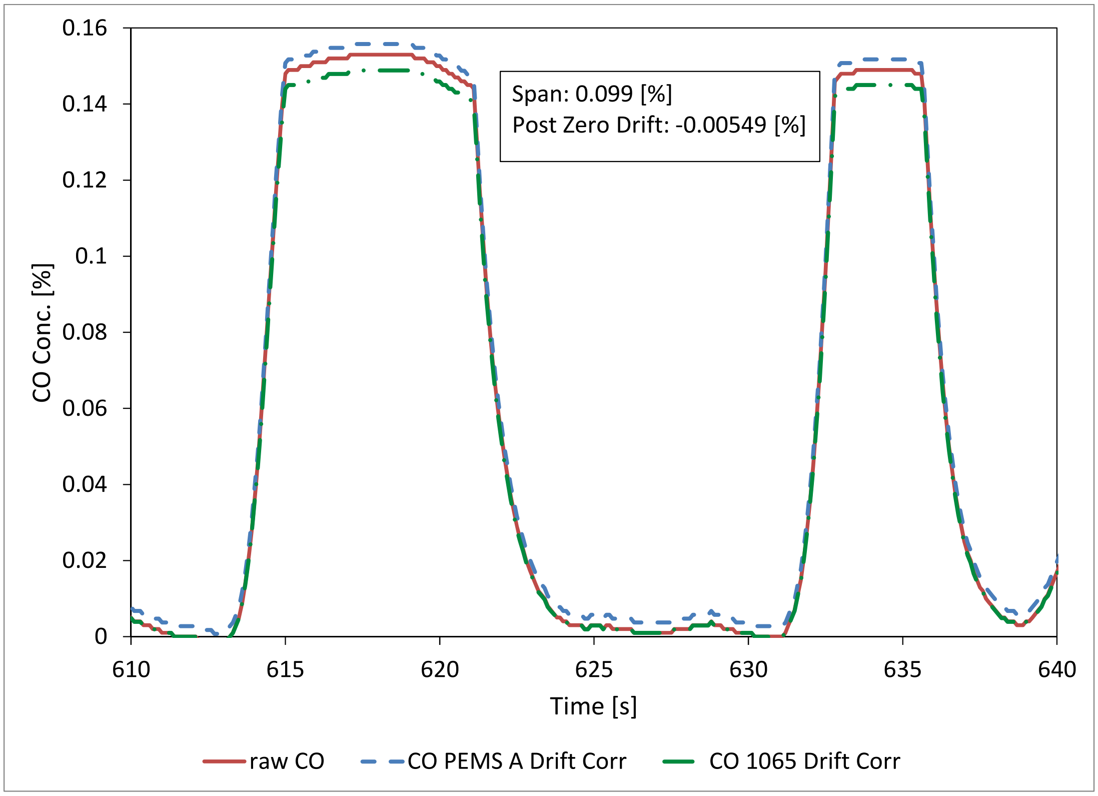


Figure 34: Comparison between 1065 and PEMS A Drift Correction Method for CO

PEMS B data post-processor does not provide any output for drift corrected emissions concentrations except for drift corrected brake-specific emissions for the NTE events. Therefore, the equation used to perform drift correction is not validated for PEMS B data post-processor. The in-house data post-processor is built based on the data structure of the PEMS A emissions data and since PEMS A reports drift corrected emissions value the in-house post-processing software lacks the ability to perform drift correction. Hence, the in-house data post-processor is not validated for drift correction.

6.4.3 Dry-to-Wet Correction of Emissions Concentrations Validation Results

As per CFR 40 1065, it is required to convert concentration of exhaust constituents to wet concentrations if measured on dry basis before calculating the emissions mass rate. This is accomplished either by measuring the amount of water in the exhaust or by using carbon balance method to determine the amount of water in the exhaust. Furthermore, EPA requires emissions concentration data to be reported in both raw, and emissions mass rate obtained from concentrations corrected for dry-to-wet compensation and analyzer zero drift. The reference dataset is set to reflect the raw concentration measured on dry basis. The raw dry emissions concentrations are corrected for drift and converted from dry-to-wet as explained in sections 3.3 and 3.7 and used as input values for PEMS A data.

PEMS A is the only PEMS device that is capable of measuring emissions concentrations on wet basis as the analyzers report concentration compensated for water in the exhaust that is measured using

NDIR analyzer. Therefore, it is recommended to measure emissions concentrations on wet basis when using PEMS A because converting the native wet concentrations to dry using the measured water concentrations and converting back to wet would introduce error at both steps leading to higher error.

Note that in-use emissions regulations requires raw concentrations and emissions mass rate that are corrected for zero and span drift and reported on wet basis. Therefore, it becomes difficult to de-couple the values of emissions corrected for zero and span drift from dry-to-wet compensated emissions rate. However, PEMS B data post-processor provides a data channel of dry-to-wet compensation factor k_w, which is used here to compare between the expected and the actual values over a period of 60 seconds.

The results are shown in Figure 35, which illustrates that the PEMS B evaluated k_w varies over a range of 2.5% to -0.3% relative to the expected values. This could be attributed to the difference in the relationship used to calculate the water content in the exhaust as k_w is a function of fraction of water in the exhaust.

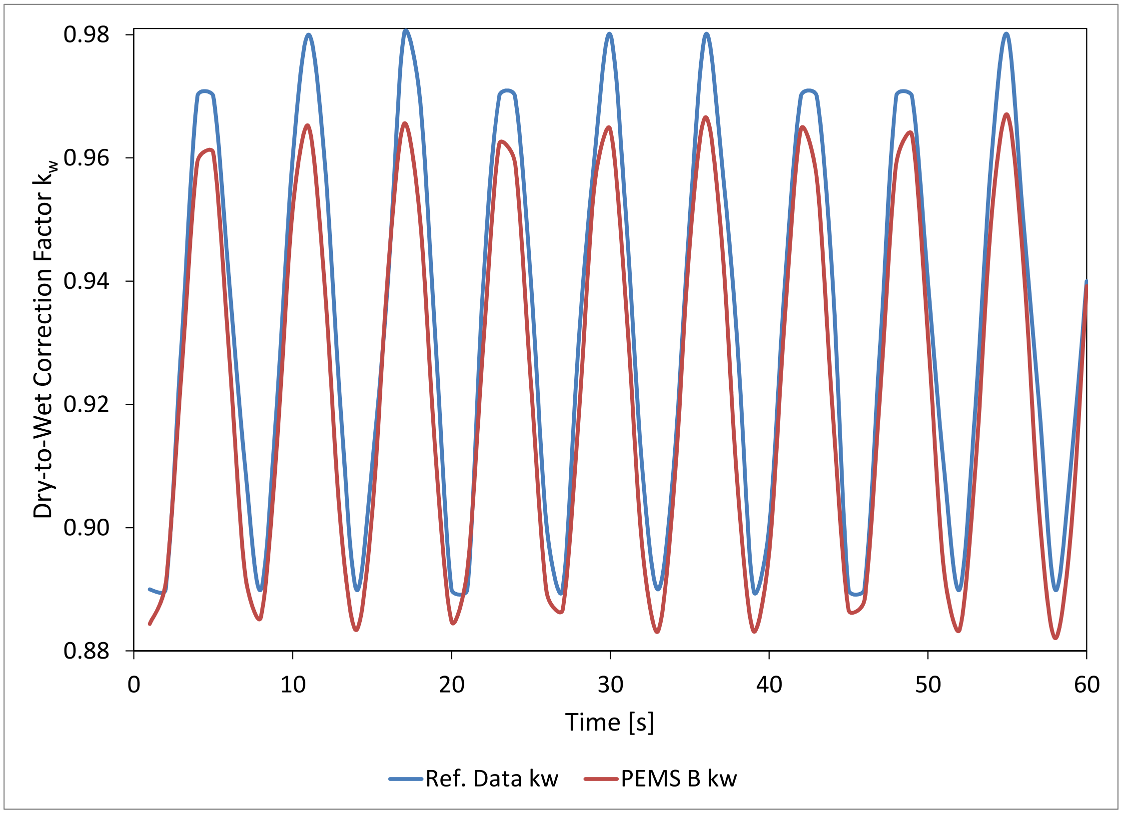


Figure 35: Comparison between Expected and PEMS B Dry-to-Wet Compensation Factor

Since the in-house data post-processor is developed on the basis of PEMS A emissions data, it does not have the capability of using dry concentrations, which needs to be converted to wet in order to quantify mass-based emissions rate. Therefore, the in-house post-processor is not validated for dry-to-wet compensation factor.

6.4.4 Intake Air Humidity Correction for NOx Emissions Validation Results

It has been shown that exhaust NOx varies with intake air humidity resulting in lower NOx with increased intake air humidity and vice versa. Therefore, it is a common practice as per CFR 40 part 1065 to correct NOx emissions for standard intake air humidity [64] of 75 grains H_2O/lb dry air. However, in-use emissions regulation requires NOx emissions to be corrected for two intake air humidity conditions namely correct NOx emissions to 55 grains H_2O/lb dry air if the intake air humidity is less than the above value, correct it to 75 grains H_2O/lb dry air if the intake air humidity is higher than the above value and report the NOx emissions without any correction if the intake air humidity is between 55 and 75 grains H_2O/lb dry air. Since the intake air humidity is a function of ambient temperature and pressure, the reference dataset is set to results in intake air humidity values ranging between 88.9 to 44.1 grains H_2O/lb dry air which in-turn results in k_h values of 0.98 and 1.04.

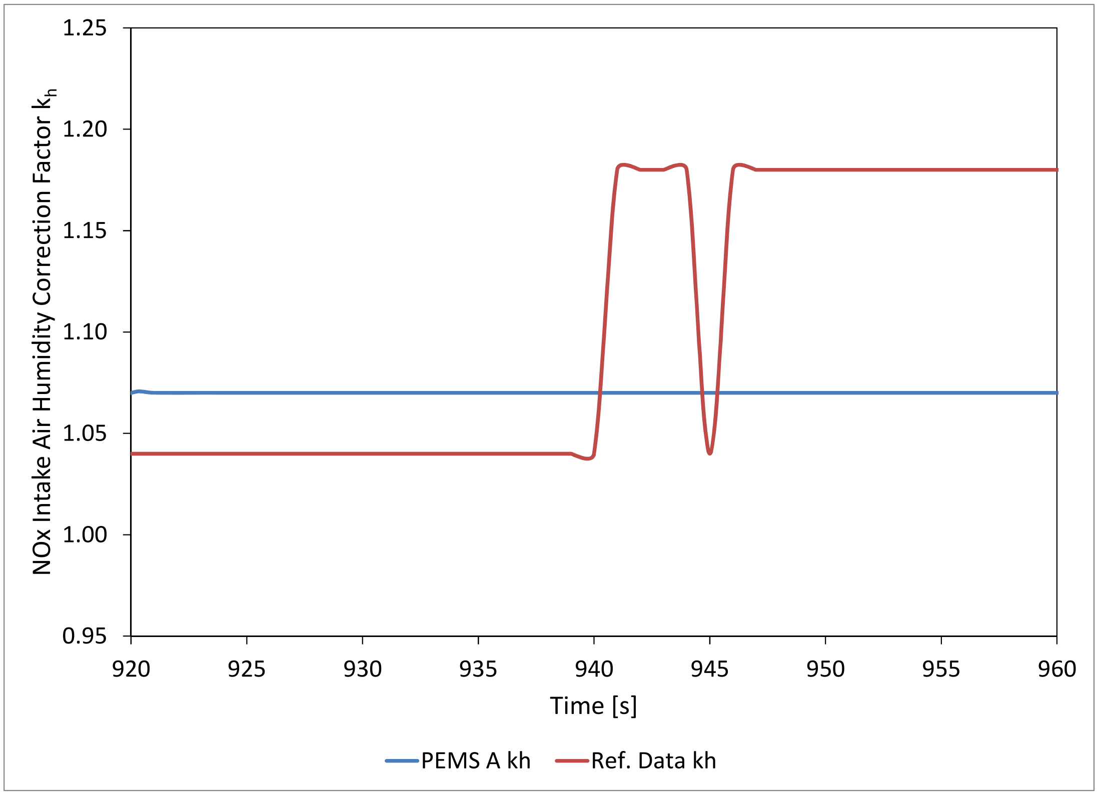


Figure 36: Comparison between PEMS A and In-Use Emissions NOx Correction Factor Based on Actual Ambient Conditions

