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Berk Demirgok

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Development of an Emissions Monitoring Methodology Using On-Board NO_x Sensors and Revision to Current In-Use Emissions Regulatory Protocols

Berk Demirgok

**Dissertation submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University**

in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy
in
Mechanical Engineering**

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EMS

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ABSTRACT

Development of an Emissions Monitoring Methodology Using On-Board NO_x Sensors and Revision to Current in-use Emissions Regulatory Protocols

Berk Demirgok

Measurement of in-use emissions from heavy-duty (HD) vehicles under real-world operation has been widely performed by using portable emissions measurement system (PEMS). PEMS serve as an accurate and lightweight emissions measurement system to evaluate in-use emissions from HD vehicles. However, emissions measurement using PEMS instrumentation can be time consuming and labor intensive. Advantage of utilizing already existing on-board sensors such that they can potentially provide an alternative measurement methodology to the PEMS. A successful implementation of an on-board NO_x sensor-based methodology for assessing in-use NO_x emissions will allow for a cost-effective and simplified approach to monitor real-world, NO_x emission rates. The technology of on-board NO_x sensors is in its initial stages to be used to monitor in-use NO_x emissions and the ability of the sensor to measure NO_x concentration during selective catalytic reduction (SCR) activity period is of concern. Furthermore, the on-board NO_x sensors are also subject to various cross-sensitivity and durability concerns.

The primary objective of this dissertation is to compare the on-board NO_x sensor response and accuracy against laboratory grade instrumentation that include PEMS using Non-Dispersive Ultra-Violet (NDUV) and Fourier transform infrared spectroscopy (FTIR) measurement to assess the measurement thresholds of on-board NO_x sensors. The study compares the cross-sensitivity of the NO_x sensors to ammonia (NH₃) concentration in the exhaust. NH₃ slip from SCR is believed to interfere with NO_x measurements using Zirconium oxide sensors and this study will discuss NH₃-NO_x cross sensitivity on on-board NO_x sensors during real-world HD vehicle activity. Results from this study will compare on-board NO_x sensor measurement capabilities and they will be assessed at different power levels related to different SCR conversion efficiency and different NO_x concentration levels related to measurements obtained from a laboratory grade emissions

measurement system FTIR. The secondary objective of this work is to explore and modify boundary conditions for the Not-to-exceed (NTE) and (Work-based window) WBW regulatory protocols due to deficiencies of current protocols in appropriately characterizing regulated emissions especially during the port drayage and urban activity, characterized by low-load engine operation. Thus, new revised regulatory protocols for a wide range of driving activity are needed for an accurate characterization of in-use NO_x emissions.

I dedicate this thesis to *Zahide & Bulent Demirgok*.

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1 CHAPTER I -INTRODUCTION

1.1 Introduction

Diesel engines have been primarily used as the leading propulsion systems in HD vehicles, locomotives, construction equipment and in many other applications. HDD vehicles are widely known as the main contributor to the NO_x emissions. The California Air Resources Board (CARB) estimates, over 80% of the smog forming NO_x to be contributed by the HDD transportation sector [1]. The United States Environmental Protection Agency (USEPA) has required HDD engine manufacturers to develop engines that are following emissions standards set by the agency. USEPA has required HDD engines to be certified on an engine dynamometer using the Federal Test Procedure (FTP) cycle up until 2004. Additional emissions testing requirements has been introduced after the 1998 Consent Decrees with six HDD engine manufacturers.

In a landmark settlement between the USEPA and the six HDD engine manufacturers Cummins, Detroit Diesel Corp., Mack Trucks, Navistar International Transportation Co., Caterpillar and Volvo for violating the Clean Air Act by installing defeat devices into their engines to defeat emission controls resulted in consent decrees for these seven engine manufacturers in 1998. The manufacturers had agreed to spend \$1 billion in research development to develop cleaner engines to reduce pollution from HDD engines [2]. A Supplemental Emissions Test (SET) cycle a steady-state test to confirm that HDD engine emissions are controlled during steady-state operations has been introduced and USEPA has required the SET cycle testing for all HDD engine manufacturers as a result of Consent Decrees. Moreover, a new compliance testing procedure has introduced to quantify emissions during real-world vehicle operation as part of 1998 Consent Decrees with HDD engine manufacturers. HDD engine manufacturers have been required to measure in-use emissions under real-world vehicle operating conditions.

The new requirement to measure in-use emissions has been performed using portable emission measurement systems (PEMS). West Virginia University (WVU) was selected by the settling HDD engine manufacturers to lead the in-use emission measurements and develop a measurement system to quantify emissions during real-world driving conditions. Furthermore, WVU developed a measurement system which ultimately led to the creation of the current PEMS

market [3]. Currently, measurement of in-use emissions from HD vehicles under real-world operation has been widely performed by PEMS. PEMS serve as an accurate and lightweight emissions measurement system to evaluate in-use emissions from HD vehicles. However, PEMS are complex and costly. They are not easy to install and potentially cause interruption of regular operation of a HD vehicle in its daily operation. Advantage of utilizing already existing on-board sensors in HD vehicles is that they provide a cost-effective alternative monitoring system to the PEMS. A successful implementation of an on-board NO_x sensor-based methodology for assessing in-use NO_x emissions will allow for a cost-effective and simplified approach to monitor real-world, in-use NO_x emission rates and simultaneously verify compliance of a large fleet of HD vehicles with in-use emission regulations.

1.2 Problem Statement

The majority of the transportation sector is powered by HDD engines which have historically shown to be characterized by high NO_x and PM emissions. However, stringent emission regulations have forced U.S engine manufacturers to adopt PM and NO_x aftertreatment systems to cut tailpipe emissions of NO_x and PM by orders of magnitude compared to legacy diesel engine technology. Brake-specific PM (bsPM) emissions standard of 0.01 g/bhp-hr has been accepted since 2007, while the US-EPA planned to phase-in the 0.20 g/bhp-hr NO_x emission standard as two phases between 2007 and 2010. Engines developed during the phase-in period were certified at 1.2 g/bhp-hr NO_x. All engines were designed to meet the NO_x emissions limit of 0.20 g/bhp-hr since 2010. The engines developed under the phase-in period were equipped only with a DPF and NO_x control was achieved entirely through an EGR and combustion optimization strategy. All engine manufacturers with the exception of Navistar adopted the SCR pathway to achieve the US-EPA 2010 NO_x emissions limit. Navistar adopted the high EGR rate coupled with an advanced combustion strategy to achieve NO_x standards. With this strategy, Navistar 2010 engines were certified by US-EPA and CARB at or above 0.5 g/bhp-hr NO_x. However, with the use of emissions credits, Navistar was able to meet the US-EPA 2010 NO_x emission standard of 0.20 g/bhp-hr.

Manufacturers utilizing the SCR technology were able to certify engines below the 0.20 g/bhp-hr NO_x emission standard. The SCR technology injects aqueous urea into the exhaust stream (Diesel Exhaust Fluid-DEF) to release ammonia through a process of thermal hydrolysis in the hot exhaust. The SCR catalyst in the presence of the ammonia reduces NO_x to nitrogen and water. However, the efficiency of the SCR aftertreatment system is strongly dependent on exhaust gas temperatures. A temperature threshold of 200-250 °C has been identified as the lower operating temperature of the SCR aftertreatment system depending on the SCR aftertreatment technology. Manufacturers do not intend to inject urea below the 200-250 °C temperature threshold to prevent urea deposits and undesired secondary emissions.

The minimum operating temperature requirement of an SCR system could contribute to significant mass emission rates of NO_x from certain applications that are characterized by extended idle and creep mode operation. Traffic conditions and vehicle vocation can contribute to significant differences between certification NO_x values and in-use NO_x emissions from HDD SCR equipped vehicles.

The USEPA requires HDD engines to be certified on an engine dynamometer using FTP and SET cycles. Post-consent decree, the USEPA promulgated the in-use compliance procedure, that requires manufacturers to demonstrate emissions compliance within the NTE region for a minimum duration time of 30 seconds. The USEPA relies primarily on the data gathered by engine manufacturers to assess in-use compliance. Although, NO_x and PM emissions of HDD engines are regulated during in-use operation, studies have highlighted upon the significant deviations in break-specific NO_x (bsNO_x) emissions compared to certification values during off-cycle operation [4]. These high NO_x emissions from HDD engines are often observed during cold start and low-load engine operation, during which the selective catalytic reduction (SCR) aftertreatment system (primary NO_x control) is not active [5]. Furthermore, the low-load operations linked to high NO_x emissions are outside the bounds of the NTE region and hence, exempt from compliance.

Furthermore, activity of the SCR during off-cycle operations of port drayage trucks, characterized by low-load engine operation have shown bsNO_x emissions to be six to nine times higher than certification values and HDD engines between MY13 and MY14 equipped with diesel

particular filter (DPF) and SCR show similar trends over real-world vehicle operation during the near-port activity, characterized by low-load operations [4]-[6]. However, the magnitude of deviation from these newer MY vehicles were between two and five times from the certification standard of 0.20 g/bhp-hr. Since, the promulgation of the in-use emissions standards, USEPA and engine manufacturers have agreed to multiple exclusions to the NTE standard [7]. Moreover, the 30 second NTE window criteria is more conducive to evaluate compliance of long-haul truck application with sustained highway speeds and consequently a constant engine load, as opposed to urban delivery trucks, transit buses and refuse truck applications. Like the USEPA's in-use compliance program, European Union (EU) has introduced the HD Euro VI Regulation (EC) No 595/2009 and implemented Regulation (EC) 582/2011 an in-use compliance procedure to evaluate in-use emissions from HD vehicles [8]. In this procedure, emissions of each pollutant in the entire test route is recorded using PEMS as a function of engine work. Then, these recorded data are binned into segments which are called "work-windows" based on the reference work obtained over the World Harmonized Transient Cycle (WHTC) cycle. This method is referred as WBW method to evaluate off-cycle emissions from HD vehicles in Europe.

Studies have seldom reported data on the details of NTE and WBW emission rates of HD truck operation. This lack of literature could be attributed to the fact that a majority of the in-use compliance testing is conducted by the engine manufacturers for submitting data to the USEPA. There exists, therefore a critical need to assess and characterize off-cycle NO_x emission rates from modern HD trucks operating in urban, port drayage activity and extended freeway type operation.

Currently, measurement of in-use emissions from HD vehicles under real-world operation has been widely conducted by utilizing PEMS. However, an alternative and cost-effective measurement method can be developed using on-board NO_x sensors. These sensors are available on every modern HD vehicle and they are already used by OEMs for purpose of on-board diagnostics (OBD). Thus, development of a cost-effective emissions monitoring system based on these sensors will provide broad in-use emissions assessment from a large number of HD vehicles.

The rationale of this work is that on-board tailpipe NO_x sensors can be used to accurately quantify NO_x emissions from HDD vehicles and a successful implementation of an on-board NO_x sensor-based methodology for assessing in-use NO_x emissions will allow for a cost-effective and simplified approach to monitor real-world, in-use NO_x emission rates and simultaneously verify compliance of a large fleet of HDD vehicles with in-use emission regulations. This work will assess the measurement accuracy of on-board NO_x sensors and evaluate whether on-board NO_x sensors can measure accurately in-use NO_x emission rates at near-zero levels. Moreover, this research will significantly improve current boundary conditions for the NTE and WBW regulatory protocols to characterize in-use NO_x emissions during real-world vehicle operation especially during the port drayage and urban activity, characterized by low-load engine operation.

1.3 Objectives

The *global objective* of this study is to assess the measurement thresholds of on-board NO_x sensors to evaluate real-time NO_x emission rates and provide an in-use NO_x emissions monitoring system that can be easily implemented into large number of vehicles while the monitoring system utilizes updated in-use emissions regulatory protocols. The following three specific objectives are proposed to accomplish the global objective of this work:

Specific objective 1: *Development of a Matlab®-based software tool for in-use data analysis according to the WBW and NTE regulatory protocols, with a graphical user interface*

A Matlab®-based software tool is developed for both NTE and WBW regulatory protocols. The tool allows users to select between different reduction methods (i.e. NTE and WBW) for on-road applications while providing the flexibility of selecting a range of exclusions as well as set the threshold values for these exclusions and other parameters, including power, torque threshold and window size. The window criterion is implemented such that different windowing methods (reference engine work or CO₂ mass) are possible.

Specific objective 2: *Conduct a sensitivity analysis on the existing NTE and WBW approaches and identify potential changes to specific thresholds and exclusion boundaries of these regulatory protocols to represent the emission factors of HDD vehicles operating under low-load driving conditions as well as propose changes for new in-use emissions regulatory protocols*

From a real-world testing perspective, and depending on the vocation of vehicle operation, the in-use compliance procedure using current NTE or WBW methods could potentially result in no valid NTE or WBW events to assess in-use compliance. This part of the research performs a comprehensive sensitivity analysis on the existing in-use emission regulatory protocols to examine the effect of critical thresholds and exclusions. After the assessment of the effect of these thresholds and exclusions, a revision is made to the existing protocols to represent the emission factors from HDD vehicles operating under low-load conditions.

Specific objective 3: *Investigate on-board NO_x sensors from HDD trucks and demonstrate their potential to monitor real-world bsNO_x emissions of HDD vehicles*

This part of the research consists of developing a cost-effective in-use NO_x emissions monitoring methodology making use of current available on-board NO_x sensors technology already existing on HDD vehicles to evaluate in-use bsNO_x emissions by demonstrating that on-board NO_x sensors are accurate enough for this purpose. It is necessary to show that the accuracy in utilizing these sensors that they are accurate enough to be accepted as a sensor that will be used in development of a cost-effective emissions monitoring system.