In the case of PEMS A, NOx emissions are corrected for intake air humidity using the equation prescribed in §1065.670 during the process of data acquisition. The NOx emissions corrected for intake air humidity are reported as brake-specific emissions rate, which is converted back to emissions rate in the post-processor. Since the NOx emissions correction is performed during the data acquisition stage, the difference in the values of NOx emissions when corrected as per in-use emissions regulations and the method used by PEMS A data acquisition system will be demonstrated using actual data collected in the field. The illustration shown in Figure 36, is created based on the value of k_h as derived by PEMS A data acquisition software and the same if derived based on the in-use emissions NOx correction factor regulations, discussed in section 3.6, based on measured values of ambient condition. It is evident that the NOx correction factor used by the PEMS A data acquisition software is not in accordance to the in-use emissions regulations.

It is evident in Figure 37, which illustrates the difference between expected k_h values from the reference dataset and the actual values obtained from PEMS B and in-house data reduction software is significantly different and lower than the expected values leading to lower NOx emissions.

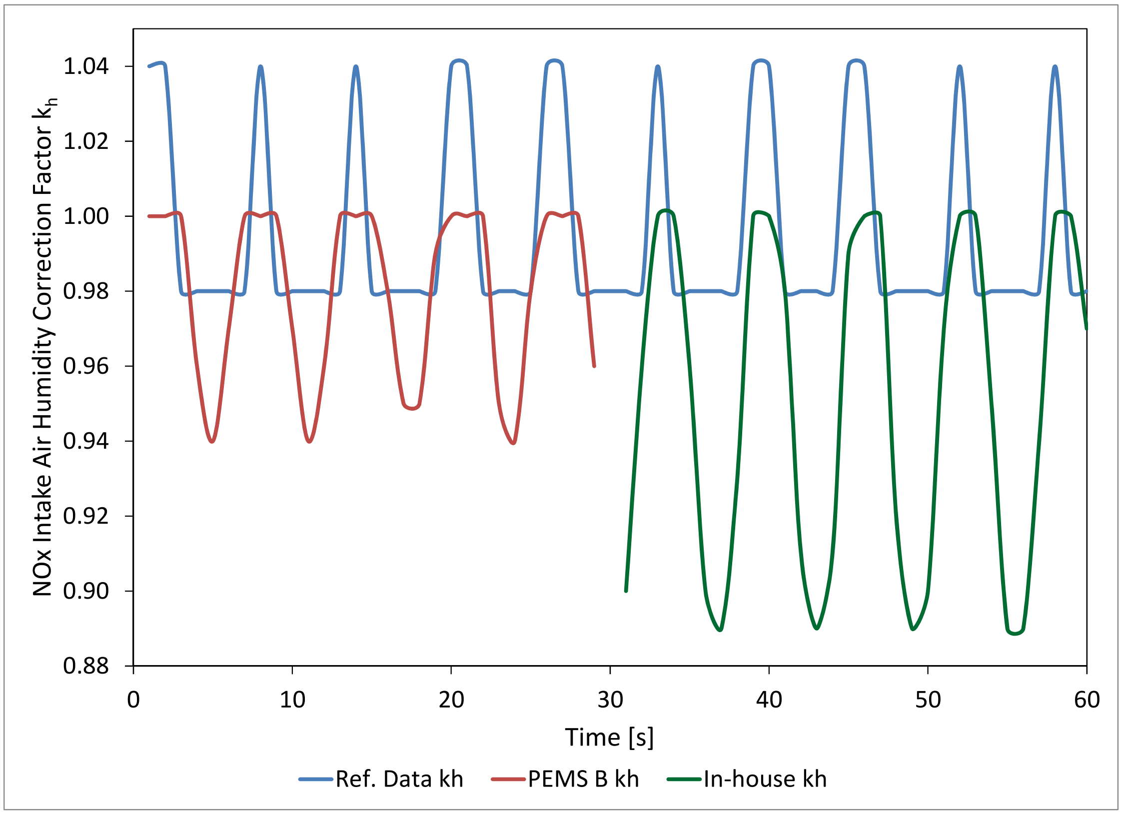


Figure 37: Comparison between Expected, PEMS B and In-House Data Reduction NOx Humidity Correction Factor

6.4.5 Addressing of Negative Emissions Concentration Validation Results

An hour long of reference dataset with average concentrations of emissions constituents set to zero while varying between a positive and negative maximum value is used to validate in-use emissions data post-processors procedure to address negative emissions concentrations. The results show that PEMS A post-processor not only reports negative emissions concentrations but also integrates it while reporting total brake-specific emissions for a given NTE event. The results are shown in Figure 38 against the expected values.

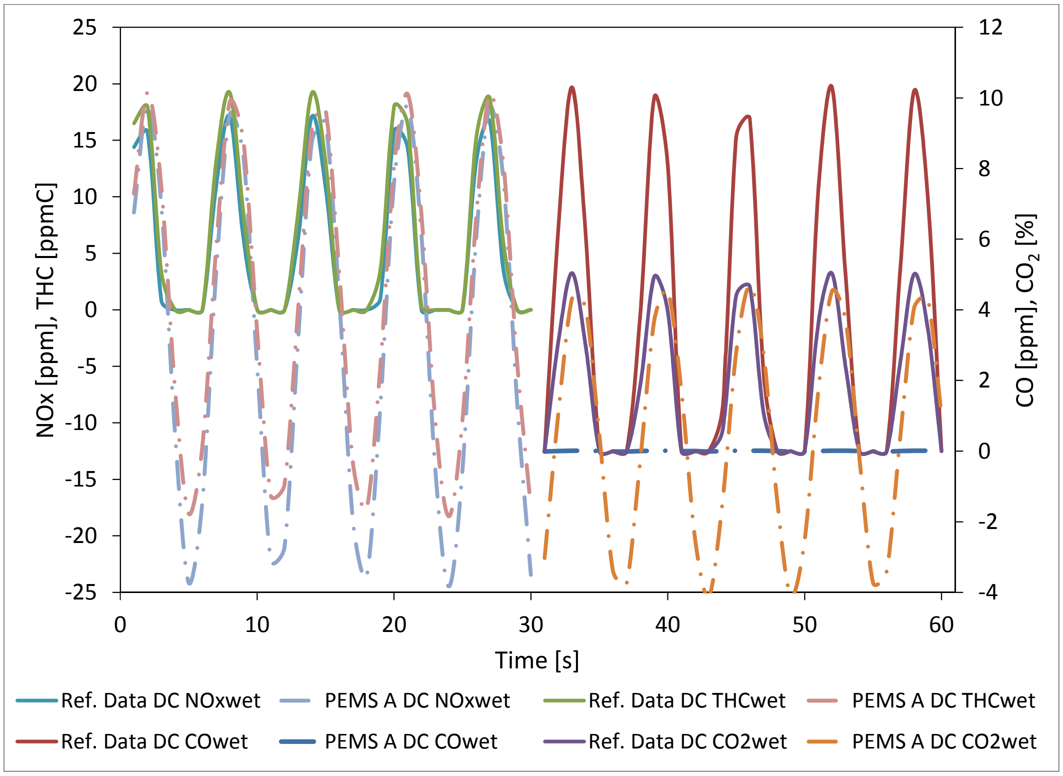


Figure 38: Comparison between Expected and PEMS A Results for Negative Emissions Concentrations

The PEMS B emissions reduction software sets the negative emissions concentrations to zero and therefore does not integrate negative emissions rate and agrees with the expected brake-specific emissions results. However, the NOx correction factor used by the PEMS B data post-processor leads to a higher error when compared to the expected results. The trace comparing the NOx emissions rate between expected and PEMS B results are illustrated in Figure 39 and the brake-specific emissions for the first valid NTE event where the engine speed is equal to 1057 rpm are shown in Table 33. Note that emissions rate of other pollutants are not shown in the illustration as they closely match the expected results as shown in the Table 33.

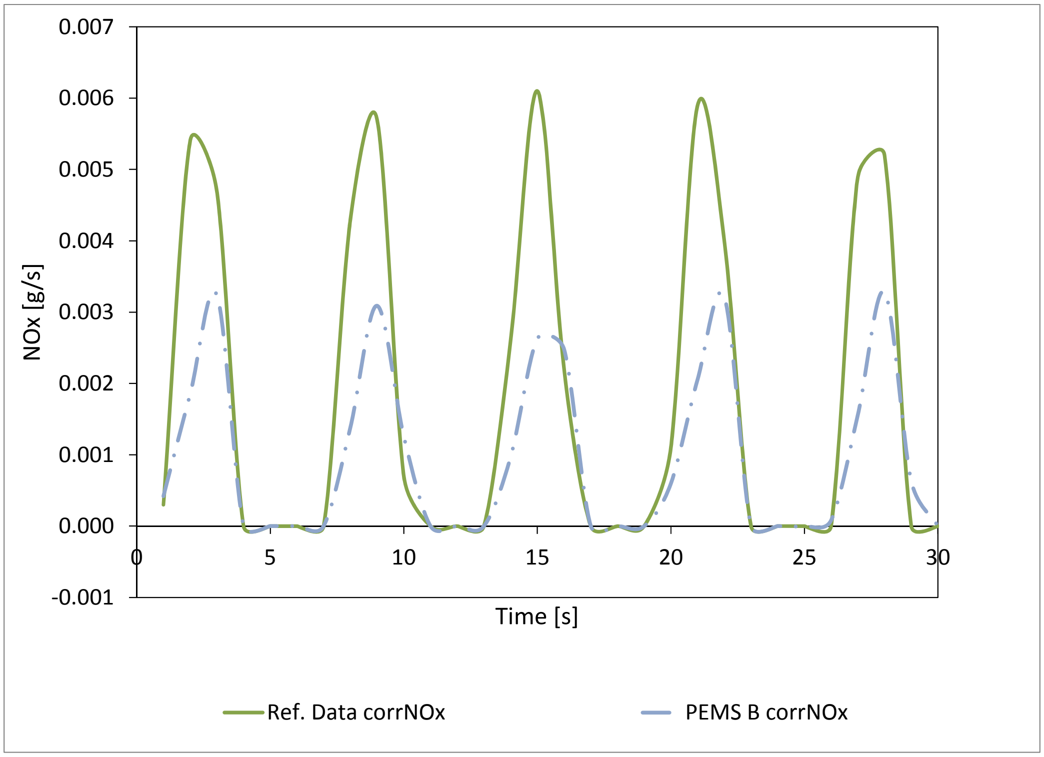


Figure 39: Comparison between Expected and PEMS B NOx Emissions Rate for Negative Concentrations

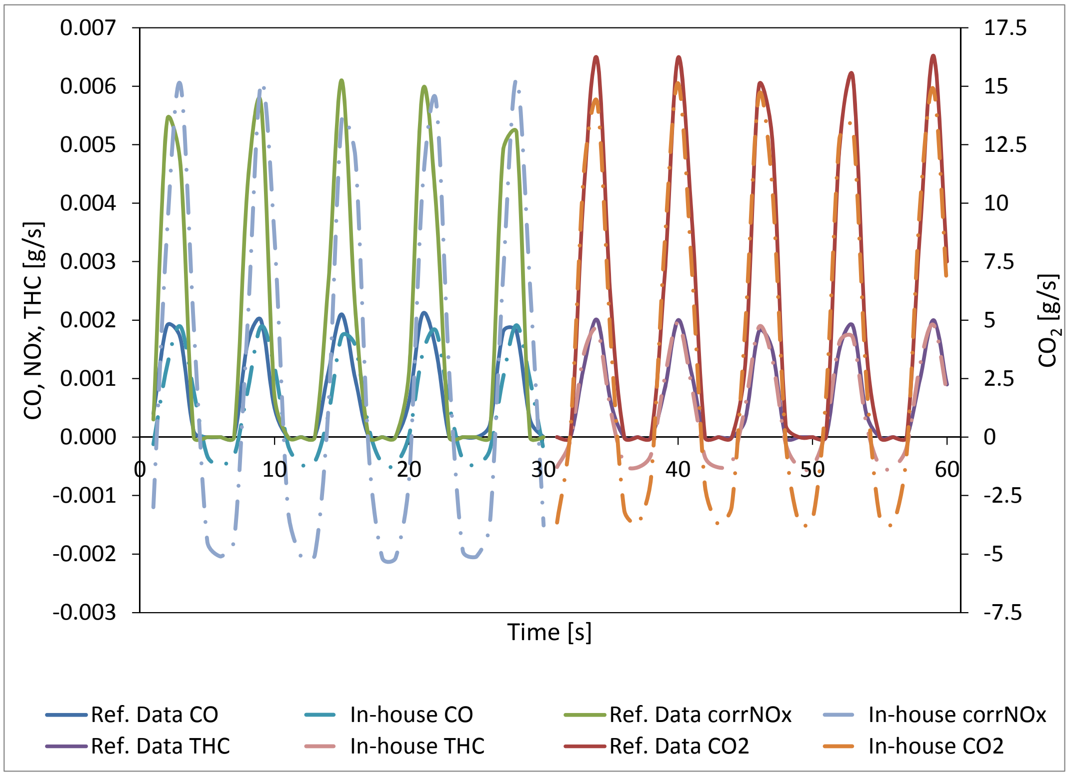


Figure 40: Comparison between Expected and In-House Emissions Post-Processor Emissions Rate with Negative Concentrations

The in-house emissions data post-processor also did not address negative emissions concentrations by setting them to zero thus integrating them while reporting the total mass for a given NTE event. The results of the in-house emissions post-processor are shown in Figure 40 and the brake-specific NTE emissions for the first valid event where the engine speed is 1057 rpm is used to compare the results with the expected values in Table 33. Note that from the traces shown in Figure 40 it is apparent that the emissions rates, shown in dotted lines, calculated by the in-house post-processor take negative concentrations into consideration.

Table 33: Brake Specific Emissions with Negative Emissions Concentrations

NTE BS Emissions	THC	CO	CO$_2$	NOx	Engine Work	BS THC	BS CO	BS CO$_2$	BS NOx
	[g]	[g]	[g]	[g]	[bhp-hr]	[g/bhp-hr]			
Ref. Data	0.0186	0.0207	159.4855	0.0531	1.50	0.01	0.01	106.32	0.04
PEMS A	0.0124	0.0135	107.5751	0.0394	1.38	0.01	0.01	77.95	0.03
PEMS B	0.0183	0.0187	144.2250	0.0290	1.38	0.01	0.01	104.51	0.02
In-house	0.0135	0.0148	116.5471	0.0318	1.38	0.01	0.01	84.45	0.02

6.4.6 Down Sampling of Emissions Measurement Data Validation Results

There are several methods followed to down sample a high frequency measurement data to lower frequency of which EPA recommends taking an average of ten data points from a 10 Hz data in order to down sample it to 1 Hz. Among other methods used to down sample high frequency data to low frequency, decimation is argued to be the most accurate method. In the case of PEMS A post-processor, it was programmed to use only 10 Hz data as it was averaging every 10 data points to result in 1 Hz output. The results showed that the PEMS A post-processor implemented forward averaging in which the down sampled data is shifted to the right by half seconds as illustrated in Figure 32. The in-house data post-processing software also followed the similar approach of forward averaging and PEMS B post-processor was not tested for this aspect as the sample data file used is a 1 Hz data file.

6.4.7 Emissions Mass Rate and Engine Horsepower Validation Results

The in-use emissions regulations requires engine manufacturers to submit one Hz file of the data collected in the field as well as post-processed data, which includes emissions mass rate corrected for dry-to-wet compensation and zero drift and the calculated horsepower produced by the engine. The emissions rate and engine horsepower results produced by post-processing the reference dataset using different commercial and in-house data post-processing software are compared against the expected results that are known *a priori*. Figure 41 shows the comparison of PEMS A emissions rate with expected values for different emission constituents. It is evident that the emissions rate obtained from PEMS A post-processor closely agrees with the expected results with the PEMS A emissions rate being lower than the expected emissions values.

Figure 42 illustrates the difference between expected and the PEMS B post-processor emissions rate, where the PEMS B emissions rate closely agrees with the expected values but is lower. However, the NOx emissions rate is the lowest of all the emissions constituents in comparison to the expected NOx rate. The difference between expected emissions rate and in-house post-processor results is illustrated in Figure 43 where once again the emissions rates are in close agreement with the expected results. Note the emissions rate from PEMS A and in-house post-processor are shifted by 0.5 seconds as the 10 Hz data is forward averaged to arrive at 1 Hz results.