2 CHAPTER II - REVIEW OF LITERATURE

Diesel engines also known as compression ignition engines are used in various field. They are used in on road trucks to deliver goods, transit buses, refuse trucks and many other on and off-road applications. However, HDD engines had been known for high NO_x and PM emissions. In 1974, EPA initiated a program to assess emissions from diesel engines. Since then, engine manufacturers are subjected to shifting emissions regulations established by the EPA and CARB. Stringent emission regulations and fuel economy demands have pushed the engine manufactures and researchers to explore newer technologies and develop advanced engine and aftertreatment control strategies to reduce emissions and lower fuel consumption. Currently, USEPA 2010 regulations require the bsNO_x emissions from HD engines tested over the FTP engine dynamometer cycle to be at 0.20 g/bhp-hr or below and bsPM emissions at 0.01 g/bhp-hr or below. In 2014, CARB has introduced a program called “Optional Low NO_x Standards” where HD engine manufacturers may choose to certify their engines at low NO_x standards of 0.1, 0.05 or 0.02 g/bhp-hr [9]. It is well known that FTP cycle is not capable of accurately representing of real-world vehicle operation conditions. Even though, the SET cycle introduced as an additional testing for all HDD engine manufacturers, emissions measured in a test cell varies from in-use emissions. There was still a need for additional emissions testing requirements to measure emissions levels in real-word driving conditions. Hence, an in-use emissions testing program in an agreement with the HD engine manufacturers was developed after the Consent Decrees in 1998.

The Consent Decrees has required in-use emissions testing for HD engine manufacturers and the HD engines must meet with the NTE standards. Similarly, EU has initiated an in-use testing program in 2004. The HD Euro VI Regulation (EC) No 595/2009 and implemented Regulation (EC) 582/2011 an in-use compliance procedure to evaluate in-use emissions from HD vehicles has been introduced in Europe since 2011.

2.1 NTE and WBW Regulatory Protocols

2.1.1 NTE In-use Emissions Regulatory Protocol

The US EPA has introduced NTE evaluation as part of 1998 Consent Decrees with HDD engine manufacturers. The Consent Decrees require that engines must meet the NTE standards. Since, the promulgation of the in-use emissions standards, USEPA and engine manufacturers have agreed to multiple exclusions to the NTE standard. In addition to the requirement of a minimum of 30 seconds of operation within the NTE region, the current NTE regulatory protocol provides multiple exclusions such as exhaust aftertreatment temperature requirements, intake manifold temperature (IMT) requirements, engine coolant temperature (ECT), altitude restrictions [10]. The exclusion criteria will decide the validity of a 30 second NTE operation to be used for compliance assessment. Moreover, the NTE zone is defined by the USEPA in an agreement with Engine Manufacturer Association (EMA) as a representing area under the engine performance (lug) curve in which engine mostly operates at high-load and the steady state test modes of the SET cycle. In NTE regulatory protocol, break-specific emissions are calculated when engine is operating in the NTE zone for at least 30 seconds and they must be lower than the in-use emissions standards derived from the engine certification standards. Figure 1 represents the current NTE zone defined by engine speed, torque and power thresholds. To find a vehicle is operating in the NTE zone, following exclusions and boundary conditions must be satisfied [7], [11]:

- i) All engine speeds must be above 15% above the European Stationary Cycle (ESC) speeds ($n_{ESC\ 15\%}$) as shown in eq. 1:

$$n_{ESC\ 15\%} \leq n_{lo} + 0.15 * (n_{hi} - n_{lo}) \quad (1)$$

where: n_{hi} : The highest engine speed obtained from the engine lug curve where 70% of the maximum power is observed

n_{lo} : The lowest engine speed obtained from the engine lug curve where 50% of the maximum engine power is observed

Currently, the engine speed is recorded directly from the engine control unit (ECU) through J1939 protocol. However, n_{hi} and n_{lo} engine speeds are not directly broadcasted in ECU and must be calculated as described above.

- ii) All engine load points must be equal or greater than 30% of the maximum engine torque value obtained from the engine lug curve
- iii) All speed and load points must be excluded where the engine power produced by the engine is less than 30% of the maximum power produced by the engine

The engine brake torque is not directly broadcasted through ECU and it is determined based on the parameters broadcasted through J1939 protocol such as actual engine percent torque (AEPT), nominal friction torque (NFPT) and engine reference torque. The engine brake torque can be calculated as shown in eq .2 [10]:

$$T_{brake} = [(AEPT - NFPT) * T_{engine\ reference\ torque}]/100 \quad (2)$$

Once the engine brake torque is determined, the engine power and work can be calculated as shown in eq. 3 and 4 respectively [12]:

$$P_{brake} = brake_{torque} * Speed/5252 \quad (3)$$

$$W_{brake} = [Engine_{power} * \Delta t]/3600 \quad (4)$$

where: Δt is sampling time (s)

T_{brake} is the engine brake torque (ft*lb)

P_{brake} is the break engine power (bhp)

W_{brake} is the engine brake work (bhp-hr)

Besides of the speed and load boundary conditions, NTE regulatory protocol includes temperature, altitude and aftertreatment temperature exclusions as follows:

- iv) Engines equipped with EGR systems to reduce NO_x emissions. This exclusion was introduced due to the issues of EGR operation at cold IMT. During cold temperature operation, the EGR system may be disabled to prevent damage to the system [13]. IMT values obtained from ECU (IMT_{ECU}) must be equal or greater than the theoretical IMT (IMT_{IMP}) calculated as a function of absolute intake manifold pressure. IMT_{ECU} (°F) must be equal or greater than IMT_{IMP} calculated as shown in eq. 5:

$$IMT_{IMP} = (IMP_{abs} + 7.75) / 0.0875 \quad (5)$$

where: IMP_{abs} is the absolute IMP (bars)

- v) Similar to the NTE-IMT exclusion, ECT exclusion was introduced to eliminate in-use emissions to be evaluated in the NTE zone from cold operation conditions. ECT values obtained from ECU (ECT_{ECU}) must be equal or greater than the theoretical ECT (ECT_{IMP}) calculated as a function of absolute intake manifold pressure. ECT_{ECU} must be equal or greater than ECT_{IMP} derived as shown in eq. 6:

$$ECT_{IMP} = (IMP_{abs} + 9.8889) / 0.0778 \quad (6)$$

- vi) Vehicle altitude must be equal or less than 5500 ft. This exclusion was recommended by EMA and the reason behind this recommendation was that it was difficult to meet with emission standards at high altitudes due to lower air density and related ambient air conditions.
- vii) Ambient temperature ($T_{amb-ECU}$) must be equal or less than $T_{amb-Altitude}$ calculated as show in eq. 7:

$$T_{amb-Altitude} = -0.00254 * \text{Altitude} + 100 \quad (7)$$

where: $T_{amb-Altitude}$ is in °F

Altitude is the elevation at any given point in ft

- viii) In vehicles equipped with aftertreatment systems to reduce NO_x and NMHC emissions. The aftertreatment temperature $T_{aftertreatment}$ must be greater than 250 °C. The aftertreatment temperature must be measured within 12 inches from the downstream of aftertreatment device.

More details on NTE break-specific emissions calculation and evaluation will be detailed in methodology section.

Figure 1. Illustration of the NTE zone control area.

Several studies have investigated the performance of current NTE protocol to evaluate in-use emissions during different type of vehicle operation condition. From an on-road vehicle emissions testing standpoint, the in-use compliance procedure utilizing the NTE regulatory protocol with its current settings of NTE zone control area and exclusions fails to capture off-cycle emissions from routes having extensive low-load vehicle activity such as port drayage and delivery vehicles which shown high in-use NO_x emissions. However, the current NTE boundary conditions are more conducive to evaluate compliance of long-haul truck application in which

high engine load and aftertreatment temperature are observed, as opposed to urban delivery and port drayage trucks [4]. A report by Joint Research Commission (JRC) demonstrates that only a minor section of the in-use data (10 to 20%) can be evaluated to assess in-use emissions [14]. Previous studies showed that the current NTE definition is not capable of capturing significant data from transient operation commonly seen in low-load operation where engine frequently drops out of the NTE control area and 30 seconds duration time for an NTE event is found to be too long [15]–[17]. Figure 2 illustrates the total time spent in NTE zone and Routes PA1 and SW2Sab have the highest urban type driving operation compared to other routes in this study [15].

Figure 2. Time spent as 30 second NTE event duration time on different routes[15].

Another study demonstrates that current NTE power threshold (30%) is too high to evaluate NO_x emission rates from low-load operation [18]. Figure 3 shows that reducing power threshold from 30 to 20 percent significantly increases the number of NTE events occurred during the test from this study [18]. This study also points out that 30 seconds duration time is too high and authors suggests that duration time of an NTE event can be lowered to 20 seconds.

Figure 3. Number of NTE events and average bsNO_x emissions of different power thresholds [18].

2.1.2 WBW In-use Emissions Regulatory Protocol

WBW is another method to evaluate in-use emissions from HD vehicles. It has been demonstrated that the WBW method produces in-use bsNO_x emissions values comparable to the bsNO_x emissions obtained with the NTE regulatory protocol [19]. Studies have shown that the WBW methodology allows to evaluate in-use emissions for a wider range of vehicle operation compared to the NTE method [19], [20]. In 2004, The European Commission and JRC agreed to start a research program to develop a regulatory protocol for on-road emissions measurement from HD vehicles in Europe. The HD Euro VI Regulation (EC) No 595/2009 and implemented Regulation (EC) 582/2011 initiated a PEMS based in-use emissions testing program as a mandatory part of the type of approval legislation to check conformity of HD engines with the applicable emissions certification limits [14], [20]. Furthermore, Euro VI HD vehicles must comply with in-use emissions requirements which already at the approval [21]. WBW approach is a moving average method that calculates integrated break-specific emissions over a window that has accumulated certain amount of work that equals a reference characteristic value. Using the

engine work as a reference value which is the fundamental characteristic of the WBW method and leads to the same level of averaging characteristics of emissions results from different engines. Furthermore, the WHTC work of any give engine is considered as the reference value to separate out individual segments defined as “windows” in the WBW regulatory protocol. The first window is attained between the first data point and the data point where the reference work value is achieved. After a window is obtained by achieving the reference value, that specific window’s average power must be between 15-20% of the maximum engine power depending on the percentage of valid windows at least 50% or above for the entire test. The WBW approach generates a significantly large number of data points, compared to NTE methodology, that can be considered for analysis of real-world emissions. Individual work windows are characterized by different metrics such as bsNO_x, bsCO₂, bsCO, bsTHC and average power. The result of the WBW analysis is finalized by calculation of CFs. These factors must be calculated as required by the European Commission and CFs determine whether a vehicle passes or fails a test.

Like the NTE regulatory protocol, WBW methodology has some exclusions for the data set to be valid. These exclusions are defined as follow [8]:

- The data is invalid if ambient pressure is less than 82.5 kPa. Like the NTE altitude exclusion, WBW methodology excludes data in which it is difficult to meet with emission standards at high altitudes where ambient pressure is lower than the ambient pressure at sea level due to lower air density and related ambient air.
- The data is invalid if ambient temperature is less than -7 °C or greater than the temperature determined by the following equation:

$$T = -0.4514 * (101.3 - pb) + 311 \quad (8)$$

where: T is the ambient air temperature in K

pb is the ambient pressure in kPa

- The data is invalid if the engine coolant temperature is less than 70 °C. Like the NTE-ECT exclusion, ECT exclusion was introduced in WBW regulatory protocol to eliminate in-use emissions in which the limitations of EGR operation can occur at cold temperatures. However, WBW methodology does not have any exclusions for IMT.

- The data is invalid during the periodic verification of the instruments and zero drift verifications
- Along with the ambient pressure exclusion, WBW methodology has a limit for altitude. The data is invalid if altitude is above 1600 m

In the following section, the details of the WBW calculation are presented [8].

- The duration $(t_{2,i} - t_{1,i})$ of the i^{th} averaging windows is determined as follows:

$$(W(t_{2,i}) - W(t_{1,i})) \geq W_{reference} \quad (9)$$

where: $W(t_{j,i})$ is the engine work obtained between the start and time $t_{j,i}$ in kWh

$W_{reference}$ is the reference engine work for the WHTC cycle in kWh

- $t_{2,i}$ should be determined as:

$$(W(t_{2,i} - \Delta t) - W(t_{1,i})) < W_{reference} \leq (W(t_{2,i}) - W(t_{1,i})) \quad (10)$$

where: Δt is the data sampling time must be equal to 1 second or less

Calculation of the specific emissions (e_{gas}) in mg/kWh must be calculated for each window as follows:

$$e_{gas} = \frac{m}{W(t_{2,i}) - W(t_{1,i})}$$

where: m is the mass emission for the specific pollutant in mg/window

$W(t_{2,i}) - W(t_{1,i})$ is the engine work obtained during the i^{th} window

It should be noted that WBW methodology does not have any condition for aftertreatment temperature. Thus, it evaluates off-cycle emissions during low exhaust temperature conditions (below 250 °C) where the SCR aftertreatment systems have a lower NO_x conversion efficiency.

After all the windows are determined, selection of valid windows should be performed. The valid windows are the windows in which average window power must be greater or equal to the power threshold of 20% of the specific maximum engine power. Total number of valid windows must be 50% of the total windows determined from the test. If the percentage of valid windows is less than 50%, calculation of valid windows re-evaluated by reducing the starting power threshold 20% in increment of 1% until the percentage of valid windows is at least 50%. If the percentage of valid windows is not equal or greater than 50% with lowest power threshold 15%, the test is invalid. Finally, the CFs can be calculated for each valid window as follows:

$$CF = e/L \quad (11)$$

where: e is the bs emission of the component in mg/kWh

L is the applicable limit for the specific pollutant

2.2 Exhaust Flow Measurement and Estimation

One of the critical measurement during in-use emissions testing is the flow rate measurement. Accurate flow rate measurement is necessary when mass emissions and fuel consumption rates are need to be measured during on-road vehicle emissions testing [22]. PEMS are widely used for on-road HD vehicle testing [17], [23]. PEMS measure the concentration of the pollutants in the exhaust and multiply the measured exhaust flow rate with the concentration of the pollutants to get mass emission rates [24]. The exhaust flow is usually determined by numerous direct measurements, such as pitot tube, vortex and ultrasonic flowmeters [24]–[27]. However, direct measurement of exhaust flow is costly and difficult to implement during real-world vehicle operation [24], [28]. The exhaust mass flow rate from internal combustion engines has characteristics that make difficult to directly measure it with a regular gas flow measurement instrument. These characteristics are the high concentration of condensable water, PM and reverse flow during low engine speed levels [29], [30]. Currently, PEMS utilize pitot-type flow meters to measure exhaust gas flow since they are cost-effective and capable of measuring high temperature gasses [24]. In pitot-type flow meters, the exhaust flow is measured utilizing the average pitot static tube and calculated as a function of various parameters such as static pressure, temperature and differential pressure.