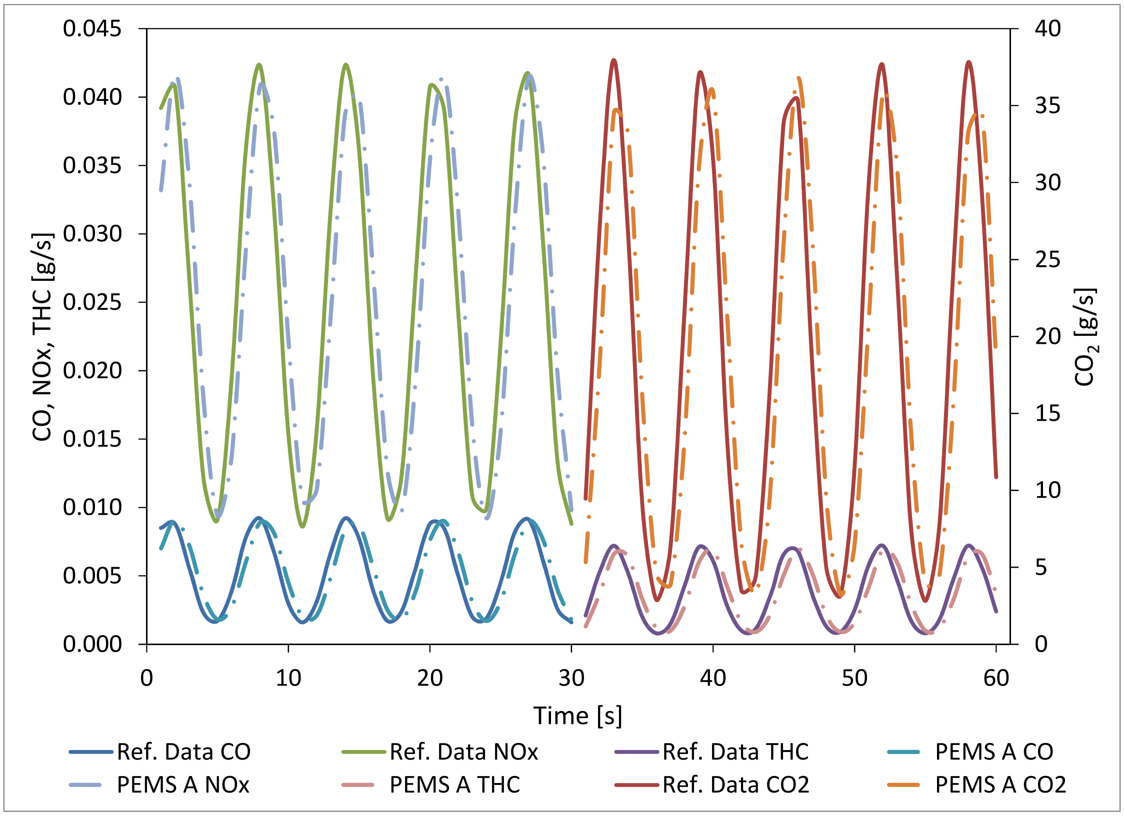


Figure 41: Comparison between Expected and PEMS A Emissions Mass Rate

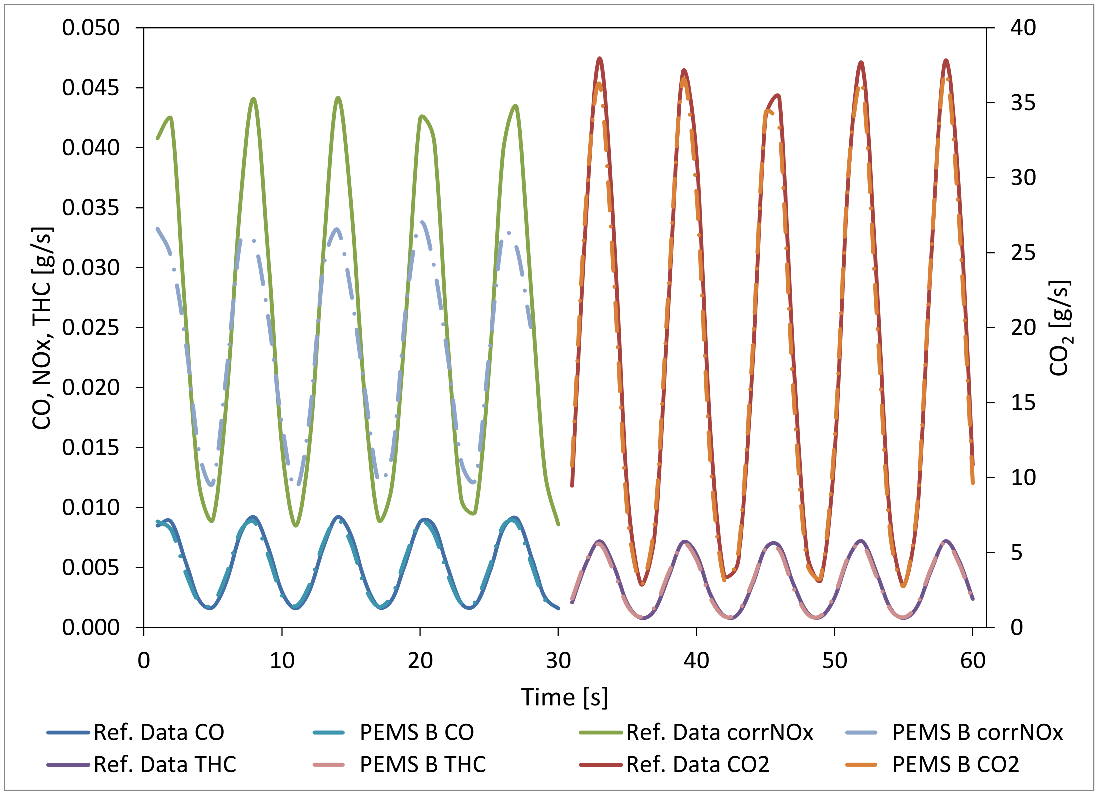


Figure 42: Comparison between Expected and PEMS B Emissions Mass Rate

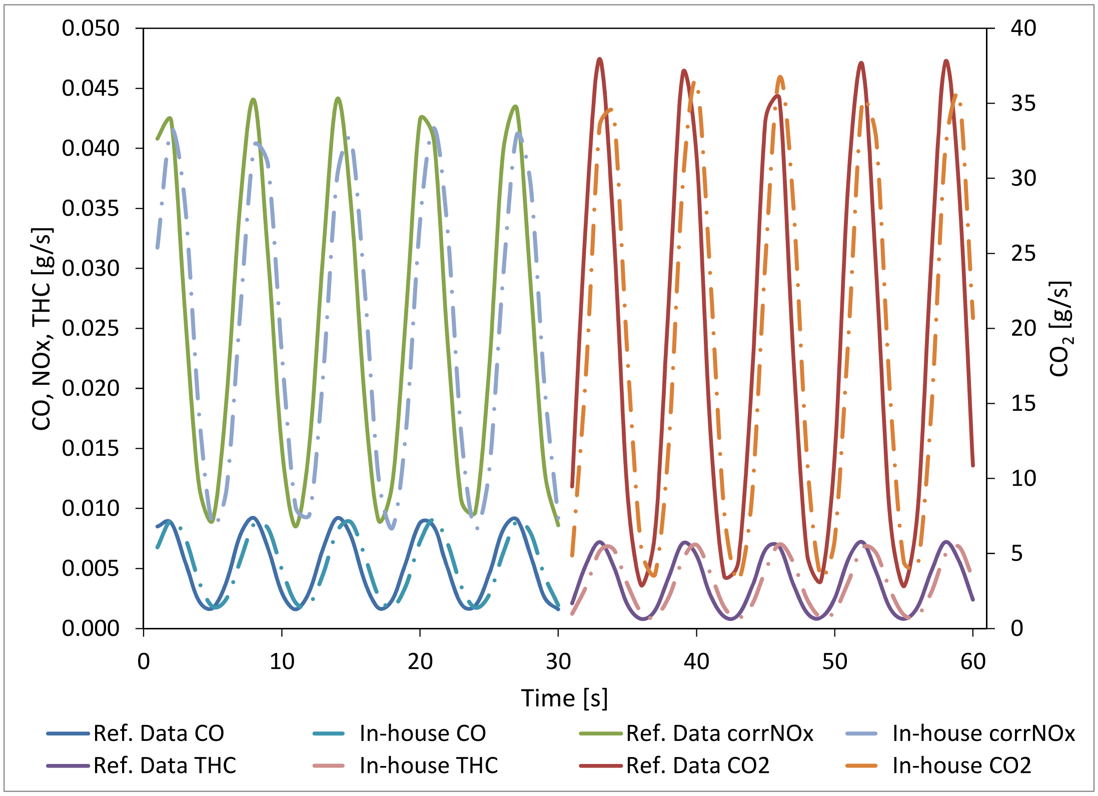


Figure 43: Comparison between Expected and In-House Post-Processor Emissions Mass Rate

Engine power trace shown in Figure 44 compares engine horsepower values derived using engine speed and torque data between expected and different emission post processor results over a period of the first ninety-three seconds, which also represents the data used to validate NTE event engine speed. It is clear from the results that engine power values agree with the expected values within a range of 0.01%. This difference can be attributed to the conversion factor and rounding off errors.

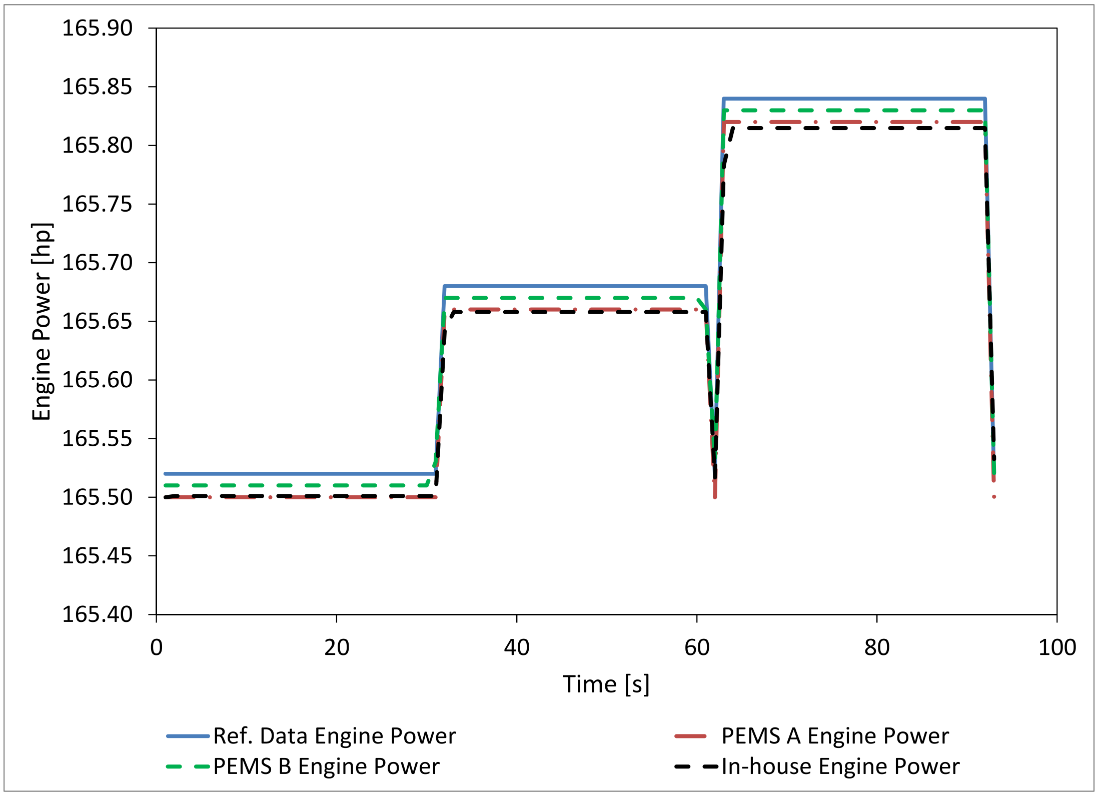


Figure 44: Comparison between Expected and In-Use Emissions Post-Processor Engine Power

6.4.8 Brake-Specific Emissions Over an NTE Event Validation Results

Brake-specific NTE emissions are calculated as the ratio of total mass of emissions constituents over a given NTE event to the total engine work produced during that event. In order to verify that the brake-specific emissions reported at one Hz are not being integrated to calculate the NTE event brake-specific emissions the engine speed and torque are varied sinusoidally with a 90 degrees phase difference between each other to mimic a transient operation over a minute long NTE event. The brake-specific emissions results obtained for this event from different post-processing software are compared against the expected results. An illustration of the engine speed and torque used for this NTE event is shown in Figure 45 and the emissions compared between different post-processor results are shown in Table 34. Note that the engine torque values are offset from the speed values by thirty seconds to improve lucidness of the illustration.

The results of brake-specific NTE emissions quantified over a sixty second long transient NTE event by different processing software closely agrees with the expected results and it is evident from the Table 34 that the brake-specific emissions are calculated as the ratio of total mass of emissions over total brake work produced over an NTE event and not the integrated value of continuous brake-specific emissions rate. Furthermore, the error between PEMS B and reference brake-specific emissions results for this event is highest of all post-processing software at 8 and 9 % for NOx and CO_2, respectively.

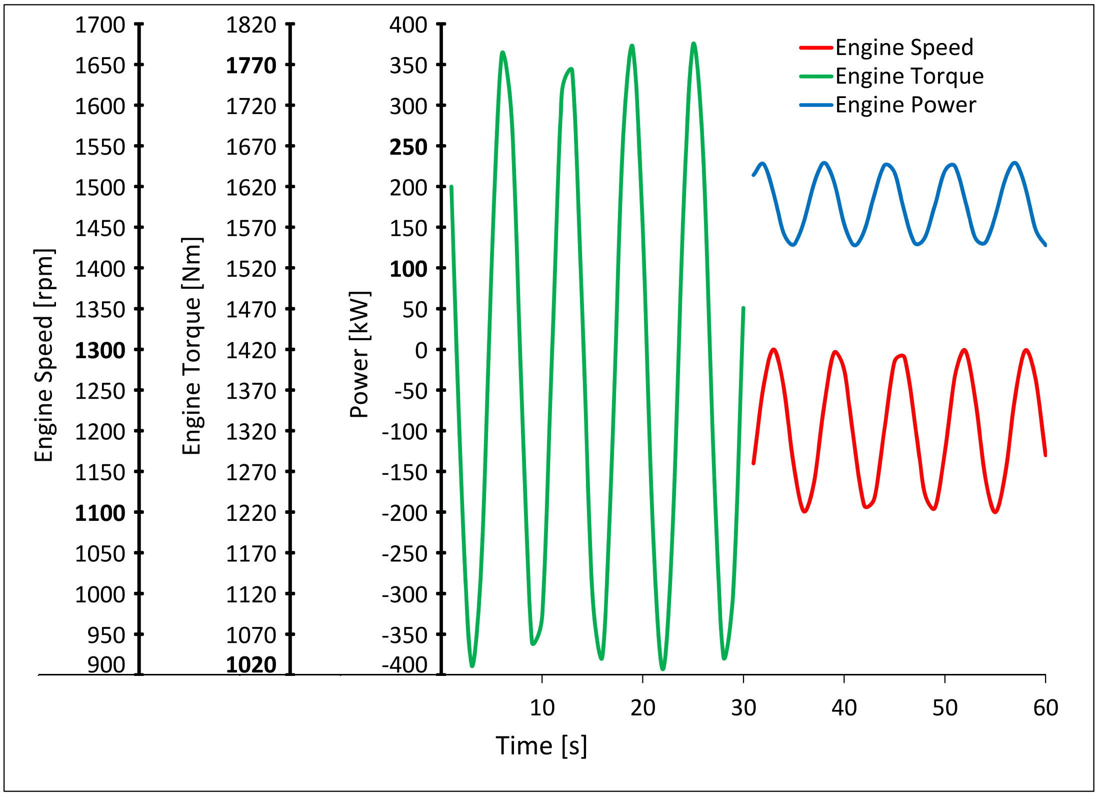


Figure 45: Engine Speed and Torque of Transient NTE Event

The in-house data reduction software reports the engine brake work at an order of magnitude higher than the expected value. However, the brake-specific emissions values are at the same order of magnitude as the expected results with an error of approximately 2 and 5% for CO_2 and NOx, respectively. This could be an error resulting in calculating the engine brake work caused by not accounting for the data rate, this error cancels out for brake-specific emissions as it is a ratio of total emissions to engine work. Note that positive error signifies the reference results being higher than post-processor results.