However, an accurate exhaust mass flow rate measurement from HD vehicles with the current pitot-type flow meters is complex and requires a professional operator to function. Moreover, the measurement accuracy of the pitot-type exhaust flow measurement at low flow rates is not good enough and has an effect on in-use emissions and fuel consumption rate calculations during low-load vehicle operation such as urban type driving condition in which an engine has large idling and low speed operation [29], [31]. A study has demonstrated that the speed-density method is found to be more accurate compared to the direct measurement from a MAF meter during transition and idle operation [32]. Thus, an accurate exhaust flow estimation can be achieved by utilizing the speed-density method to have an accurate exhaust flow rate at lower exhaust flow levels due to the inaccuracies in direct exhaust flow measurement at low flow rates such as idling operation [33].

Currently, modern HD vehicles are capable of broadcasting important engine parameters such as engine speed, intake manifold temperature, intake manifold pressure, fuel flow and intake air flow [24], [27], [30]. Based on these parameters, it is possible to have an accurate exhaust flow model that can be used for the calculation of mass emission rates [35]. Furthermore, latest updates of the J1939 protocol requires OEMs to soon broadcast the engine exhaust flow rate on the CAN bus [36]. Intake air flow rate necessary for exhaust flow estimation can be analytically calculated using “the speed-density method [34], [37]. The speed-density method uses engine speed, intake manifold temperature, engine displacement, intake manifold pressure and volumetric engine efficiency. Moreover, Figure 4 shows the regression analysis between the derived and direct measured intake air flow [34].

Figure 4. Derived mass air flow versus directly measured mass air flow form an HD diesel vehicle [34].

It has been observed that the difference between the calculated intake air flow using speed-density method and the reference direct measurement is within 10% for most of the vehicle operation when EGR is not used during low engine speed and at medium loads with medium engine speed level as well. At high loads the derived air intake flow is overestimated due to EGR

flow going back to intake [34]. One of the critical parameter for an accurate exhaust flow modeling is the volumetric efficiency (η_v). It is mostly applicable for four-stroke engines and defined as the ratio between the air mass flowing into the engine cylinders from intake manifold divided by the theoretical air mass calculated in the cylinders at the specific temperature and pressure [12]. The determination of engine volumetric efficiency is crucial in order to have an accurate charge estimation since it highly induces the speed-density methodology. An accurate model is necessary for volumetric efficiency since it cannot be directly measured. It has been found that the engine volumetric efficiency highly depends on the engine type (e.g. gasoline, diesel, etc.), inlet manifold geometry, air/fuel ratio, crankshaft speed, valve timing, engine speed and load[12], [38], [39]. Dynamics physical approaches have been used to develop models for η_v [38]. However, physical models need to know some parameters that are not usually available during vehicle operation such as exhaust gas pressure. Subsequently, various black-box approaches based on parametric, non-parametric and neural network methods have been developed to determine η_v [40], [41]. Figure 5 demonstrates η_v derivation utilizing radial based function (RBF) neural networks. Crankshaft speed and boost pressure were selected as the primary inputs for the RBF neural network system [38].

Figure 5. Volumetric efficiency as a function of crankshaft speed and boost pressure [38].

2.3 On-board NO_x Sensors

Significant deviations in off-cycle emissions have been observed from HD vehicles in FTP certification value. Hence, there is a need to quantify and monitor in-use emission rates of NO_x from a large population of diesel vehicles. Such a large and continuous effort is not possible through PEMS instrumentation. This problem can be solved by developing miniature PEMS that can be instrumented on vehicles to collect and post-process data for long periods of time. Moreover, all modern HD diesel vehicles are equipped with zirconium oxide (ZrO₂) based NO_x sensors been standardized and implemented in HD diesel vehicles for a long time that are used for OBD and aftertreatment control strategies [42], [43]. The development of ZrO₂ layers based on-board NO_x sensors were initially able to measure wet NO_x concentrations [44]–[46]. However, initially developed on-board NO_x sensors were not accurate enough and had to go through major design modifications [47]. After the design modifications, on-board NO_x sensors have been manufactured with the planar ZrO₂ multilayer technology [48]. Current on-board NO_x sensors are much more improved in terms of lower cost, reduced warm-up period, smaller size and improved accuracy compared to previously developed on-board NO_x sensors [49].

The working principle of on-board NO_x sensors is based on the diffusion of oxygen ions through ZrO₂ chambers usually coated with platinum. On-board NO_x sensors require operation temperature of 700 °C [50], [51]. The sensor is divided into two small chambers as shown in Figure 5 where the key reactions in these two chambers are demonstrated. In the first chamber, the oxygen concentration is adjusted from the diffusing gas to a predefined value by supplying current to a section of the first chamber wall. Moreover, NO is oxidized to NO₂. In the second chamber, NO₂ is dissociated into N₂ and O₂. The dissociated NO₂ is pumped out by an electrochemical pump. The output of this pump is proportional to the NO_x concentration in the exhaust gas. However, on-board NO_x sensors have some limitations including accuracy, response time, durability during high temperature fluctuations and dependency on O₂ concentration in the exhaust [45], [49], [50]. Water in the exhaust gas highly impacts the performance of ZrO₂ operation. At lower exhaust temperature under urban driving conditions (idling and low-load operations), water condensation occurs in the exhaust stream and causes rapid cooling. This fast cooling effect can seriously damage the on-board NO_x sensors.

Figure 6. Illustration of a ZrO₂ based NO_x sensor [49].

Many studies have investigated the accuracy and response time of on-board NO_x sensors for HD vehicle applications [51]–[55]. One of the earlier study on these sensors for NO_x emissions measurement conducted by WVU showed that ZrO₂ based NO_x sensors are the most suitable cost-effective devices for use in on-road NO_x emissions measurement system and the errors are between 6-12% while measuring low concentrations in the range of 5-175 ppm [53]. Most recently, on-board NO_x sensor manufacturers improved these sensors accuracy to possibly compile with current and future emissions limits and on-board diagnostics regulations. Another study has demonstrated that on-board NO_x can potentially monitor low NO_x concentration within 10% of measurement error at 100 ppm NO_x concentration as shown in Figure 7 [45].

Several studies investigated the cross-sensitivity of the on-board NO_x sensors to ammonia [56]–[58]. In these studies, ammonia disturbance on the accuracy of on-board NO_x is demonstrated as shown in Figure 8 and following relation is derived as shown in eq. 12:

$$NO_{x_{on-board\ sensor}} = NO_x + \alpha * NH_3 \quad (12)$$

where: $NO_{x_{on-board\ sensor}}$ is the corrected on-board NO_x sensor value

NO_x is the measured NO_x from a laboratory grade measurement

α is defined as the ammonia correction factor in the literature

Figure 7. Comparison of NO_x sensor output and NO_x emissions from a laboratory grade analyzer [45].

Figure 8. Ammonia disturbance on the on-board NO_x sensor [57].

2.4 Mini PEMS

An alternative cost-effective measurement system to the PEMS is necessary to evaluate real-time NO_x emission rates and fuel consumption from large number of HD vehicles. During the last few years, several compact and cost-effective emissions measurement systems (mini-PEMS) have been developed for measurement of CO , CO_2 , NO_x , HC , and O_2 from various instrument manufacturers. Below, some of the commercially available mini-PEMS are addressed.

- **TNO'S Smart Emissions Measurement System (SEMS)**

Toegepast Natuurwetenschappelijk Onderzoek (TNO) SEMS is a highly compact sensor-based system that measures emissions (NO_x and CO_2) and can be easily assembled into a vehicle without interrupting vehicle's daily operation while the measurements are performed. This means that measurements can be taken over a longer period of time, making it possible to gather large quantities of practical data. Because of these characteristics, SEMS shown in Figure 9 can be used by many different parties, such as fleet owners, regulatory agencies, and vehicle manufacturers [59].

Figure 9. TNO's SEMS measuring system [59].

- **ECM's mini-PEMS™**

Engine Control and Monitoring (ECM), ECM's mini-PEMS™ shown in Figure 10 is a low-cost and durable instrumentation package for the monitoring of engine emissions (NO_x , NH_3 , and O_2). Main feature of mini-PEMS™ is the use of ceramic exhaust emissions sensors (ZrO_2), a technology founded by ECM. Ceramic exhaust sensors are smaller, more

rugged, and faster responding than classical gas analyzers. The base configuration of the system is capable of measuring GPS positioning, O₂, Lambda and NO_x emissions [60].

Figure 10. ECM's mini-PEMS™ [60].

- **Firefly Micro-PEMS**

Firefly Micro-PEMS as shown in Figure 11 developed by GLOBALMRV is designed to acquire low-cost data collection from large number of vehicles. The Firefly Micro-PEMS is a lightweight, compact and weighing under 4kg and drawing only 3 amps, while providing continuous monitoring of performance and emissions (CO, CO₂, HC, NO and O₂). Moreover, the system also collects GPS and OBDII data. Firefly generates numerous reports as standard, plus a full AI analytics engine allows for performance enhancement, fault prediction and reduced development times. Firefly Micro-PEMS's data collection and

processing unit is mounted onboard the vehicle with a sensor attached to the tailpipe and another sensor attached to the vehicle's OBDII system. A software analyzes the collected data streamed to the cloud and downloaded by the user [61].

Figure 11. Firefly Micro-PEMS: The on-board device continuously monitors tailpipe emissions and can be adapted for diesel, gasoline, and CNG engines [62].

3 CHAPTER III -EXPERIMENTAL SETUP AND PROCEDURES

This section provides a detailed description of the experimental setup, procedures, vehicle information, data collection and instruments employed for this thesis. There are two studies that provide data from both on-road and chassis dynamometer HD vehicle testing. For the on-road data collection Cross-Cali study is evaluated, South Coast Air Quality Management District (SCAQMD) and CARB jointly funded a study named “Real-World Evaluation of Modern Heavy-Duty Truck Emissions Using Portable Emissions Measurement Systems (PEMS) and a Transportable CVS Emissions Measurement System” at WVU to evaluate HD vehicle emissions during real-world vehicle operation using a transportable CVS measurement system. In this study, the main objective was to evaluate real-world emissions from HDD and natural gas vehicles operating in California to capture the urban, high traffic operation conditions using PEMS and transportable CVS measurement called Transportable Emissions Measurement Systems (TEMS). For the chassis-data, WVU performed a study to evaluate NO_x emissions for HD class 8 Trucks by utilizing on-board NO_x sensors.

3.1 WVU’s Transportable Emissions Measurement Systems and Transportable Chassis Dynamometer

3.1.1 Transportable Emissions Measurement Systems (TEMS)

In-use emissions from seven HD vehicles were performed with WVU’s TEMS for the on-road data collection. TEMS was designed as a laboratory-grade emissions measurement system according to recommendations suggested in CFR40/1065 [63]. The TEMS reconstructed on a 30ft long cargo container. TEMS was built with a gaseous analytical emissions bench instrumentation system, a heating, ventilating and air conditioning (HVAC) system, a high efficiency particulate filter (HEPA) for the primary dilution part, two primary full-flow dilution tunnels, chassis dynamometer control systems, data acquisition system, a subsonic venture for a secondary particulate matter sampling system, an air compressor, vacuum pumps, zero-air generator and pressurized air tank as shown in Figure 12. The two primary dilution tunnels inside the container

were designed to provide measurement capability for both low PM emissions (clean CVS tunnel) vehicles, as well as legacy diesel-fueled vehicles with high PM levels (referred as dirty CVS tunnel) [64]. This provision diminishes tunnel history effects between test programs of differing exhaust emission composition. A stainless-steel plenum box has two HEPA filters for filtering primary dilution air, as well as twin dual-wall exhaust transfer inlet tubes dedicated as exhaust inlets for the upper and lower tunnels. The HEPA plenum is connected into the main dilution tunnels, which are selectively connected to the subsonic venturi via stainless elbow sections. The air compressor and two vacuum pumps are installed inside a noise isolating overhead. An air tank stores compressed air and provides shop air to the zero-air generator for instrumentation use. A PM sampling box for the secondary dilution tunnels is located alongside the primary tunnels, downstream of tunnels' sample zones. The secondary PM dilution tunnel of either the dirty or clean tunnel is connected to the PM sampling box for PM measurement during the test [64].

Figure 12. CAD drawing of the TEMs developed by WVU: 1) exhaust inlet-dirty tunnel, 2) exhaust inlet-clean tunnel, 3) clean CVS tunnel, 4) dirty CVS tunnel, 5) air compressor, 6) vacuum pumps, 7) Horiba® MEXA-7200D oven, 8) PM sampling section, 9) PM filter handling section, 10) zero-air generator, 11) Horiba® MEXA-7200D motor exhaust gas analyzer, 12) computer and data acquisition table, 13) pressurized air tank, 14) DAQ rack, 15) subsonic venture, 16) Air-conditioner section, 17) Outlet to blower, 18) ventilation fan, 19) HEPA filters [64].

The TEMs was designed in 2007 by WVU researchers and more details related to the design is provided by Wu [64]. Figure 13 shows the TEMS container on the transportation Landoll 435 trailer while performing real-world emissions testing. In 2015, the dirty tunnel has been removed

as testing of legacy diesel, non-DPF equipped vehicles has been significantly reduced. Removal of the dirty CVS tunnel eventually created extra space for additional instrumentation and upgrades required for upcoming projects.

Figure 13. the TEMS on a HDD vehicle while performing a real-world emissions testing.

Currently, The WVU TEMS is equipped with one full scale CVS dilution tunnel (clean) designed to perform emissions measurement as per procedures set forth in 40 CFR Part 1065 [63]. All seven test vehicles pulled the mobile laboratory, which was connected to a flatbed trailer along with an on-board power generator, and other emissions measurement equipment. The CVS flow was set to 1800 cubic feet per minute (CFM), upon which both gaseous and PM measurements were conducted. Moreover, the laboratories CVS flow control is reached through a subsonic venturi (SSV) and a variable speed blower. To ensure the accuracy and repeatability of SSV flow rate measurement, a straight section of Schedule 5in pipe, ten feet in length, was flanged and attached to each end of the subsonic venturi to minimize the effect of flow wakes, eddies and flow circulation which might be stimulated by pipe bends and coarse inside walls. This particular SSV was calibrated with a reference SSV from 400 scfm to 4,000 scfm following the procedure defined in 40 CFR Part 1065.340 [63]. The flow rate of the SSV is calculated, in real time, using the calculations in 40 CFR Part 1065.640 and 40 CFR Part 1065.642 [63]. HEPA filtered ambient air is used as the dilution air in the clean CVS tunnel. Dew point and ambient humidity are continuously recorded in order to calculate instantaneous NO_x correction factors. Exhaust emissions are drawn from the sampling line and routed to the gaseous analytical emissions

instrumentation system through heated and temperature controlled ($191^{\circ}\text{C} \pm 11^{\circ}\text{C}$) probes and sampling lines as shown in Figure 14. Figure 15 shows the schematic of the TEMS container and experimental setup for the raw or diluted gaseous and PM sampling methodology adopted for the on-road emissions testing. The TEMS is equipped with the Horiba MEXA 7200D exhaust gas analyzers to serve as the primary gaseous emissions measurement system [64]. The MEXA 7200D can measure all regulated emission species including THC, CO, CO₂, NO_x and CH₄ through a non-methane cutter equipped secondary hydrocarbon channel.

Figure 14. Illustration of the sampling probes on the two CVS dilution tunnels (clean-upstream and dirty-downstream) installed in TEMS.

Figure 15. Schematic diagram of CVS sampling and instrumentation for gaseous and PM sampling system in WVU TEMS.

Raw emissions data were post-processed as given in CFR procedures for performing drift correction (40 CFR Part 1065.672), intake-air humidity NO_x correction (40 CFR Part 1065.670), performing dry-to-wet conversion of analyzers operating downstream of a chiller (40 CFR Part 1065.659), and applying dilution air background correction (40 CFR Part 1065.667) CVS background-correction [63]. Moreover, several high-speed raw exhaust flow modules (EFM) were placed between the flexible tubing and the inlet to the CVS that were utilized for the various PEMS that were utilized in this study. These PEMS were a MKS FTIR-2030 HS, Semtech-DS, Horiba OBS-2200 and AVL MOVE-493 [4].

3.1.2 WVU HD Chassis Dynamometer

The study with on-board NO_x sensors to evaluate NO_x emissions for HD class 8 Trucks was performed with TEMS and WVU's HD transportable chassis dynamometer. The chassis dynamometer test bed houses rollers, flywheel assembly, eddy current power absorbers, differentials, hub adapter, torque and speed transducer built onto a tandem axle semi-trailer, thus the dynamometer can be pulled with a tractor as a regular trailer. The chassis dynamometer is unique in design as loading of the test vehicle axle is accomplished through direct coupling of the drive axle with the flywheel and power absorbing systems as shown in Figure 16. This specific design approach eliminates tire slipping and damage to the tractor tires from overheating. Hub adapters replace the outer tires of the drive axle, to directly connect the laboratory load simulation system to the vehicle drive axle. The load simulation system consists of eddy current power absorbers and a flywheel assembly to simulate road load power and vehicle inertia respectively. The chassis dynamometer is capable of simulating vehicle weight of up to 70,000 lbs. Figure 17 illustrates a test vehicle installed on WVU's transportable HD chassis dynamometer. Detailed description of WVU's HD chassis dynamometer can be found in the following references [65], [66], thereafter, only limited details of the chassis dynamometer will be provided in this section.

Figure 16. Demonstration of direct coupling of the drive axle with flywheel and power absorbing systems.

Figure 17. WVU HD transportable chassis dynamometer: 1) test vehicle, 2) flywheel assembly, 3) exhaust routing line, 4) hydraulic column.

- **Rollers:** The chassis dynamometer consists of two sets of free spinning rollers at the front that supports forward drive axle or single axle and a set of two paired free spinning rollers at the back to support the rear axle of a HD vehicles. The rear pairs can be placed in three different positions to adjust tandem spacing of 4 to 5ft and each free spinning roller is 12.6in diameter with their axis along the length of the test bed. Each pair of rollers is connected by a flexible coupling to have unvarying rotational speed on either side of the vehicle and the coupling is capable of accepting 20% of the wheel torque in case of any imbalance due to uneven surface at the test location [65].
- **Hub Adapters:** The hub adapters are used to couple the engine drive axle with the flywheel assembly and eddy current power absorber by speed and torque transducers. The adapter is built with a 0.5in thick aluminum plate of diameter 1.8ft [65].
- **Load Simulation System:** The road load simulation system consists of a flywheel assembly, a speed and torque transducers, double differentials, an eddy current power absorber and universal couplings on both side of the testing vehicle. The power from vehicle drive axle is transmitted to the flywheel assembly and power absorbers via a hub adapter connected to a 24in long spline shaft running into a pillow block. The torque and speed transducers can provide the data logging computer torque output signal at 10 Hz time resolution [65].
- **Flywheel Assembly:** The flywheel assembly is built to simulate gross vehicle weights between 40,000 at a wheel diameter of 4ft to 60,000 lb at a wheel diameter of 3.25ft. The flywheel assembly consists of a drive shaft with four drive rotors running in two pillow blocks. Each drive shaft supports eight flywheels of different sizes with bearings resting on the shaft. By selectively engaging the flywheels to the drive rotors, vehicle mass can be attained in 250 lb increments [65].
- **Eddy Current Power Absorbers:** An air cooled, eddy current power absorber (Mustang CC300) mounted on two bearing is used as power absorbers. The power absorbers are to simulate load due to rolling friction of the vehicle tires and aerodynamic drag resistance. The eddy current power absorbers can absorb 300 hp instantaneously and 1000 hp intermittently during high peak operation. The load from dynamometer is

controlled by the direct current supplied to the coils at any given speed. Power absorbed is measured via the torque arm-force transducers [65].

- **Variable Speed Motor:** A 20hp variable speed alternating current (AC) motor mounted to the eddy current power absorbers provides restricted motoring capabilities and helps to overcome frictional losses in the chassis dynamometer.

While the driver can control of the speed, an automated system must control the transient torque. The load supplied by the flywheels simulates the aerodynamic drag resistance and the rolling friction between the road surface and the vehicle tires, inertial mass of vehicle and road grade is simulated by the eddy current power absorbers during a vehicle operation on the chassis dynamometer. In general, a generic chassis dynamometer driving cycles are develop assuming zero-grade, thus the impact of road grade is negligible in road-load equation. The eddy current power absorbers are controlled by a Dyn-Loc IV control system provided by Dyne-Systems. The Dyn-Loc IV control system is operated by a proportional–integral–derivative (PID) control loop. Thus, PID controller provides a quick and smooth response in controlling the transient torque set points. The data is being logged by the data acquisition system at 10 Hz. The power absorbers receive the transient toque set points from the Dyn-Loc IV system. The set point which is the road load power can be calculated as given in equation 13. The calculated road load power as a function of vehicle speed is employed to control the power applied by the eddy current power absorbers and variable speed motors in closed loop.

$$P_{RL} = C_r * M * g * V + (0.5 * \rho_a + C_d * A * V^3) \quad (13)$$

where: P_{RL} is road load power

C_r is the coefficient of rolling resistance

M is the vehicle mass

ρ_a is the ambient air density

A is frontal cross-sectional area of the vehicle

C_d is the drag coefficient

V is the vehicle speed

3.2 On-Road HD Vehicle Testing (Cross-Cali Study)

3.2.1 Test Vehicles

In-use data collected during a research program jointly funded by SCAQMD and CARB carried out by WVU is used as the on-road emissions data for further evaluation in this thesis. The study included on-road measurements from HD trucks over test routes specifically selected for low-load operation that have been shown to increase in NO_x emissions from HDD vehicles equipped with SCR technology in California. Collected in-use data is used to conduct a sensitivity analysis on the existing NTE and WBW approaches and identify potential changes to specific thresholds and exclusion boundaries of these regulatory protocols to represent the emission factors of HDD vehicles operating under low-load driving conditions as well as propose changes for new in-use emissions regulatory protocols in this thesis. Table 1 shows the vehicle specifications and technology standards along with certification NO_x emission rates for the HD vehicles tested in this study.

Table 1. Details on modern HD tractors for real-word emissions evaluation selected fin Cross-Cali study [4].

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7
<i>Engine MY</i>	2007	2013	2013	2014	2014	2011	2013
<i>Model</i>	Diesel	Diesel	CNG	Diesel	Diesel	Hybrid Diesel	Diesel
<i>Aftertreatment Configuration</i>	DPF	DPF+SCR	TWC	DPF+SCR	DPF+SCR	DPF	DPF+SCR
<i>Displacement [L]</i>	15.0	15.0	11.9	14.8	12.8	7.6	12.4
<i>Rated Power [hp]</i>	550	450	400	505	405	260	475
<i>FTP Cert. NO_x [g/bhp-hr]</i>	2.0	0.22	0.15	0.09	0.06	0.46	0.20
<i>NTE Cert. NO_x [g/bhp-hr]</i>	2.10	0.45	0.45	0.45	0.30	0.70	0.30

Vehicles were selected specifically to represent foremost emission technology groups dominant in California as (1) MY 2007 diesel vehicle equipped with only DPF aftertreatment system and certified to 2.0 g/bhp-hr NO_x on FTP cycle, 2.10 g/bhp-hr NO_x in NTE standards, (2) MY 2013 diesel vehicle equipped with both DPF and SCR, and certified to 0.22 g/bhp-hr NO_x on FTP cycle, 0.45 g/bhp-hr NO_x in NTE standards, (3) MY 2013 natural gas vehicle equipped with a three-way catalyst (TWC), and certified to 0.15 g/bhp-hr NO_x on FTP cycle, 0.45 g/bhp-hr NO_x in NTE standards, (4) MY 2014 diesel vehicle equipped both DPF and SCR, and certified to 0.09 g/bhp-hr NO_x on FTP cycle, 0.45 g/bhp-hr NO_x in NTE standards, (5) MY 2014 diesel vehicle equipped both DPF and SCR, and certified to 0.06 g/bhp-hr NO_x on FTP cycle, 0.30 g/bhp-hr NO_x in NTE standards, (6) MY 2011 hybrid-diesel equipped with only DPF, and certified to 0.46 g/bhp-hr NO_x on FTP cycle, 0.70 g/bhp-hr NO_x in NTE standards, (7) MY 2013 diesel vehicle equipped both DPF and SCR, and certified to 0.20 g/bhp-hr NO_x on FTP cycle, 0.30 g/bhp-hr NO_x in NTE standards. All seven engines utilized exhaust gas recirculation (EGR) as part of the emission control system. All seven engines were certified by the manufacturers with PM emissions of at least three times below the current standard (PM 0.01 g/bhp-hr), and CO and non-methane hydrocarbon (NMHC) emission of at least two times below current standards (CO 15.5 g/bhp-hr and NMHC 0.14 g/bhp-hr) [4].

ECU data were recorded using the SAE J1939 protocol over the controller area network. All vehicles broadcast engine speed, engine torque, some temperatures at several locations of the engine and aftertreatment system, and other information needed for quantification of bs emissions during on-road vehicle operation. However, the HD-OBD requirements were phased between engine MY 2010 and MY 2016, some acquired data channels were not standardized and may be inconsistent among vehicles. For example, aftertreatment temperatures and on-board NO_x sensors data were not available from all engines. Thus, only the vehicles (Vehicle 2, 4 and 7) colored green in Table 1 were selected for further analysis in this work. Reasons behind the selection of these three vehicles are 1) this thesis focuses only on HDD vehicles equipped with DPF and SCR technologies 2) SCR-out NO_x and temperature data are not available publicly on the SAE J1939 CAN bus the vehicles not selected for further analysis. All J1939 data, emissions information, and geographical position data were logged using a WVU developed in-house

software package. 3) Only the Vehicle 2 was suitable for the analysis of on-board NO_x sensor performance to measure in-use NO_x emission rates.

3.2.2 Routes

The six driving routes include real-world characteristic of conditions throughout the California state have been categorized into five major types of driving conditions namely: 1) Hill Climb, 2) Extended Freeway, 3) Regional, 4) Local 5) Urban and 6) Near-Dock. Test routes were designed to represent freeway operation, port delivery operation, urban delivery operation and urban freeway operation as shown in Figure 18. One of the outstanding feature of this study is the large capture of data from unique traffic conditions characterized by extensive low-load vehicle operation. The six routes were driven over five to seven days and covered 1,500 miles along some of the major freight operation paths in California.

Figure 18. Test routes planned in the cross-California study to represent major freight transport paths in California.