Table 34: Brake Specific Emissions for an NTE Event

NTE BS Emissions	THC	CO	CO_2	NOx	Engine Work	BS THC (error)	BS CO (error)	BS CO_2 (error)	BS NOx (error)
	[g]	[g]	[g]	[g]	[bhp-hr]	[g/bhp-hr] (% wrt ref. results)			
Ref. Value	0.2249	0.3191	1119.1322	1.5312	3.95	0.06	0.08	283.32	0.39
PEMS A	0.2236	0.3189	1111.8251	1.5257	4.05	0.06 (0)	0.08 (0)	271.19 (4.3)	0.37 (5.1)
PEMS B	0.2114	0.3030	1027.271	1.4450	3.95	0.05 (16.7)	0.08 (0)	258.09 (8.9)	0.36 (7.7)
In-house	0.2400	0.3000	1123.740	1.5000	40.06	0.06 (0)	0.08 (0)	277.10 (2.2)	0.37 (5.1)

6.5 In-Use Emissions Compliance Results

Finally, after quantifying brake-specific emissions over different NTE events the in-use emissions compliance results of different emissions post-processing software is validated using eight hour long complete dataset, along with two more supplementary datasets whose last hour emissions data are changed to test different in-use emissions pass/fail criteria. The results of the in-use compliance test based on the above three eight hour long datasets will be discussed in the following sections.

6.5.1 NTE Emissions Threshold Validation Results

As discussed in section 4.4.1, NTE emissions threshold is defined as a function of certification standards, NTE multiplier, accuracy, and compliance margin. The user is prompted to enter values for the above variables through a user interface in the post-processing software or through initialization file. These values are in-turn used for qualifying a valid NTE event to pass or fail if the measured brake-specific emissions are lower than the threshold. EPA requires the vehicle manufacturers to report the threshold values of different emissions constituents along with the values used to calculate them. The results of different in-use emissions post-processing software show that the threshold values are calculated accurately as recommended by the EPA. However, it was found that PEMS A post-processing software did not have the provision to input the compliance margin values, which is a function of vehicle miles, for NOx. The result of NTE emissions threshold values as calculated by different post-processing software is illustrated in Table 35. Note that the in-house post-processor does not have the feature of declaring the NTE emissions threshold values

6.5.2 Time-Weighted Vehicle Pass Ratio and Upper Limit Fail Validation Results

A vehicle tested for in-use emissions is said to comply with in-use emissions standards for respective criteria pollutants when the ratio of the sum of NTE event durations whose emissions are below threshold values to the sum of all other valid NTE event durations, which satisfies all the different exclusion criteria, is greater than or equal to 90%. The valid NTE event durations are weighted based on the minimum NTE event time such that the maximum duration cannot exceed ten times the minimum NTE event, or 600 seconds. This applies to all the valid NTE event durations used in evaluating time weighted vehicle pass ratio.

In addition to satisfying the above condition of vehicle pass ratio, the total emissions of valid NTE events that are above NTE threshold values must not exceed two times the NTE threshold values of the respective emissions constituents. In the case of NOx emissions for MY2010 and later engines that are certified for 0.2 g/bhp-hr, the upper limit of all valid NTE events should not exceed 2.0 g/bhp-hr. These conditions are tested with a set of three eight hour long reference datasets wherein the first dataset referred to as “Master” dataset is fabricated to satisfy all in-use emissions pass criteria resulting in the vehicle to comply with in-use emissions regulations.

Table 35: NTE Emissions Threshold Validation Results

NTE Emissions Threshold for MY2010 & Later HHDDE		Ref. Data	PEMS A	PEMS B
		[g/bhp-hr]	[g/bhp-hr]	[g/bhp-hr]
CO	Cert. Std.	15.5	15.5	15.5
	NTE Multiplier	1.25	1.25	1.25
	Accuracy Margin	0.25	0.25	0.25
	Compliance Margin	NA	NA	NA
	NTE Threshold	19.63		
NOx	Cert. Std.	0.2	0.2	0.2
	NTE Multiplier	1.5	1.5	1.5
	Accuracy Margin	0.15	0.15	0.15
	Compliance Margin	0.1	n/a	0.1
	NTE Threshold	0.55		
NMHC	Cert. Std.	0.14	0.14	0.14
	NTE Multiplier	1.5	1.5	1.5
	Accuracy Margin	0.01	0.01	0.01
	Compliance Margin	NA	NA	NA
	NTE Threshold	0.22		
NOx + NMHC	Cert. Std.	0.34	0.34	0.34
	NTE Multiplier	1.5	1.5	1.5
	Accuracy Margin	0.16	0.16	0.16
	Compliance Margin	0.1	n/a	0.1
	NTE Threshold	0.77		

The second eight hour long dataset referred to as “upper-limit” dataset is exactly same as the master dataset except for the last hour where the emissions concentrations are set such that the vehicle would fail for exceeding the upper limit of NOx emissions, which is 2.0 g/bhp-hr.

The third eight hour long dataset referred to as “Rfail” dataset is also same as the master dataset but for the last hour data where the emissions values are designed to fail the emissions threshold values for known number of NTE events such that time-weighted vehicle pass ratio for NOx emissions is lower than 90% leading to failure of the vehicle for in-use emissions compliance.

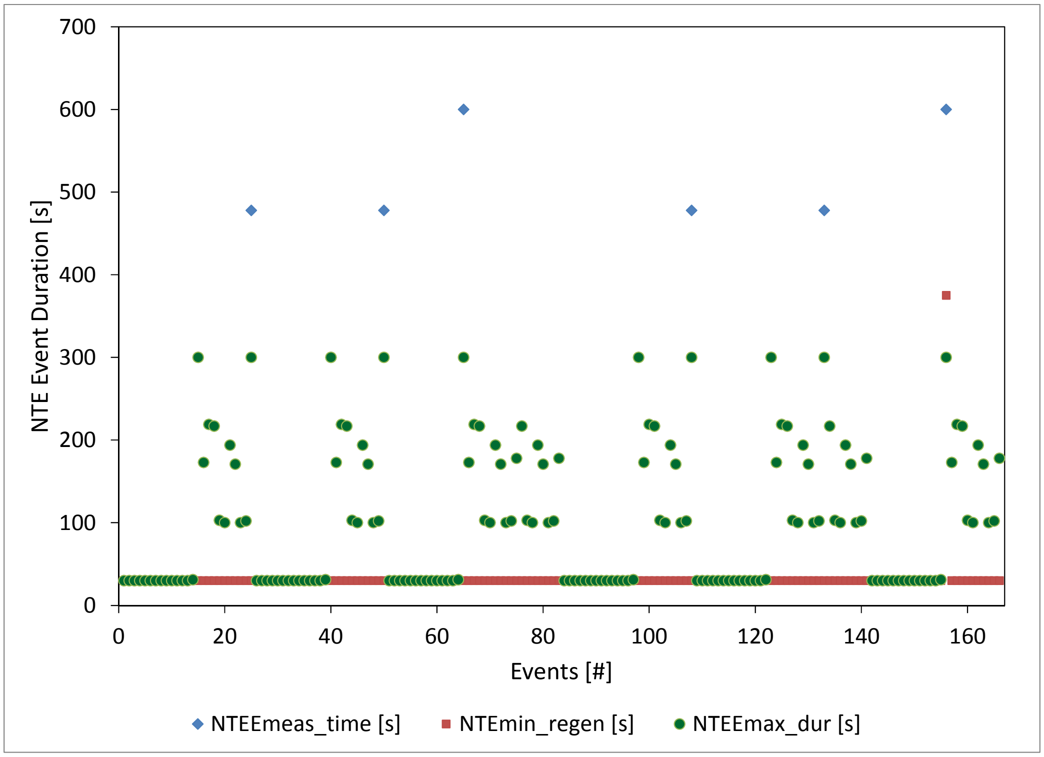


Figure 46: Trace of Expected Number of NTE Events and Durations

The expected number of NTE events and their durations for all the three different 8 hour reference dataset are illustrated in Figure 46. It also shows the minimum event time, referred to as "$\text{NTE}_{\text{min\_regen}}$," resolved based on DPF regeneration periods along with time-weighted duration, referred to as "$\text{NTE}_{\text{max\_dur}}$," used in determining vehicle pass ratio. Note that all three different 8 hour reference datasets consists of same number of NTE events except for the emissions rate of the last hour. The results of the number of NTE events, their duration, vehicle pass ratio resolved based on the number of events that satisfies the emissions threshold of different pollutants, and the number of events that fail the NTE upper limit as obtained from three different emissions post-processing software for three different datasets is illustrated in Table 36.

The brake-specific emissions of regulated pollutants for the master dataset along with NTE event threshold brake-specific emissions are illustrated in Figure 47, Figure 48 and Figure 49. It is evident from the trace that brake-specific NTE event emissions are below threshold values for all pollutants except for NOx where it exceeds the threshold for 12 out of 166 NTE events. However, the vehicle still passes the in-use emissions compliance test with a NOx vehicle pass ratio of 98%.