The Hill Climb Highway Route is shown in Figure 18a, which includes driving through the passes on highway I-5 and highway I-15 to characterize emissions associated with freight movement in and out of the South Coast Air Basin and the Interstate Highway Route, which includes driving on

north-south passages through the San Joaquin Valley on SR-99 and I-5, and on east-west corridors to the eastern California-Arizona border via SR-40 and I-10. Figure 18b shows Regional Highway Routes that included driving at speeds commonly around 55 mi/hr, but also frequent periods of slower highway driving, drayage Routes included corridors to capture emissions associated with freight movement leaving the Ports of Long Beach and Los Angeles and the Near-Dock Drayage Route simulates the stop-and-go operations associated with cargo loading from ocean-going vessels followed by brief higher-speed driving onto local highways. The Local Drayage Route shown in Figure 18c replicates transport to regional rail yard in the City of Commerce near downtown Los Angeles, CA [4]. Figure 19 shows the characteristic speed profiles associated with each route. Demonstrated speeds and work per distance characterize the average of all trips made over that route classification [4].

Figure 19. Typical speed versus time for each of the six route classifications. These include the (A) Hill Climb Highway Route, (B) Interstate Highway Route, (C) Regional Highway Route, (D) Local Drayage Route, (E) Near-Dock Drayage Route, and (F) Urban Arterial Route [4].

3.2.3 Instrumentation Setup and Data Collection During Cross-Cali Study

Figure 20 shows the configuration of the WVU TEMS during cross-Cali study, exhaust routing, and instrument setup as details associated with WVU TEMS given in the previous section. ECU data were recorded using the SAE J1939 protocol over the controller area network. All vehicles broadcast engine torques, engine speed, temperatures at various locations of the engine. However, aftertreatment system, and other information that allowed for quantification of bs emissions from a vehicle ECU data during on-road operation were not broadcasted from all vehicles. This is due to the HD-OBD requirements were phased between engine MY 2010 and MY 2016, some acquired data channels were not standardized and may be slightly inconsistent among vehicles. In cross-Cali study the emission rates and analyzes are reported in terms of CO, CO₂, THC, NO_x, and PM using data from the laboratory-grade analyzers that sampled directly from the CVS. Several additional gaseous and particulate measurements were made, including an evaluation of commercially-available PEMS systems (Horiba OBS-2200, Semtech DS, AVL MOVES) for criteria gas measurement, the evaluation of the FTIR spectroscopy systems for measurement, in particular, N₂O and NH₃ emissions, and measurement of real-time particle number using condensation particle counters and size distribution using electrometer-based mobility spectrometers. These instruments and their setup used to generate data in cross-Cali study are shown in Figure 20 below.

Figure 20. Setup used for on-road testing in cross-Cali study. This study included a comprehensive suite of PEMS and real-time particulate instruments [4].

3.3 Chassis Dynamometer HDD Vehicle Testing

WVU performed a study with on-board NO_x sensors to evaluate NO_x emissions for HD class 8 Trucks. Data collected during this study is used to demonstrate that on-board NO_x sensors are accurate enough to develop a cost-effective in-use NO_x emission monitoring methodology making use of currently available NO_x sensor technology already existing on HDD vehicles to evaluate in-use bsNO_x emissions. Specifically, collected data is utilized in defining measurement accuracy and error assessment of on-board NO_x sensors.

3.3.1 Instrumentation Setup and Data Collection During Chassis Dynamometer HDD Vehicle Testing

WVU's chassis dynamometer built onto a flat-bed trailer was setup on a flat surface and leveled to avoid any variation in the vehicle's inertial loading simulated by the rotating flywheels. The emissions measurement was done with WVU's TEMS housing the analyzers, CVS, and dynamometer control and was placed close to the chassis dynamometer. Moreover, two Continental NO_x (one aged and one new) and one NH₃ sensors were installed to the vehicle's exhaust pipe along with the FTIR instrument in order to perform accuracy analysis of on-board NO_x sensors. The aged NO_x sensor was taken from a HDD vehicle which has accumulated 60,000 miles of operation. Figure 21 illustrates the experimental setup for the accuracy analysis of ZrO₂ based on-board NO_x sensors. Before installing the test vehicle on the chassis dynamometer, the correct flywheel weight combination was determined and placed in position to simulate the inertial load for the vehicle. The inertial weight was set to 45,000lbs for the vehicle. The outer rear wheel of the drive axle was removed and hub adapters were attached to the drive axle. The drive axle driving the flywheel set and eddy current power absorbers were connected through hub adapters. The vehicle was leveled with the drive axle and tires were checked for any distortion and low-air pressure as it is necessary to check tires not to add extra loading to the test weight.

Figure 21. Instrumental setup of the HD test vehicle in chassis dynamometer testing for on-board NO_x sensor accuracy analysis.

After vehicle was set onto the chassis dynamometer, the vehicle exhaust was connected to the dilution tunnel of WVU's TEMS via insulated transfer pipes. The vehicle was chained down to the chassis dynamometer bed for safety and the ECU connections are made to receive ECU broadcasting and ambient temperature, pressure and relative humidity data. Before starting vehicle testing, the vehicle was run at high speed on the chassis dynamometer in order to warm up the lubrication oil across the differentials in the chassis dynamometer components and on the vehicle. It is important to perform a warm-up run in order to reduce the additional load on the test vehicle due to highly viscous oil in differentials. After the warm up period, the vehicle was shut down and allowed to soak for twenty minutes and soak time of twenty minutes was applied after each run of the test cycles.

A coast-down procedure of the vehicle was performed to evaluate the system losses in the chassis dynamometer. Briefly, the coast-down procedure includes taking up the vehicle to 50 mph and then the vehicle was set to coast-down by the drive with no breaking and gear shifts. The coast-down procedure is repeated to evaluate the frictional losses in the chassis dynamometer. The coast-down procedure is well defined and performed based on SAE J1263 suggested road load determination [67]. The coast-down fundamentals match the vehicle theoretical on-road coast-down time and the time taken for cost-down on the chassis dynamometer [68].

3.3.2 Routes Test Cycles

Two chassis dynamometer cycles, namely Urban Dynamometer Driving Schedule (UDDS), and the Heavy Heavy-Duty Diesel Truck (HHDDT) Transient cycle were selected for this study. The UDDS cycle simulates the freeway and non-freeway operation of a HD vehicles as shown in Figure 22. In principal, the UDDS and the FTP cycles used for engine certification were derived from the same data set. The cycle is exercised over 5.5 miles over the entire cycle and it is 1063 seconds long while attaining maximum speed of 58 mph. Average speed is 18.8 mph over the entire cycle. More details are given in Table 2. The UDDS cycle is very similar in terms of load characteristics to that of the FTP transient cycle used engine dynamometer testing procedure.

Figure 22. Speed versus time of the UDDS cycle.

The HHDDT cycle is a chassis dynamometer test developed by CARB with cooperation of WVU. The HHDDT schedule consists of four speed-time trace modes namely idle, creep, transient and cruise. The HHDDT-transient cycle was selected for this study because it has the closest cycle characteristics with the UDDS cycle as shown in Figure 23. Cycle statics for the particular HHDDT modes are compared with the UDDS cycle are shown in Table 2. The HHDDT transient and UDDS cycles are colored in green in Table 2.

Figure 23. Speed versus time trace of the HHDDT transient cycle.

Table 2. Statics for UDDS and HHDDT cycles

<i>Parameter</i>	<i>HHDDT Creep</i>	<i>HHDDT Transient</i>	<i>HHDDT Cruise</i>	<i>UDDS</i>
<i>Duration [sec]</i>	253	668	2083	1063
<i>Distance [mile]</i>	0.124	2.85	23.1	5.55
<i>Average Speed [mph]</i>	1.77	15.4	39.9	18.8
<i>Stop/Mile</i>	24.17	1.8	0.26	2.52
<i>Max. Speed [mph]</i>	8.24	47.5	59.3	58
<i>Max. Acceleration, [mph/s]</i>	2.3	3.0	2.3	4.4
<i>Max. Deceleration, [mph/s]</i>	-2.53	-2.8	-2.5	-4.6
<i>Percent Idle</i>	42.29	16.3	8.0	33.4

3.4 Analyzers and Gaseous Emissions Sampling Systems

The regulated gaseous emissions sampling system consist of gas sampling systems including heated lines and probes, gas conditioning system including chiller system and heated

filter, gas metering system including rotameter, magnahelic pressure gauges, calibration systems, CO analyzers, CO₂ analyzers, NO_x analyzers. Analyzers used for this study are summarized in Table 3.

Table 3. Analyzers used for gaseous emissions measurement

<i>Gaseous Emissions</i>	<i>Semtech-DS</i>	<i>MultiGas™ 2030 FTIR</i>	<i>MEXA-7200D</i>
<i>CO</i>	NDIR	IR Spectroscopy	NDIR
<i>CO₂</i>	NDIR	IR Spectroscopy	NDIR
<i>NO</i>	NDUV	IR Spectroscopy	CLD
<i>NO_x</i>	Calculated from NO and NO ₂	Calculated from NO and NO ₂	CLD
<i>NO₂</i>	NDUV	IR Spectroscopy	Calculated by difference of NO _x and NO
<i>THC</i>	FID	IR Spectroscopy	FID

3.4.1 MultiGas™ 2030 FTIR

The MultiGas™ 2030 FTIR used in this study was developed by MKS Instruments, Inc. The MultiGas is a FTIR based gas analyzers capable of ppb to percent sensitivity for measuring various gases in numerous of applications such as diesel, locomotive, vehicle emissions monitoring, SCR reduction performance monitoring and ambient air monitoring. The MultiGas can perform analysis in gas streams containing up to 30% water, and can simultaneously analyze and display more than 30 gaseous constituents [69]. The MultiGas has a single sample cell with a total absorption length of 5.11m, maintained at 191 °C, and can measure raw exhaust emissions in wet conditions. All sampling system components such as sampling lines, heated filters are heated and maintained at 191 °C in order to prevent condensation in the sampling system. The principle of operation of the MultiGas is based on IR spectroscopy.

Briefly, the FTIR analyzer generates interferograms of two infrared radiation (IR) beams of changing length optical paths. The beams are initiated from the same source. One of them is reflected on a fixed mirror and the second on a vibrating mirror. Differences in optical paths are

induced by the amplitude of the vibrating mirror. A simple spectrometer scheme is shown in Figure 24. When the beams recombine, interference fringes are created which contain all the information on the spectral distribution of the source radiation. When that radiation is sent to the gas mixture, spectral components corresponding to the absorption spectra of the different gases are absorbed. Results are generated by a computer that runs the mathematical Fourier transform to obtain the intensity distribution as a function of wavelength from the intensity distribution as a function of the optical path. Particular gas concentrations are obtained from the intensity distribution on the basis of their known IR absorption spectra [69].

Figure 24. Simple spectrometer scheme and components of an FTIR measurement system [70].

Although the response time of FTIR instruments is rather slow (over 5s) the actual measurement cycle is less than 1s, thus allowing real-time measurements. The method is particularly useful for analysis of NO, NO₂, N₂O, CO, CO₂ and NH₃, as well as several other compounds. During the operation of the FTIR, the FTIR analyzer cell and sampling conditioning components are continuously purged with dry zero air before and in-between repeated test cycles to ensure the removal of ammonia and water from the previous test run. Due to the FTIR's sensitivity to pressure within the sample cell, the instrument is operated under slight vacuum with the sampling pump located downstream of the sample cell and the cell pressure is slightly kept under the ambient pressure to have fast response measurement.

3.4.2 Semtech-DS

Semtech-DS is used as the primary PEMS equipment for this study and was designed by Sensors Inc. The Semtech-DS is mainly intended for in-use raw emissions measurement from both spark ignition and compression ignition engines. The Semtech-DS uses a compact FID for THC, an NDUV analyzer for an instantaneous and separate measurement of NO and NO₂, an NDIR analyzer for CO and CO₂, and an electrochemical cell for O₂ while ensuring compliance with EPA's CFR 1065 [71]. The Semtech-DS can also collect ECU data, ambient weather data through an external probe. The ambient temperature, pressure and relative humidity must be recorded to compute NO_x humidity correction factors as well as other parameters. Time-specific mass emissions are calculated by combining the emission concentrations and exhaust flow rate. The system uses the Semtech-EFM-electronic exhaust flow meter, a differential pressure type flow meter to accurately measure the vehicle exhaust flow. Then, this exhaust mass flow data is used to calculate exhaust mass emissions for all measured exhaust gases. The system uses a heated line and filter to prevent condensation of hydrocarbons. The exhaust gas sample is dried by a thermoelectric chiller before transferred into the NDUV, NDIR and electrochemical analyzers. More details associated with Semtech-DS and measurement principles can be found in the following reference [71].

Figure 25. SEMTECH-DS on-board, in-use emissions analyzer.

3.4.3 Horiba MEXA-7200D

The Horiba MEXA-7200D is used as the primary dilute emissions measurement system inside WVU's TEMS. The full flow CVS tunnel simulates the mixing of vehicle exhaust gasses with ambient dilution air. The MEXA-7200D uses a FID for THC, a CLD analyzer for instantaneous measurement of NO and NO_x, an NDIR analyzer for CO and CO₂ and finally, a second FID analyzer to quantify CH₄ through a non-methane cutter. The Horiba MEXA-7200D can be fitted with many analyzer modules, and the current unit setup consists of an AIA-721A CO analyzer, an AIA-722 CO/CO₂ analyzer and a CLA-720 "cold" NO_x analyzer part of the cold sample stream, the FIA-725A THC analyzer, and CLA-720MA NO_x analyzer part of the heated sample stream.