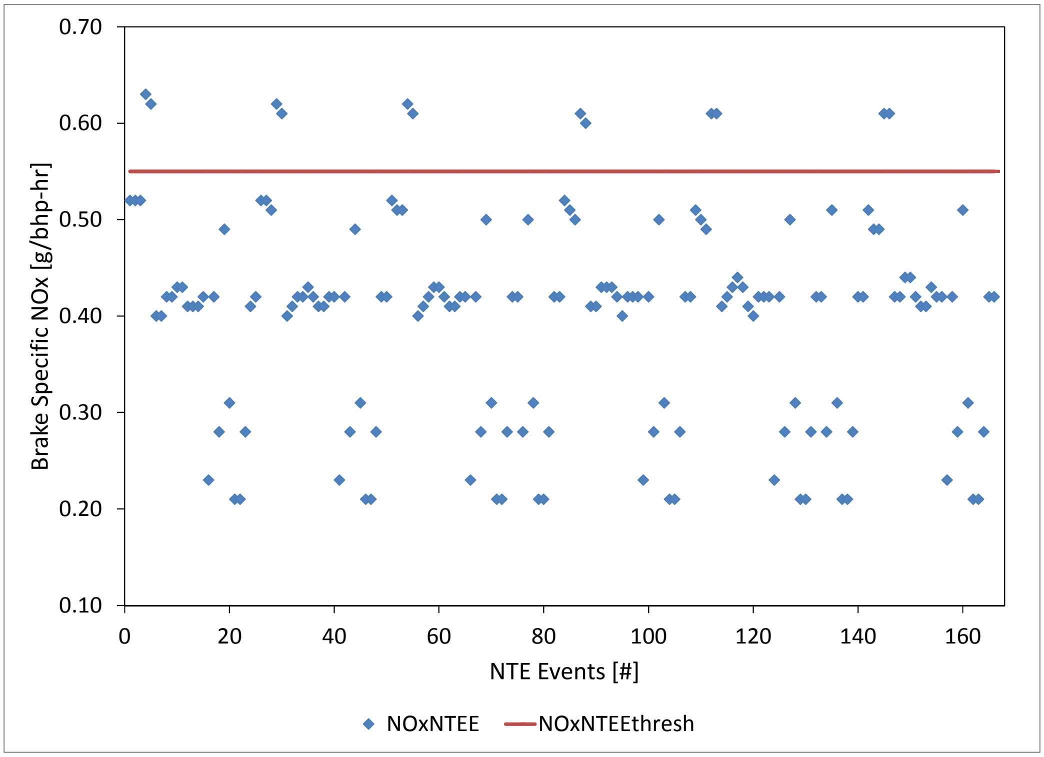


Figure 47: Trace of Expected BSNOx Emissions for Different NTE Events

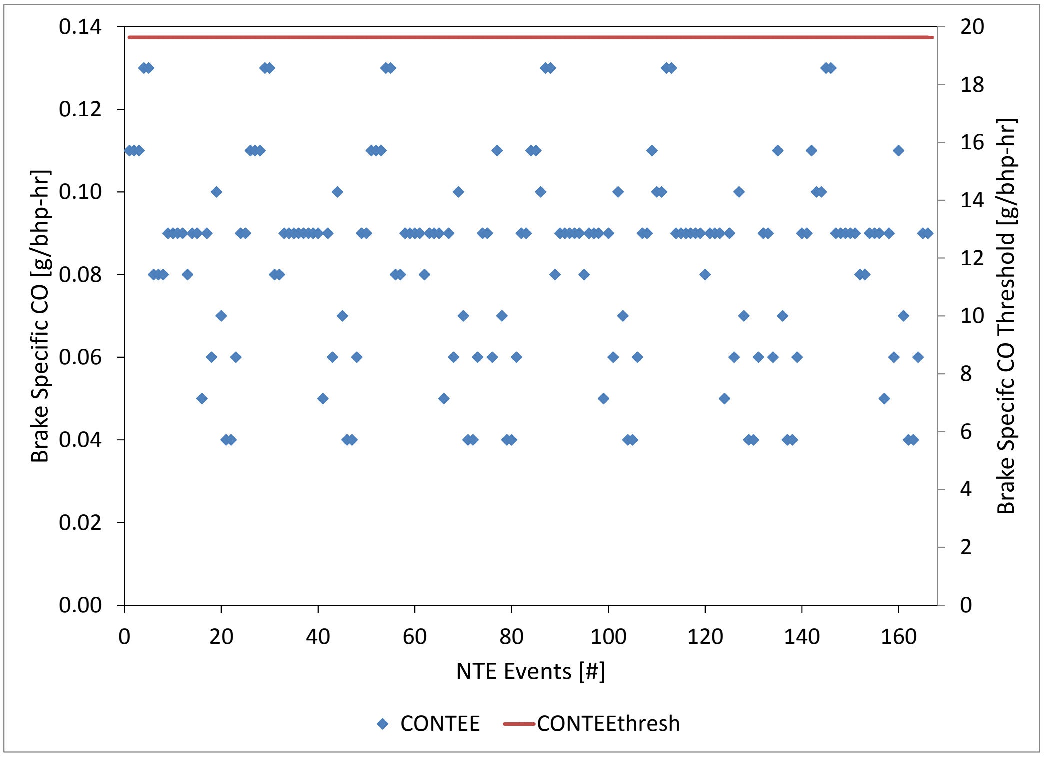


Figure 48: Trace of Expected BSCO Emissions for Different NTE Events

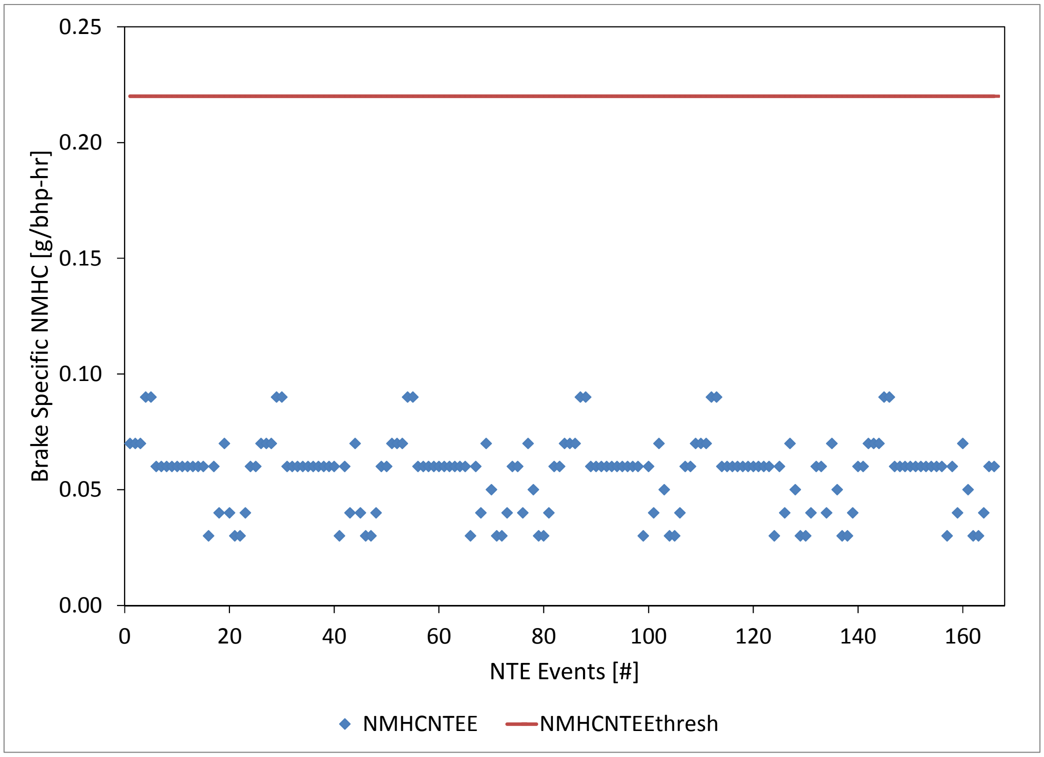


Figure 49: Trace of Expected BSNMHC Emissions for Different NTE Events

The brake-specific emissions of NOx for the other two 8 hour datasets are illustrated in Figure 50 and Figure 51 which results in failing the vehicle for NOx emissions not meeting the vehicle pass ratio and the other for not satisfying the upper limit of NOx emissions for the events that do not meet the NTE event NOx threshold.

A comparison of the number of NTE events and their duration derived from the first hour of reference dataset using PEMS A and in-house data post-processing software with the expected values that are known *a priori* is illustrated in Figure 52. It is evident from the illustration that the two data post-processors do not follow the trend of the expected results exactly. Note that the expected results with zero duration represents non-NTE event. The in-house post-processor results are the closest to the expected results except for two extra events due to error in the engine speed definition of the NTE zone and incorrect interpretation of exhaust aftertreatment temperature exclusion. In the case of PEMS A post-processor it fails to identify the non-NTE events except for the one with high altitude exclusion, and one for ambient temperature exclusion. The PEMS B post-processor result, which is not illustrated, shows that the number events, their occurrence and durations are different from the expected results.