4 CHAPTER IV-METHODOLOGY

4.1 Development of the NTE and WBW In-use Emissions Analysis post-processing tool

The development of a user friendly and robust Matlab® GUI-based post-processing tool for NTE and WBW in-use emission regulatory protocols is developed as a robust in-use emissions post-processing software as a part of this research. The tool is designed in such a way that the user is able to select between two different reduction methods for off-cycle emissions while providing the flexibility of selecting a range of exclusions and boundary conditions as well as set the threshold values for these exclusions, boundary conditions and other critical parameters, including power, work and torque thresholds. The tool is capable of reducing any type of data collected by PEMS in CSV format. The analysis tool summarizes the results with the final calculated WBW or NTE results (i.e. conformity factors, vehicle pass ratio etc.) into a Microsoft Excel® readable spreadsheet.

4.1.1 Data Import and Description of the NTE in-use Emissions Section of the Tool

An in-use data set collected by a PEMS can be imported into the tool as a CSV file. Then, channel selection is performed for the in-use data analysis as shown in Figure 26. Once channel selection is completed, the current channel configuration can be saved to apply the saved configuration to the other data set to post-process. In the channel selection window, units are defined for each channel required for analysis and they are given at the end of each channel name. Next, work and power calculation method as pre-calculated power or ECU based calculated power needs to be selected. If engine power and torque is not pre-calculated in the imported raw in-use PEMS data set. In NTE analysis, engine work is calculated from the ECU broadcast. NTE analysis requires a lug curve of the respective engine to identify the NTE boundaries. The tool can use the six points of the lug curve broadcasted by the ECU to develop a complete curve using linear interpolation or use manufacturer provided lug curve. The tool calculates the vehicle power, work and torque using ECU broadcasted parameters AEPT, NFPT, and engine reference torque as defined in eq. 2, 3 and 4. AEPT is the indicated torque of the

specific engine. AEPT cannot be less than zero as it has the torque required to overcome the friction. NFPT is the friction torque of the specific engine. NFPT has the thermodynamical and frictional losses of the engine, pumping losses, fuel, oil and coolant pump losses [10].

Moreover, if the data is not time-aligned, the tool can perform a time alignment procedure via cross-correlation of selected two channels (i.e. engine power and CO₂) as seen in Figure 27 and a statistical summary plot is given at the end of time alignment procedure as shown in Figure 28. After data alignment procedure is completed, engine lug curve is imported, which is required to perform NTE analysis and the calculation of theoretical cycle work needed in WBW procedure.

The screenshot shows the 'ChannelSelection' window of a software tool. It features a list of channels on the left, each with a dropdown menu for selection. On the right, a table displays statistical data for the selected channels, including MIN, MAX, and Mean values. At the bottom, there are buttons for 'Load Previous List', 'Save current channel list', and 'ACCEPT'. A 'PLOT' button is also visible near the bottom right.

Channel Name	MIN	MAX	Mean
Time [sec]	0.0345234	68.3563	53.0005
Vehicle Speed [mph]	60.4	196	139.445
Altitude GPS [m]	-12.0642	94.6321	34.8289
Actual Engine Percent Torque [%]	-0.130719	16.4744	8.6308
Nominal Friction Percent Torque [%]	0	3089.17	3065.77
Engine Reference Torque [%]	-2.72335	1899.13	1234.25
Engine Speed [rpm]	0	1887.35	635.723
Engine Torque [ft-lbs]	-0.00428412	555.68	155.466
Engine Power [bhp]	0	101.086	99.3845
Barometric Pressure [kPaA]	14.2291	18.6174	16.464
Ambient Air Temperature [degC]	-9.14118	88.7347	25.8848
Fuel Rate [L/h]	-0.482517	209.655	57.7285
Boost Pressure [kPa G]	0	57.0976	42.2184
Intake Manifold Temperature [degC]	0	91.0442	82.4179
Engine Coolant Temperature [degC]	0	344.027	270.715
SCR Inlet Gas Temperature [degC]	0	337.674	265.129
SCR Outlet Gas Temperature [degC]	0	0.09039	0.0171631
CO [g/s]	0	61.524	19.0669
CO2 [g/s]	0	0.00244	1.75086e-05
THC [g/s]	0	0.12887	0.00509549
NO [g/s]	0	0.13343	0.00561662
NOx [g/s]			

Figure 26. Channel selection of the NTE and WBW in-use emissions analysis post-processing tool.

Data Time Alignment

Original Rsquared: 0.037 Reference Channel: EnginePower

Aligned Rsquared: 0.819 Align Channel: CO2

Data Shift [sec]: 97

Align Data

Plot Data Plot Time Aligned Data

Figure 27. Selection of reference and align channels for time alignment process.

Figure 28. Time alignment section of the in-use post-processing tool.

After, lug curve of the engine is imported the raw data under the lug curve can be plotted by clicking the “Plot Engine Lug Curve” button on the first tab of the tool as shown in Figure 29.

IMPORT DATA	N-T-E Analysis	W-W Analysis
Toolbox Path Settings <div> Set Tool Path: C:\Users\gcvkhg\Desktop\NTE-Paper\NTE_WorkBased\Window\NTE Toolbox Version 2_16_201 </div> <div> Set Project Path: C:\Users\gcvkhg\Desktop\NTE-Paper\NTE_WorkBased\Window\Data </div>		
Data Import <div> Import CSV File: 0007-001-70_Part1.csv </div> <div> Data Sample Rate: 1 Hz Data Length: 5111 sec </div>		
Assign Channels <div> Work Calculation Method: ☐ ECU using Percent Torque ☒ pre-Calculated Power </div> <div> Enter Reference Torque in Nm: 0 </div> <div> Confirm Data Channels for Analysis </div>		
Data Time Alignment <div> Original Rsquared: 0.084 Aligned Rsquared: 0.933 Data Shift [sec]: 324 </div> <div> Reference Channel: EnginePower Align Channel: CO2 </div> <div> Plot Data Align Data Plot Time Aligned Data </div>		
Import Lug Curve <div> Import Lug Curve: Vehicle2_CumminsDiesel.csv </div> <div> Plot Engine Lug Curve </div>		
Data Plot for Assigned Channels <div> VehicleSpeed </div> <div> Time [sec] </div>		
<div> REOPEN TOOLBOX CLOSE TOOLBOX Export N-T-E Results Export W-B Results </div> <div> © Copyright of CAFEE </div>		

Figure 29. Import data section of the NTE and WBW in-use emissions analysis post-processing tool.

After a successful data import is achieved, NTE zone settings are required to be defined by clicking “NTE Zone Settings” button in the N-T-E tab of the tool. Once the new window is open to apply setting, by default tool NTE zone settings are set to the current NTE in-use regulatory protocol settings such as power and torque thresholds as described in section 2.1.1. Figure 30 demonstrates the NTE zone settings window of the tool.

Figure 30. HD-NTE zone settings window of the post-processing tool.

Subsequently, the NTE zone under the vehicle lug curve by clicking “Define New NTE Zone” button is defined. In this section, n_{Low} and n_{hi} needs to be selected as defined in the current NTE in-use regulatory protocol. Then, exclusions defined in section 2.1.1 in any combination and order can be selected and applied. Moreover, aftertreatment outlet temperature, altitude and NTE event time values can be changed to any values by simply changing numbers corresponding to each exclusion as shown in Figure 31. By default, all exclusions are set to be applied and their values are set to default values accepted by the current NTE in-use regulatory protocol. Once exclusions are selected, NTE analysis can be executed click “Apply NTE Analysis” button.

Figure 31. Illustration of NTE analysis section of the tool.

Once the NTE analysis is executed, the tool shows all valid NTE events under the engine lug curve as shown in Figure 31. In the N-T-E Summary section, all valid NTE events bsNO_x , bsCO_2 and bsCO emissions are illustrated for a quick summary plot as shown in Figure 32. Furthermore, all valid NTE events bsNO_x can be compared to NTE emission thresholds settings which are detailly defined in the following reference [10]. The tool employs NTE emissions settings as shown in Figure 33. On the right-hand side of the N-T-E Summary section, number of total valid NTE events, VPR, average NTE power, average NTE bsNO_x and total route bsNO_x are tabulated. Moreover, the valid NTE events respect to the total data can be illustrated by simply clicking the “Plot NTE Event Trace” button. Figure 34 shows default event trace plotting, the vehicle speed-time trace, aftertreatment-out temperature-time trace, ECT-time trace and one specific selected channel-time trace (it was selected as IMP channel in this case) are plotted.

Figure 32. Summary section of the tool for NTE analysis.

NTE Emission Threshold Settings

Engine MY MY 2009 & later

Testing Method 1065.650(a)(1)

Odometer Reading [miles] < 110,000

[g/bhp-hr]

Certification Std. 0.2

NTE multiplier 1.5

Accuracy Margin 0.45

Compliance Margin 0.1

Pollutant

☒ NOx

☐ CO

Save

Close

Figure 33. NTE Emission Threshold Settings

Figure 34. Valid NTE events over entire data set associated with the selected channels-time trace illustration.

4.1.2 WBW of the In-Use Emissions Section of the Tool

The WBW section utilizes the same data set imported, time alignment procedure applied during NTE analysis. Firstly, applicable emissions standards for a specific cycle such as FTP and WHTC test cycles. Similar to the NTE section of the post-processing tool, exclusions defined in section 2.1.2 for WBW regulatory protocol can be selected and applied in any order. Altitude, ECT, ambient temperature and ambient pressure threshold values can be changed to any values by simply changing numbers corresponding to each exclusion as shown in Figure 35. Once applicable limits and exclusions are selected and applied, reference work is required to execute WBW analysis. In case, the reference work over a cycle of a specific engine is not known, the tool can calculate the theoretical reference work of a given specific cycle. The set points for FTP and WHTC cycles that are required in the theoretical reference work calculation.

For this thesis, the theoretical FTP cycle work was used to as the reference work in WBW analysis. By applying setpoints given for the FTP cycle to the specific engine lug curve, the theoretical FTP is calculated as given in 40 CFR Part 1065.510 [7]. After the reference cycle work is defined in the software, power and reference work thresholds in percentage are defined. By default, these thresholds are set to current thresholds defined in the WBW regulatory protocol [8]. Once the values are set for the power and reference work thresholds, WBW analysis is executed by clicking “Apply Work Based Analysis” button. After a successful execution of WBW analysis, number of total windows, valid windows, percentage of valid windows and ninety-percent cumulative percentile pass or fail are demonstrated as shown in Figure 35. Lastly, a chart is given to have a quick overall summary of the WBW analysis for the in-use data set. The chart illustrates average power of each valid window scaled by the engine maximum power versus average bsNO_x emissions of each valid window as shown in Figure 35.

IMPORT DATA	N-T-E Analysis	W-W Analysis
Work Window Analysis Settings		
Applicable Limit for NOx [g/bhp-hr]	0.2	☐ Altitude [m] less than 1600
Applicable Limit for CO2 [g/bhp-hr]	475	☐ Engine Coolant [C] 70
Applicable Limit for CO [g/bhp-hr]	15.5	☐ Amb. Temperature [K] 266
Applicable Limit for THC [g/bhp-hr]	1.4	☐ Ambient Pres [Pa] 82500
Reference Work		
Import Test Cycle	FTP_points.DAT	Calculated Reference Work [bhp-hr]: 30.66
Calculate Reference Work		Apply Work Window Exclusions
Execute Analysis		
Work Window Based		
Power Threshold [%]	20	Total Windows : 6543
Ref Work Threshold [%]	100	Valid Windows : 4013
Apply Work Based Analysis		% of Valid Windows : 61.3% Pass
		90 % cum CF check : Pass
CO2 Based Window		
Reference CO2 [g/bhp-hr]:	525	Total Windows : -
Apply CO2 Base Analysis		% of Valid Windows : -
		Valid Windows : -
		90 % cum CF check : -
CHART		
REOPEN TOOLBOX Export N-T-E Results Export W-B Results		
CLOSE TOOLBOX © Copyright of CAFEE		

Figure 35. Illustration of WBW analysis section of the tool.

4.2 Sensitivity Analysis of Current In-use Emissions Regulatory Protocols

A comprehensive sensitivity analysis on the existing in-use emissions regulatory protocols (NTE and WBW) to examine the effect of each threshold and exclusion defined in these regulatory protocols on a large data set collected from two HDD vehicles during the cross-Cali study was conducted using the previously introduced Matlab®-based software tool for in-use data analysis. Table 4 shows the HDD vehicle specifications and technology principles along with NO_x emission certification values. This sensitivity analysis identifies critical changes to specific thresholds and exclusion boundaries of NTE and WBW regulatory protocols that would result in near-limit in-use NO_x emissions for a wide range of driving conditions, specifically, focusing on urban, low-load driving in-use emissions control. The sensitivity analysis includes a ranking of the boundaries and thresholds that affect the final evaluation for both methods the most.

Finally, determination of in-use emission factors with adjusted regulatory in-use emissions regulatory protocols for HDD trucks under a set of aftertreatment and power bins. Table 5 demonstrate the matrix of the sensitivity analysis. Findings of this sensitivity analysis propose changing some of the current thresholds and exclusions of in-use regulatory protocols (NTE and WBW) to better represent in-use NO_x emissions from low-load engine operation.

Table 4. Details on HDD vehicles selected for sensitivity analysis.

	Vehicle 1	Vehicle 2
<i>Engine MY</i>	2013	2014
<i>Model</i>	Diesel	Diesel
<i>Aftertreatment Configuration</i>	DPF+SCR	DPF+SCR
<i>Displacement [L]</i>	15.0	14.8
<i>Rated Power [hp]</i>	450	505
<i>FTP Cert. NO_x [g/bhp-hr]</i>	0.22	0.09
<i>NTE Cert. NO_x [g/bhp-hr]</i>	0.45	0.45
<i>Transmission</i>	Manual	Automatic

Test routes were selected to represent freeway and urban delivery operation for the sensitivity analysis. Freeway route includes driving on I-5 interstate between Sacramento and Ontario, CA to characterize emissions associated with long haul trucks. Urban route simulates urban good delivery driving activity in Irvine, CA. The route has urban traffic and frequent stop and go driving condition. More details on the routes are given section 3.2.2.