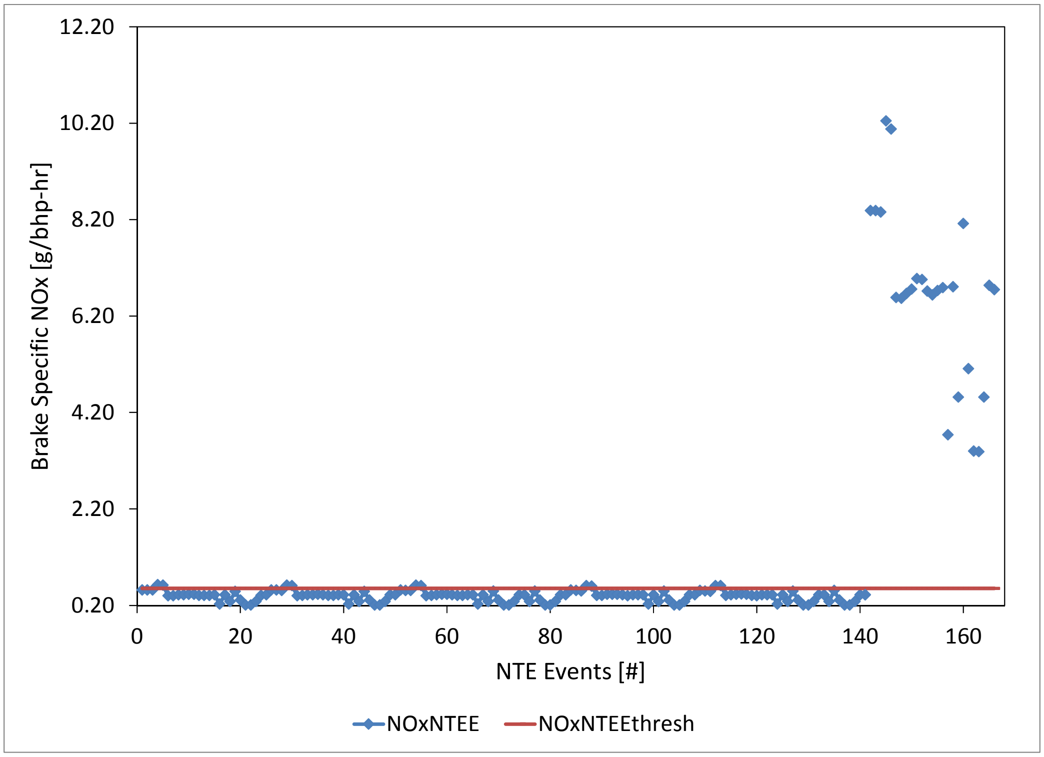


Figure 50: Trace of Expected BSNOx Emissions for Rfail 8-Hour Dataset

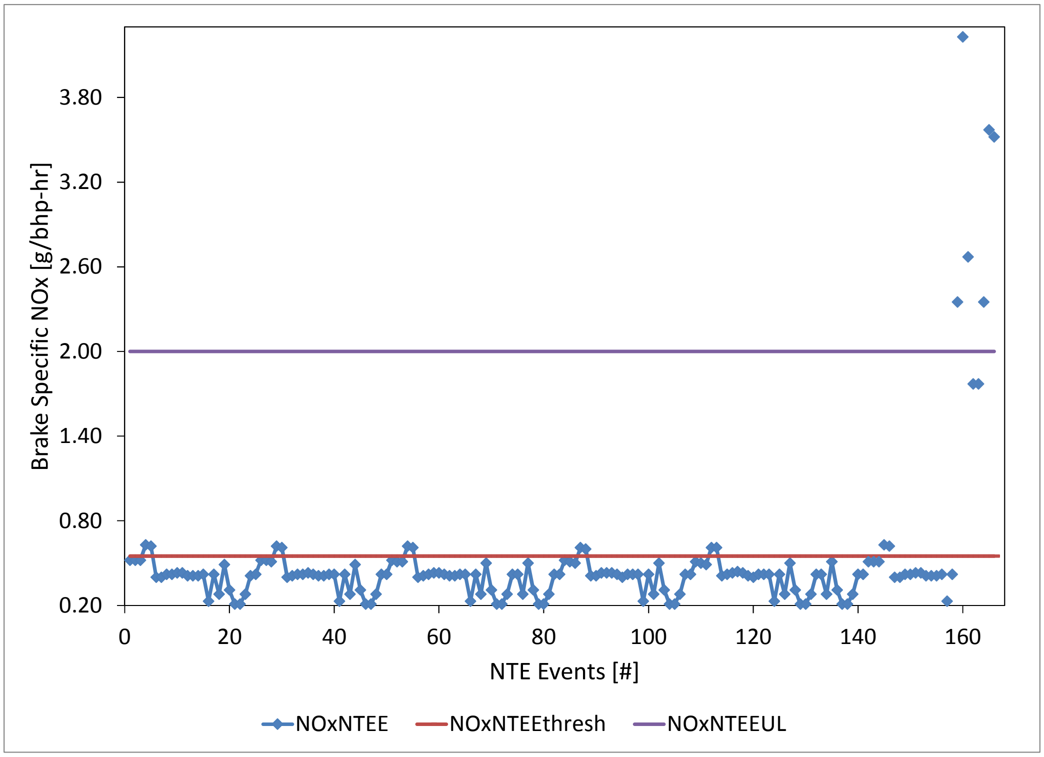


Figure 51: Trace of BSNOx Emissions for ULfail 8-Hour Dataset

A summary of the number of NTE events, vehicle pass ratio for each regulated pollutant, number of events that fail threshold emissions for each emissions constituents that results in a vehicle pass ratio of less than one, and the number of events that fail the NTE emission upper limit for each of the eight hour long reference dataset is illustrated in Table 36. Note that the events produced by PEMS A and PEMS B post-processors does not consider the IMT and ECT exclusions as it would result in zero NTE events. Furthermore, the NTE events produced by PEMS B post-processor does not align with the same time as that of the expected results because of the difference in the definition of NTE zone and the inconsistent time interval of the input dataset.

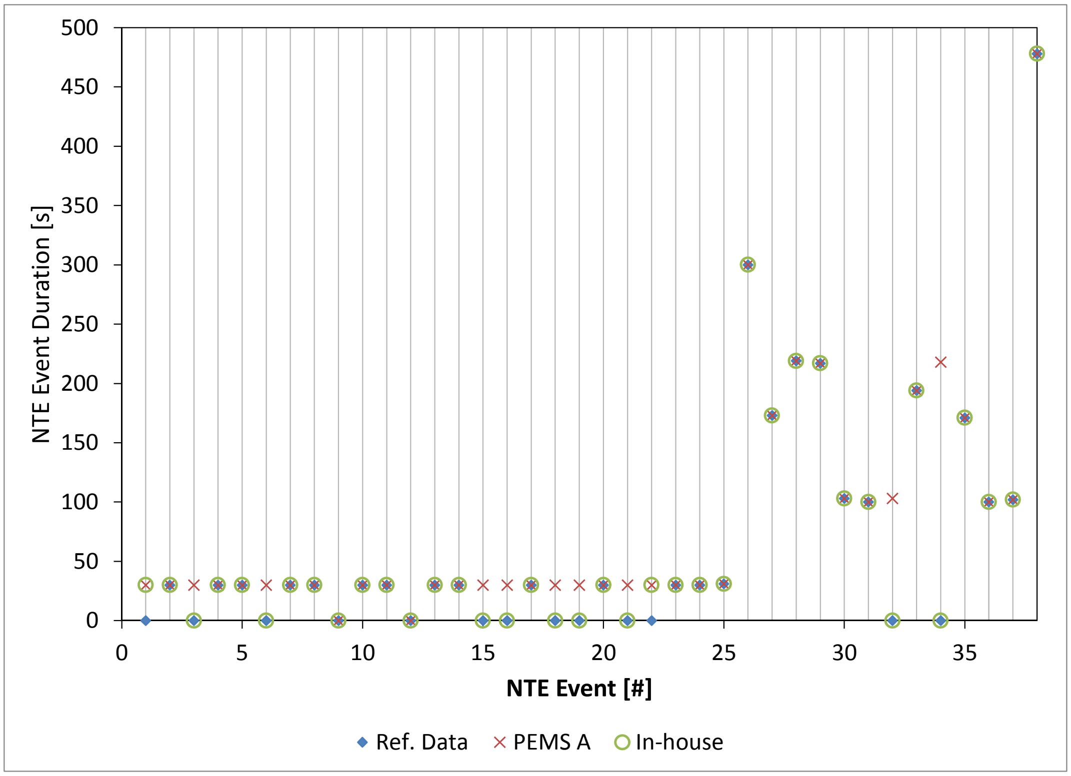


Figure 52: Comparison of NTE Event Numbers and Duration with Expected Results

It is evident from the summary table which lists only the Meta data based on which a vehicle, without going into the detail of verifying the correctness of exclusions and other emissions quantification method, can be classified to comply with in-use emissions regulations using the PEMS B and in-house data post processing software. Whereas, the vehicle would not comply with in-use emissions based on PEMS A data reduction software. Note that all three data post-processor are being supplied with same input dataset.

Table 36: Summary of 8-Hour NTE Reference Datasets Results From Different PEMS Post-Processors

Dataset	Meta Data	Ref. Data	In-house‡	PEMS B†	PEMS A#
8 Hour Master Dataset	Total Valid NTE Events with Exclusions	166	216	190*	288
	Maximum Measured Duration	600	600	613	600
	Maximum Time Weighted Duration	300	300	300	300
	NOx Vehicle Pass Ratio	0.98	0.97	0.97	0.85
	NMHC Vehicle Pass Ratio	1	1	1	1
	CO Vehicle Pass Ratio	1	1	1	1
	Number of Events failing NOx NTE Threshold	12	16	9	51
	Number of Events NOx NTE Upper Limit	0	0	0	0
8 Hour Rfail Dataset	Total Valid NTE Events with Exclusions	166	216	190*	288
	Maximum Measured Duration	600	600	613	600
	Maximum Time Weighted Duration	300	300	300	300
	NOx Vehicle Pass Ratio	0.84	0.84	0.85	0.74
	NMHC Vehicle Pass Ratio	1	1	1	1
	CO Vehicle Pass Ratio	1	1	1	1
	Number of Events failing NOx NTE Threshold	35	41	35	82
	Number of Events failing NOx NTE Upper Limit	25	27	27	36
8 Hour ULfail Dataset	Total Valid NTE Events with Exclusions	166	216	190*	288
	Maximum Measured Duration	600	600	600	600
	Maximum Time Weighted Duration	300	300	300	300
	NOx Vehicle Pass Ratio	0.91	0.92	0.90	0.79
	NMHC Vehicle Pass Ratio	1	1	1	1
	CO Vehicle Pass Ratio	1	1	1	1
	Number of Events failing NOx NTE Threshold	20	24	17	60
	Number of Events failing NOx NTE Upper Limit	6	6	6	8

*NTE event duration and occurrence do not align with the expected results.

‡Does not include RF exclusion.

†Does not include RF, IMT, ECT, and aftertreatment exhaust temperature exclusion.

#Does not include RF, 0.3Tmax, 0.3Pmax, IMT, ECT, and aftertreatment exhaust temperature exclusion.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The new discipline of in-use emissions regulations and measurement for on-road heavy-duty diesel engines have created opportunities to further reduce harmful emissions produced by engine operating under conditions that are not represented in the certification test cycles. Furthermore, it has also increased the prospects to develop portable emissions measuring devices that can measure emissions constituents over long hours with accuracies close to laboratory grade emissions analyzers. Additionally, the advances in engine and vehicle on-board diagnostics along with the drive-by-wire technology being adopted for engine control have made the in-use emissions measurement and engine performance analysis an innovative approach in developing engines. As a result, increased effort have been employed in standardizing the emissions measuring devices used for in-use emissions measurement and the protocols adopted to qualify such devices for in-use applications. Furthermore, EPA in negotiation with EMA have developed in-use emissions regulations used for quantifying brake-specific emissions within a defined engine operation region known as NTE zone. The boundaries for this zone are fixed based on engine maximum torque curve, maximum power, maximum torque and engine speed, which is a function of speed used to create ESC operating points. In addition to this zone there are several exclusions that invalidate engine operation in the NTE zone based on test altitude, ambient temperature of the test location, cold operating conditions based on emissions reduction technology, and based on the aftertreatment technology the minimum time required for an operation to be considered as a valid event. Since there are no protocols to validate the in-use emissions measuring system based on real world emissions produced by a baseline vehicle on a baseline route, which is designed to simulate the exclusions that are prescribed in the regulations it becomes essential to develop such protocol to verify the data reduction code. Nevertheless, PEMS devices are qualified for in-use emissions measurement by comparing its emissions results against laboratory measurement devices over the FTP cycle. Note that this test will only serve in validating the accuracy of measuring and quantifying emissions by in-use grade emissions analyzers against certification grade analyzers. Therefore, in the direction of serving the purpose of verifying the integrity of interpreting the in-use regulations in quantifying the emissions a reference dataset, which includes the exclusions as applied for on-road engine is developed. Note the dataset is synthesized and reduced to produce required results. This dataset is formatted to represent the output file of a PEMS device and then used to evaluate the response of its data reducing software against the expected results that are known *a priori*.

The reference dataset thus developed is eight hour long representing data collected over a work shift. The dataset consists of steady state engine operation at different engine speed and torque values, while exhaust flow and concentration of emissions constituents varying sinusoidally along with ambient parameters. The emissions concentrations are varied over the last hour of the test in order to produce two more datasets that fails the vehicle for vehicle pass ratio and failure of emissions upper limit for NOx. The reference dataset is developed using dry concentration values as the basis, and the ambient temperature and pressure are varied such that it leads to ambient humidity values that requires correction of NOx emissions as per in-use emissions regulations, which is different from other regulatory requirements. The reference dataset also includes DPF regeneration signal to evaluate the calculation of RF value and its application in determining minimum NTE event time in when there is DPF regeneration activity during a valid NTE event. All three datasets consists of 200 NTE events without DPF regeneration exclusion and 166 NTE events after applying DPF regeneration exclusion. A pictorial representation of the valid NTE events for the aforementioned scenarios is shown in Figure 53.