Table 5. NTE and WBW boundary parameters and range of modifications selected for sensitivity analysis.

<i>Boundary parameter</i>	<i>Vehicle 1</i>	<i>Vehicle 2</i>
<i>Size</i>	NTE duration: (30s, 20s, 10s)	Reference cycle work: (0.5xFTP, 1.0xFTP, 2.0xFTP)
<i>Power threshold</i>	30%, 20%, 10%	20%, 10%, 0
<i>Torque threshold</i>	30%, 20%, 10%	N/A
<i>Exhaust temperature Threshold</i>	250°C, 150°C, No Aftertreatment Temperature Threshold	N/A

4.3 Exhaust Flow Estimation

Development of an accurate exhaust flow estimation based on ECU parameters is critical. PEMS and on-board NO_x sensors measure the concentrations of the regulated pollutants in terms of raw exhaust in ppm levels. To calculate instantaneous mass emission rates, PEMS usually utilizes EFM type flow measurement, thus an accurate exhaust flow model is developed in order to calculate instantaneous NO_x mass emission rates with on-board NO_x sensors. Currently, modern HDD vehicles are capable of broadcasting important engine parameters required for exhaust flow estimation such as engine speed, intake manifold temperature, intake manifold pressure and fuel flow. Based on these parameters, calculation of an accurate exhaust flow estimation is developed by utilizing speed-density and map methods as a part of this research.

4.3.1 Intake Airflow Estimation

In modern diesel engines utilizing EGR, there is no direct measurement is available for the charge air including fresh air and EGR mass. The most known approach is using the speed-density method in which the theoretical intake mass airflow rate can be calculated by using speed-

density equation and volumetric efficiency [34]. Volumetric efficiency is the ratio of the mass of air sent to the cylinder to the theoretical mass of the air that can possibly occupy while cylinder volume at inlet manifold density (IMD). ECU parameters engine speed, manifold air pressure (MAP), manifold air temperature (MAT) are required in speed-density method as given in eq. 14.

$$\dot{Q}_i = \left(\eta_v * \frac{\rho_{imd}}{\rho_a} \right) * V_D * \left(\frac{N}{n} \right) \quad (14)$$

where: $\dot{Q}_i$ is intake airflow rate [m³/min]

ρ_{imd} is intake manifold air density [kg/m³]

ρ_a is ambient air density [kg/m³]

V_D is engine displacement volume [m³]

n is number of crankshaft rotations ($n=2$ for a four-stroke, $n=1$ for a two-stroke)

N is engine speed

There is no direct measurement of the IMD, however ρ_{imd} can be calculated as follows if temperature and pressure information is available at intake manifold:

$$\rho_{imd} = (IMP + P_{atm}) / (R_{air} * IMT) \quad (15)$$

where: IMP is intake manifold pressure [kPaG]

P_{atm} is atmospheric air pressure assumed 101.325 kpa

R_{air} is specific air gas constant 0.287 [kJ/kgK]

4.3.2 Estimation of Exhaust Flow

The determination of volumetric efficiency and EGR mass flow rate are crucial to accurately estimate the intake and exhaust mass flow rates. A correction factor k is implemented to estimate an accurate exhaust flow model based on intake air, fuel flow and measured exhaust flow by EFM. Exhaust gas density and air density are assumed to be at 1.2 and 1.184 kg/m³, respectively. Following relation is derived for the k as follows:

$$k = \left(\frac{\dot{m}_{exh}}{\dot{m}_i + \dot{m}_{fuel}} \right) \quad (16)$$

where: $\dot{m}_{exh}$ is measured exhaust mass flow rate [kg/s]

$\dot{m}_i$ is the theoretical intake air mass flow rate [kg/s]

$\dot{m}_{fuel}$ is ECU fuel mass rate [kg/s]

A statistical model of the correction factor k is developed in response to the four different engine parameters in order to calculate the k at any given time during a vehicle real-time operation. The following regression model is developed to predict the system response the set of four ECU parameters:

$$\begin{aligned} \hat{y} = & 0.54 - 0.003 * RPM - 0.001 * IMP - 0.0001 * Power + 0.0021 * T_{exh} \\ & + (RPM - 1407.53) * ((IMP - 79.46) * (-0.0000013)) \\ & + (IMP - 79.46) * ((Power - 190.40) * (0.00002)) \\ & + (RPM - 1407.53) * ((Power - 190.40) * (-0.000002)) \end{aligned} \quad (17)$$

In this statistical model, ECU parameters are selected to be as RPM, IMP, Power and T_{exh} represent the four main factors that effects the derivation of the k . Along with the main effects the model also includes two factor interactions. The coefficients in eq. 17 are the estimators for the parameters and their two factor interactions in the model to response to k derived in eq .16 from directly measured exhaust mass flow, fuel mass flow and estimated air intake mass flow. The coefficients are obtained from model fitting tool using JMP® Statistical Discovery software and the experimental data. The software uses a least square method in fitting the response with each factor effects. Appendix A shows the details on the statistical model obtained through JMP®. The data set for the statistical model is created from all in-use data collected from Vehicle 2 in

cross-Cali study. Measured exhaust flow rates are segregated by engine speed bins from 1000 to 2000 rpm with increment of 100 rpm. A typical value of 0.90 volumetric efficiency for 4-stroke naturally aspirated diesel engines is assumed while EGR rates are assumed to be negligible, when engine speed is less than 1000 rpm and engine load is less than 10% of the maximum engine power. If these conditions are satisfied exhaust flow is calculated as shown in eq .18 and assumed to be equal to the intake air flow plus fuel flow. The intake air flow ($\dot{Q}_i$) is calculated under two assumptions as the ideal gas law and a constant η_v value of 0.95.

$$\dot{Q}_{exh} = \dot{Q}_i + \dot{Q}_{fuel} \quad (18)$$

4.4 Accuracy and Measurement Variability of On-board NO_x Sensors

Measurement variability from on-board NO_x sensor data is quantified. A sensitivity analysis is performed to evaluate on-board NO_x sensors accuracy and assess error in terms of ppm levels of NO_x concentrations by directly comparing on-board NO_x sensor measurement to FTIR and PEMS-Semtech measurements.

In addition to the sensitivity analysis, the cross-sensitivity of CO, CH₄ and other species that would potentially influence the measurement accuracy of ZRO₂ is investigated during real-world driving condition.

Furthermore, performance of on-board NO_x sensors and developed exhaust flow model is evaluated to monitor in-use bsNO_x emissions from Vehicle 1 selected in section 4.2 under the revised in-use emissions protocols. Moreover, a comparison of in-use bsNO_x emissions measured by PEMS-Semtech, FTIR and on-board NO_x sensors is completed.

5 CHAPTER V-RESULTS AND DISCUSSIONS

5.1 Results of Sensitivity Analysis from Current In-use Regulatory Protocols

5.1.1 NTE Analysis-Urban Route

Figure 36 displays NTE analysis results for Vehicle 1 from urban route performed in the study. The following section will refer to the exclusion provided in the current NTE methodology as “base”. Changes to a certain exclusion will be denoted by “base” followed by the respective parameter changed. The results from urban route show no valid NTE events using the “base” NTE analysis. This lack of NTE windows during urban operation can be entirely attributed to the low-load engine operation that fails to satisfy the 30% maximum power threshold curve of the NTE boundary. Furthermore, highly transient vehicle activity will result in engine loads dropping out of the NTE window before the 30 sec threshold criteria is achieved. In order to evaluate the influence of the NTE window size on capturing valid NTE events, the window size thresholds were lowered to 20 and 10 seconds. Figure 36 shows the results for the NTE analysis for the 20 and 10 seconds duration time. For the urban operation, reducing the NTE duration time to 20 and 10 seconds results in 1 and 3 NTE events respectively.

A lower accumulated work within the NTE windows might result in higher errors in calculation of bsNO_x emissions for an urban type of operation characterized by low-load, low-speed engine operation. Even though the NTE duration time is reduced, in-use bsNO_x emissions of all valid NTE events were below the average total route bsNO_x emissions. To increase the NTE evaluation area under the engine performance curve, lowering torque or power threshold individually did not change the number of NTE events obtained from base settings of NTE method. It is found that torque and power thresholds must be reduced simultaneously to increase the NTE evaluation area. Figure 36 demonstrates the increase in the number of NTE events when power and torque thresholds reduced simultaneously.

Aftertreatment temperature exclusion plays a critical role to evaluate in-use bsNO_x emissions at low-load operations. Figure 36 proves the significant increase in the captured NTE events when NTE aftertreatment exclusion is removed. Furthermore, 38% of the observed NTE events have higher bsNO_x emissions from the total route and 57% of them have higher bsNO_x

emissions from the USEPA 2010 NTE bsNO_x emissions standards. It is observed that evaluation of in-use NTE bsNO_x emissions more representative when compared to in-use bsNO_x emissions observed from the total route. The average NTE bsNO_x emission rate during urban operation is found to be 0.685 g/bhp-hr, which is approximately 99% of the total route bsNO_x emission rate (0.689 g/bhp-hr) when power and torque thresholds reduced to 10% and aftertreatment temperature exclusion is removed.

Figure 36. NTE analysis results of Vehicle 1 (urban route).

Figure 37 displays NTE analysis results for Vehicle 2 from the same urban route performed in the study. The results obtained from Vehicle 2 exhibit a similar NTE events characteristics as observed in Vehicle 1. However, by applying a threshold of 10 seconds, Vehicle 2 exhibits close to six times more number of windows than Vehicle 1. Vehicle 2 employed an automatic transmission, while Vehicle 1 was equipped with a conventional 10-speed manual transmission. The difference in the gear-changing characteristics between automatic and manual transmission could potentially contribute to the vehicle operating up to 10 seconds in an NTE window compared to a driver controlled manual transmission.

The difference in results between Vehicle 1 and 2 illustrates the possible effect of engine and transmission combination on NTE results. The results show that apart from vehicle activity, vehicle technology can significantly impact the outcome of changes to certain NTE thresholds. It is also found that torque and power thresholds must be reduced simultaneously to increase the NTE evaluation area with a vehicle employed an automatic transmission. Figure 37 demonstrates the increase in the number of NTE events when power and torque thresholds reduced simultaneously. Removal of the aftertreatment temperature exclusion drastically increases the number of NTE events observed during vehicle operation. Figure 37 verifies the significant increase in the captured NTE events when NTE aftertreatment exclusion is removed.

The average bsNO_x emission rates of NTE events when the torque and power thresholds are set to 10%, without the use of aftertreatment temperature exclusion is 0.026 g/bhp-hr with a maximum and minimum of 0.158 and 1x10⁻⁵ g/bhp-hr, respectively. The high average bsNO_x emissions indicate the absence of emission reduction strategy at lower torque and power characteristics of the engine. This is entirely attributed to the non-activity of the SCR aftertreatment system. The use of in-cylinder NO_x control strategies is dependent on OEM approach to deliver engine performance, durability and fuel consumption at low-load operation [72]. Furthermore, none of the observed NTE events have higher bsNO_x emissions than the USEPA 2010 NTE bsNO_x emissions standard when torque and power thresholds are reduced to 10%, this is possibly attributed to the vehicle equipped with an automatic transmission performs better in terms of emissions control during low-load operation compared to a vehicle employed with a manual transmission.

It is also observed that in-use NTE bsNO_x emissions represents accurately the bsNO_x emissions observed for the total route when power and torque thresholds reduced to 10% simultaneously and aftertreatment exclusion is removed. With the last setting described in Figure 36, the average NTE bsNO_x emission rates during urban operation is found to be 0.163 g/bhp-hr, which is approximately 86% of the total route bsNO_x emission rate (0.189 g/bhp-hr).

Figure 37. NTE analysis results of Vehicle 2 (urban route).

5.1.2 NTE Analysis-Freeway Route

Figure 38 displays NTE analysis results for Vehicle 1 over the freeway route. The NTE compliance approach in general was oriented towards compliance assessment of long-haul truck operation with sustained highway speed and load conditions. The results from the freeway route with baseline event duration thresholds show 4 events with bsNO_x emissions rate less than the USEPA 2010 emissions standards. Freeway operation is characterized by sustained SCR activity resulting in bsNO_x emissions below the standard. BsNO_x emissions above the standard during a freeway operation is indicative of a high probability in failure of emissions control systems. Figure 38 shows the NTE analysis with 20 seconds, 10 seconds duration compared with results NTE analysis with torque and power thresholds reduced to 10%, and with aftertreatment temperature exclusion removed. The reduction in torque and power thresholds possibly includes some low speed transients because of high traffic density in California interstates. This increases the number of events captured to two times the number of events captured with a “base” NTE power and torque threshold.

The thermal inertia of the aftertreatment system during the freeway operation helps maintain exhaust temperatures above the 250 °C NTE threshold [73], as a result no significant difference in events captured is observed by removing the aftertreatment temperature threshold. Similar to the results obtained from NTE analysis performed on low-load vehicle activity, torque and power thresholds must be reduced simultaneously to increase the NTE evaluation area under freeway operation conditions. Analysis from this study suggests that torque and power thresholds can potentially be lowered to 20%. Appendix B shows that a vehicle operating on freeway sustains loads 20% and above during freeway operation. Studies have shown that exhaust aftertreatment temperatures are above the SCR operation temperature of 200 °C during major fraction of the freeway operation [74]. Appendix B shows the aftertreatment temperature activity information for Vehicle 1 and the average aftertreatment temperature of NTE events when the torque and power thresholds are set to 10%, is 298.6 °C with a maximum and minimum of 335.3 °C and 215 °C, respectively. Therefore, for a long-haul truck operation, the exhaust aftertreatment temperature threshold does not exclude a significant fraction of NTE events. The results show that event duration, torque and power thresholds have a larger influence over broadening the boundaries of the NTE.

Figure 38. NTE analysis results of Vehicle 1 (freeway route).