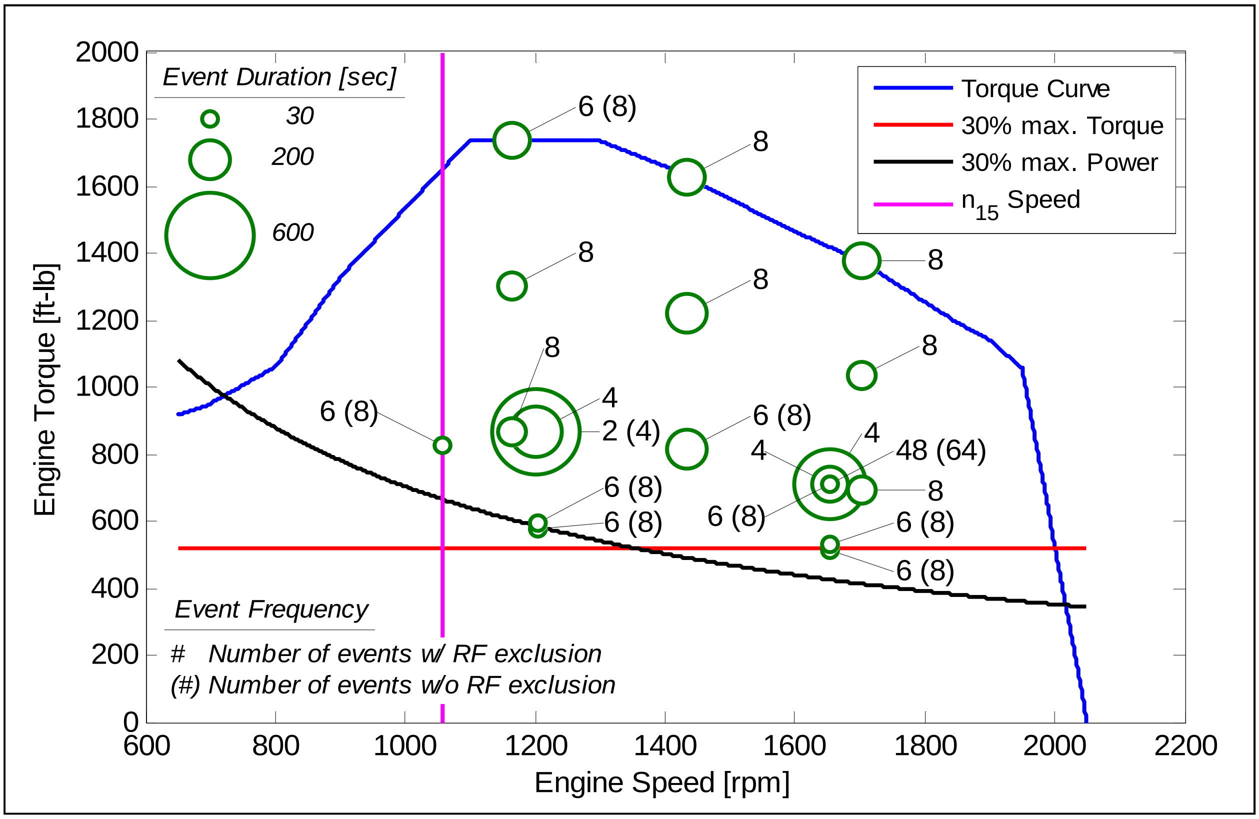


Figure 53: Illustration of NTE Events, Duration and Occurrence in Reference Dataset

The reference dataset was used to evaluate three in-use emissions data post-processing software, two of them were stand-alone emissions reduction software supplied with PEMS device and one developed in-house. It was found that all three data post-processors were not able to resolve regeneration fraction value based on DPF generation event durations and hence unable to exclude NTE events using minimum NTE event duration criteria during DPF regeneration. The NTE zone engine speed boundary value was one rpm lower than the expected value for PEMS B post-processor, also the definition used for excluding NTE operating point based on engine speed included the events where engine speed is equal to n_{15} leading to counting of extra events. Furthermore, due to inconsistent time stamps at which data is recorded by PEMS B and by fixing the time interval of the post-processed data the data reduction software interpolates the value for the fixed millisecond interval of the results leading to discontinuity and longer NTE events than expected also causing the NTE events to occur at different time intervals. Therefore, some of the exclusion criteria could not be evaluated for PEMS B post-processor. Additionally, PEMS B post-processor resulted in zero NTE events after choosing the IMT and ECT exclusions that are applied for EGR equipped engines. The humidity correction factor criteria used for NOx emissions did not agree with the reference data values hence resulting in lower total NOx emissions.

The PEMS A data post-processor required user involvement in terms of an input file which consists of user supplied equations to manipulate the input data in order to quantify emissions mass rate and engine brake work creating additional burden on the enforcement agencies to inspect the relationships used to arrive at the final brake specific emissions. The major findings in the evaluation of PEMS A post-processor are it cannot qualify NTE events based on NTE torque and power boundaries, the definition of IMT and ECT exclusions are reversed causing an NTE event to be accepted when the measured IMT and ECT values are lower than the limit, in other words when the engine is working under cold operating conditions, it cannot resolve RF values and apply to exclude NTE events with DPF regeneration that does not last longer than the minimum NTE event time with regeneration. As a result of the above shortcomings PEMS A data post-processor produced highest number of NTE events. The k_h factor used to correct NOx emissions for intake air humidity did not agree with the criteria mandated for in-use emissions measurement and was lower than the expected values resulting lower NOx emissions.

The NTE zone definition generated by the in-house data post-processing software did not agree with the expected NTE definition for engine speed boundary as it is lower by one rpm resulting in counting an extra event for engine speed equal to n_{15}. The definition of the criteria used to exclude NTE events based on exhaust temperature downstream of an oxidation catalyst was incorrect where it considers exhaust temperatures being equal to 250 °C as valid NTE point. The in-house data reduction software was not capable of resolving RF, therefore resulting higher number of NTE events. The k_h values used to correct NOx emissions were based on relationship provided in 40 CFR 1065.670 hence resulting lower NOx emissions similar to other data post-processors. Also, the in-house data post-processor was not designed to provide with vehicle pass ratio results and validating the upper limit of emissions for the events that failed the NTE emission threshold values.

Based on the above results it is clear that a reference dataset was able to identify the discrepancy in interpreting the regulations and the short coming of commercial in-use data post processors in evaluating NTE emissions as per regulations. Therefore, for the same reference dataset different post-processors produced different number of events and one of the post-processors even stated that the vehicle failed to comply with in-use emissions regulations for NOx where it actually should have passed as per the expected values.

7.2 Recommendations

As reference dataset also serves as guideline for developing data reduction software in accordance to emissions calculations mandated under different emissions measurement protocols it is recommended to develop similar dataset for other test protocols, such as transient and steady state tests conducted in laboratory and chassis dynamometer. Also there is always ambiguity associated in the interpretation of regulations and it is recommended to develop complete dataset which can be input to different data reduction software instead of providing simple examples at the end each calculation type in quantifying emissions as mandated in the regulatory text such as CFR.

Develop reference datasets that incorporates certain real world scenarios experienced over several years of data acquisition in a particular field so that certain rules developed to handle those unique situations can be tested out before deploying the data reduction software to customers. Supply a reference dataset along with the round robin test engine in order to individually test the homogeneity of data acquisition system and the data reduction methodology followed by different emissions testing laboratories with respect to EPA standards.

Maintain a reference dataset for each measurement protocol. For example, in-use emissions testing, locomotives emissions testing, emissions test for certification, etc. so that any amendment to the respective regulations that changes the emissions quantification method or any criteria applied towards validity of engine operation can be easily verified by implementing those changes in the reference dataset and employing it to verify user developed data reduction code for agreement with expected results.

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9 APPENDIX

This appendix discusses the results of the in-house data post-processing software after rectifying an interpolation mistake in the data post-processing logic based on the expected results from the reference dataset explained in the thesis.

9.1 NTE Event Validation Results

The tables comparing the expected and the actual data post-processing results from in-house data post-processing software are shown below only for those NTE event validation criterion that did not match the expected results discussed under Chapter 6 – Results and Discussion.

9.1.1 NTE Engine Speed Validation Results

The in-house data reduction software was found to be using engine power, a calculated variable, in order to define the n_{lo} and n_{hi} engine speeds discussed in section 4.2.1 instead of the published torque values that satisfies the definition of n_{lo} and n_{hi} engine speeds resulting in an n_{15} engine speed one rpm higher than the expected value due to rounding error. Upon fixing this discrepancy the in-house data post-processor resulted in expected engine speed validation results.

Table 37: NTE Engine Speed Validation Results

Test Condition	Event Start	Event End	Engine Speed	Expected Results	In-house
NTE Engine Speed > n_{15} n_{15} = 1056 rpm	1	30	1055	Not NTE event	TRUE
	32	61	1056	Not NTE event	TRUE
	63	92	1057	NTE event	TRUE
Total NTE events				1	1

9.1.2 NTE Aftertreatment Device Light-Off Temperature Validation Results

On verifying the discrepancy between the expected and the resulted number of NTE events based on the aftertreatment light-off temperature criteria it was found that the validation criteria was incorrectly applied to be greater than or equal to 250 °C resulting in one extra NTE event. The relational condition was corrected resulting in one NTE event as expected for the given reference dataset.

Table 38: NTE Aftertreatment Device Light-Off Temperature Validation Results

Test Condition	Event Start	Event End	T_{exhAT}	Expected Results	In-house
NTE T_{exhAT} > 250 °C	652	681	249	Not NTE event	TRUE
	683	712	250	Not NTE event	TRUE
	714	743	251	NTE event	TRUE
Total NTE events				1	1

9.1.3 Minimum NTE Event Time Validation During the Event of DPF Regeneration

The in-house post-processing software was modified to calculate RF based on the DPF regeneration status signal acquired during in-use emissions test. Hence, the in-house data post-processor resulted in one NTE event for the duration of DPF regeneration presented in the reference dataset.

Table 39: Minimum NTE Event Time with DPF Regeneration Validation Results

Test Condition	Event Start	Event End	NTE Event Duration	Expected Results	In-house
NTE Event with DPF Regeneration $t_{NTE_{DPF}} \geq \frac{t_{DPF_{regen}}}{RF}$	21163	21692	30	Not NTE event	TRUE
	22438	23037	600	Not NTE event	TRUE
	26038	26637	600	NTE event	TRUE
Total NTE events				1	1

9.2 NTE Emissions Quantification Results

The results of the brake-specific NTE emissions quantified over a period of sixty seconds that resulted in engine brake work at an order of magnitude higher than the expected result using the in-house post-processor was corrected to reflect the data sample rate accurately and therefore achieving the expected results.

9.3 In-Use Emissions Compliance Results

The comparison of expected number of NTE events, number of events that fail for NOx emissions resulting in NOx vehicle pass ratio failure, and number of NTE events that result in exceeding NOx upper limit illustrated in Table 40 shows that the in-house data post-processor results matched with the expected results after correcting the code. Therefore, in summary the in-house results for in-use emissions compliance with the expected results for the given reference dataset.

Table 40: Summary of 8-Hour NTE Reference Datasets Results From In-house PEMS Post-Processors After Correcting the Code

Dataset	Meta Data	Ref. Data	In-house
8 Hour Master Dataset	Total Valid NTE Events with Exclusions	166	166
	Maximum Measured Duration	600	600
	Maximum Time Weighted Duration	300	300
	NOx Vehicle Pass Ratio	0.98	0.98
	NMHC Vehicle Pass Ratio	1	1
	CO Vehicle Pass Ratio	1	1
	Number of Events failing NOx NTE Threshold	12	12
	Number of Events NOx NTE Upper Limit	0	0
8 Hour Rfail Dataset	Total Valid NTE Events with Exclusions	166	166
	Maximum Measured Duration	600	600
	Maximum Time Weighted Duration	300	300
	NOx Vehicle Pass Ratio	0.84	0.84
	NMHC Vehicle Pass Ratio	1	1
	CO Vehicle Pass Ratio	1	1
	Number of Events failing NOx NTE Threshold	35	35
	Number of Events failing NOx NTE Upper Limit	25	25
8 Hour ULfail Dataset	Total Valid NTE Events with Exclusions	166	166
	Maximum Measured Duration	600	600
	Maximum Time Weighted Duration	300	300
	NOx Vehicle Pass Ratio	0.91	0.91
	NMHC Vehicle Pass Ratio	1	1
	CO Vehicle Pass Ratio	1	1
	Number of Events failing NOx NTE Threshold	20	20
	Number of Events failing NOx NTE Upper Limit	6	6