Figure 39 displays NTE analysis results for Vehicle 2 over the same freeway route. NTE analysis using the “base’ settings show that Vehicle 2 qualifies for significantly higher and longer duration NTE events than Vehicle 1. This could be attributed to the fact Vehicle 2 was equipped with a 14.8 L displacement engine with a power rating of 400 hp versus a 15 L displacement engine (Vehicle 1) with a power rating of 450 hp. A slightly downsized engine would observe relatively higher engine loads performing the same activity has a larger engine. This difference could significantly alter the results of the NTE analysis as a larger number of load points would reside within the NTE boundary. Furthermore, Vehicle 2 equipped with an automatic transmission possibly contributed to engine loads staying within the NTE zone for a period of 30 seconds. With the removal of the aftertreatment exhaust temperature exclusion and applying an NTE duration of 10 secs, with the torque and power threshold held at 10%, 3 NTE events with bsNO_x emissions exceeding the compliance margin is observed. During these 3 NTE events, aftertreatment temperatures were on an average 140 °C and vehicle was under a heavy acceleration operation. Thus, the above settings results in the inclusion of a few high speed and load transient events with low SCR efficiency during the freeway operation.

Figure 39. NTE analysis results of Vehicle 2 (freeway route).

5.1.3 WBW Analysis-Urban Route

Figure 40 shows WBW analysis results of Vehicle 1 over the urban route, using FTP work of the engine as the reference work, and filtering the different windows at three different power thresholds 0, 10, and 20%. Results are presented as a cumulative frequency plot of all the WBW obtained over a driving route. Figure 40 and Figure 41 illustrates the impact of the combination of power threshold and window size on the cumulative frequency of the WBW based bsNO_x emissions over the urban route for Vehicle 1 and Vehicle 2 respectively. The reference work values considered are 0.5, 1.0 and 2.0 times the FTP cycle work. Reducing the power threshold from 20% to 10% of maximum engine power resulted in an increase in percentage of valid windows from 6.35% to 67%. Figure 40 shows that over the urban route, reducing the power threshold does not result in any windows with a bsNO_x emission below the USEPA 2010 NO_x standard. However, reducing the reference work to half the FTP work results in 35% and 10% of the total number windows with a bsNO_x emission below the USEPA 2010 standard.

The results show that window size has a greater influence in WBW analysis over the power threshold. The average bsNO_x emissions rate of valid windows for a reference work condition equaling FTP work and power threshold of 10%, is 0.750 g/bhp-hr. The high average bsNO_x emissions is indicative of low exhaust temperature operation, linked to low SCR NO_x conversion efficiency. However, results from Vehicle 2 shows that close to 80% of the valid windows are below the USEPA 2010 NO_x standard of 0.2 g/bhp-hr. This significant difference in average bsNO_x emissions of the valid windows between Vehicle 1 and Vehicle 2 can be attributed to the differences in engine thermal management strategies, aftertreatment packaging and in-cylinder NO_x control between engine manufacturers. The average bsNO_x emissions of the valid windows for a reference work condition equaling FTP cycle work and power threshold of 10%, is 0.097 g/bhp-hr. Average bsNO_x emissions below 0.20 g/bhp-hr while including low power thresholds is indicative of a successful strategy to lower tailpipe NO_x emissions under low-load operation in Vehicle 2. A detailed summary of the WBW analysis of Vehicle 2 can be seen in Appendix C.

Figure 40. bsNO_x emissions from the analysis WBW method on urban route with various power thresholds and reference work values of Vehicle 1.

Figure 41. bsNO_x emissions from the analysis WBW method on urban route with various power thresholds and reference work values of Vehicle 2.

Figure 42 shows a four-quadrant plot between bsNO_x and bsCO₂ emissions of the valid windows for Vehicle 1 and Vehicle 2. The four-quadrants are obtained by the intersection of the USEPA 2010 NO_x standard and the 2014-2016 heavy-duty GHG standard for long-haul vocation. The placement of the windows in to achieve simultaneous reduction in both NO_x and CO₂ emissions. The top left quadrant represents low-NO_x and high-CO₂ emissions, which is indicative of active thermal management strategy associated with a fuel penalty. The top right quadrant represents both high-NO_x and high-CO₂ emissions, indicative of minimal SCR activity coupled with possible high-EGR strategies. The bottom left quadrant represents both low-NO_x and low-CO₂ emissions, indicative of conducive conditions for SCR activity leading to improved fuel economy. The bottom right quadrant represents high-NO_x and low-CO₂ emissions, indicative of a possible failure of NO_x emissions control systems that invariably results in low CO₂ emissions.

Figure 42 shows significant difference in placement of windows in the four quadrants for Vehicle 1 and Vehicle 2. Vehicle 2 shows a larger percentage of windows in the bottom left quadrant indicating superior SCR activity that enables the manufacturer to employ low fuel consumption strategies. A significant fraction of the windows from Vehicle 2 is also placed in the top left window indicating a successful thermal management strategy aimed at increasing SCR activity while being subjected to a fuel penalty. Results from Vehicle 1 indicate both a higher NO_x and CO₂ emissions over the same route. The results indicate the differences in in-use emissions control strategy between different engine manufacturers.

Figure 42. bsCO₂ emissions versus bsNO_x emissions trade-off comparison.

5.1.4 WBW Analysis-Freeway Route

Figure 43 shows WBW analysis results of Vehicle 1 over the freeway route with same settings employed in the WBW analysis of urban route. Figure 43 demonstrates the impact of windows length. It is observed that power threshold can potentially be sustained at 20% as suggested in current WBW protocol for freeway type operation. Both Vehicle 1 and 2 sustain minimum of 20% engine load during freeway operation as shown in Appendix C. Thus, it is observed that the WBW compliance methodology was also intended towards compliance assessment of freeway type operation. Effect of window length is significant on number of windows obtained from the analysis. Reducing window length from 2xFTP to 0.5xFTP increases number of windows 15% and 20% for Vehicle 1 and 2, respectively as shown in Appendix C. The window length of one FTP used in this analysis seems acceptable for WBW analysis from freeway operation. The average bsNO_x emissions rate of valid windows from Vehicle 1 when the reference work is the work over an FTP cycle, is 0.149 g/bhp-hr with a maximum and minimum of 0.310 and 0.037 g/bhp-hr respectively. Similarly, the average bsNO_x emissions rate of valid windows from Vehicle 2 when the reference work is the work over an FTP cycle, is 0.140 g/bhp-hr with a maximum and minimum of 0.431 and 0.067 g/bhp-hr respectively. Moreover, all valid windows

observed when reference work is 2xFTP are found to be less than the USEPA 2010 emissions standards 0.2 g/bhp-hr for Vehicle 1 as shown in Figure 43. Similarly, all valid windows observed when reference work is 1xFTP are found to be less than the USEPA 2010 NTE emissions standards for Vehicle 1.

Vehicle 2 exhibits similar valid windows characteristics as seen from Vehicle 1. Figure 44 demonstrates WBW analysis results for Vehicle 2 over a freeway operation. Moreover, all valid windows observed when reference work is 2.0xFTP are found to be less than the USEPA 2010 NTE emissions standards for Vehicle 2. Also, approximately 95% of valid windows observed when reference work is 1.0xFTP and 0.5xFTP are found to be less than the USEPA 2010 NTE emissions standards for Vehicle 1.

Figure 43. bsNO_x emissions of Vehicle 1 from the WBW method on freeway route with various window lengths (2.0xFTP, 1.0xFTP and 0.5xFTP) at 20% power threshold.

Figure 44. bsNO_x emissions of Vehicle 2 from the WBW method on freeway route with various window lengths (2xFTP, 1xFTP and 0.5xFTP) at 20% power threshold.

5.1.5 NTE and WBW Analysis Results In-use Emission Factors of HDD Vehicles

Under a Set of Power and SCR-out Temperature Bins

Additional analysis of real-world vehicle operating and route parameters influencing the WBW and NTE approach is performed under a set of power and SCR-out temperature bins. Different vehicle applications and vocations could potentially impact the analysis outcome by experiencing different engine load pattern and aftertreatment temperature condition, which can potentially change the number of valid windows for the WBW analysis and NTE method events. Figure 45 represents bsNO_x emissions of Vehicle 1 and 2 combined from the NTE method on freeway route while NTE duration time is applied as 10 seconds, power and torque thresholds are reduced to 10% and exhaust temperature exclusion is not applied in order to evaluate maximum fraction of the in-use data by utilizing NTE in-use emission regulatory protocol. Vehicle 1 and Vehicle 2 result in having bsNO_x emissions below the USEPA 2010 NO_x standard of 0.2 g/bhp-hr while sustaining SCR operation temperature of 200 °C above during the freeway operation. Moreover, Figure 45 shows the results of a specific case when a vehicle has few high

speed and load transient events with low SCR efficiency during the freeway operation aftertreatment temperatures. The reason behind this case is that the above NTE analysis settings result in the inclusion of a few high speed and load transient events with low SCR efficiency during freeway operation. Overall, HDD vehicles during freeway operation sustains above 30% loads and exhaust aftertreatment temperatures above 200 °C as seen in Figure 44.

Figure 45. bsNO_x emissions of Vehicle 1 and 2 combined from the NTE method on freeway route.

Figure 46 represents bsNO_x emissions of Vehicle 1 and 2 combined from the WBW method on local route while power threshold is reduced to 10% in order to evaluate maximum fraction of the in-use data with WBW in-use emission regulatory protocol. Vehicle 1 and Vehicle 2 result in having bsNO_x emissions below the USEPA 2010 NO_x standard of 0.2 g/bhp-hr while sustaining SCR operation temperature of 250 °C and above while vehicle load observed less than 30%.

Moreover, Figure 46 shows the significant increase in terms of bsNO_x emissions when SCR operation temperature is less 250 °C. The vehicle load is observed between 15 to 20% during SCR operation temperature between 200-225 °C and 15 to 20% low-load engine operation trigger in-use bsNO_x emissions to be up to five times higher than certification. HDD vehicles show similar trends over real-world vehicle operation during the near-port activity, characterized by low-load operations [5]- [7].

Figure 46. bsNO_x emissions of Vehicle 1 and 2 from the WBW method on urban route while power threshold is reduced to 10%.

5.2 Exhaust Flow Estimation

As an alternative to direct measurement of exhaust flow, mathematical-physical exhaust model based on speed-density and map method is developed. In this section exhaust flow model results are summarized for Vehicle 1 and Vehicle 2 used in the sensitivity analysis on the current in-use emission regulatory protocols in section 5.1.

The flow rates of EFM exhaust and estimated exhaust flow from intake air flow plus fuel flow of Vehicle 1 were plotted in Figure 47. Large deviations between the flow rates were observed in entire range of flow levels. Exhaust flow model underestimates the actual exhaust flow rate because the model does not take the EGR flow into account. Although, exhaust flow modeled as intake air flow plus fuel flow provided a good agreement when compared to a directly measured exhaust flow in the following study [26]. However, vehicles tested during this study were not equipped with EGR technology. Thus, modeling exhaust flow as intake air flow plus fuel flow performs poorly when it is applied to HDD vehicles integrated with EGR technology.

Figure 47. Direct flow rate comparison between directly measured exhaust flow rate versus modeled exhaust flow rate as intake air flow plus fuel flow from Vehicle 1.

A linear regression is performed between the EFM flow rate and estimated exhaust flow from intake air flow plus fuel flow rate for Vehicle 1 as shown in Figure 48. The regression produced an R^2 of 0.856. The variability from the exhaust flow model based on intake and fuel flow is found to be within the 23% through most of the engine operation range. However, such a variability may not be acceptable for monitoring in-use NO_x emissions rates and can potentially be improved by introducing the coefficient factor k to take into account of EGR flow.

Figure 48. Regression analysis of directly measured exhaust flow rate and modeled exhaust flow rate as intake air flow plus fuel flow from Vehicle 1.

Figure 49 shows the flow rates of directly measured exhaust flow rate and corrected exhaust flow model of Vehicle 1 which now accounts EGR flow rate. Deviation between the flow rates were significantly reduced through entire range of flow levels. However, corrected exhaust flow model over estimates the actual exhaust flow rate during some engine operation points. This is highly possible from over estimating the EGR flow rate at given point. Knowledge of EGR rate would possibly improve the exhaust flow model, however, EGR rates currently are not publicly broadcasted in ECU from HDD vehicles. Thus, if EGR rate will be available through ECU, more accurate exhaust flow model can be developed.

Figure 49. Direct flow rate comparison between directly measured exhaust flow rate versus corrected exhaust flow model rate from Vehicle 1.

A linear regression is performed between the EFM flow rate and the corrected exhaust model flow for Vehicle 1 as shown in Figure 50. The regression produced an R^2 of 0.931. The variability from the corrected exhaust flow model accounting EGR rate is found to be within the 15% through most of the engine operation range. 8% reduction is achieved compared to the exhaust flow model associated with air intake flow plus fuel flow. Moreover, 15% variability may now be acceptable for monitoring in-use NO_x emission rates.

Figure 50. Regression analysis of directly measured exhaust flow and corrected exhaust flow model as intake air flow plus fuel flow from Vehicle 1.

it is important to have an exhaust flow model which can be used for the calculation of emissions mass rates and implement this methodology to monitor in-use NO_x emissions that can be easily used to screen off-cycle NO_x emission rates from a large number of HDD vehicles. For this reason, regression model of k correction factor developed for Vehicle 1 is used to evaluate exhaust flow estimation from Vehicle 2. Figure 51 shows the flow rates of directly measured exhaust flow rate and corrected exhaust flow model of Vehicle 2 which utilizes the regression model developed of correction factor for Vehicle 1. Deviations between the flow rates were observed in entire range of flow levels. Corrected exhaust flow model both over and underestimates the actual exhaust flow rate during some engine operation points. The deviation can be contributed to Vehicle 2's wastegate system utilized in the vehicle's turbo system. The primary function of the wastegate system is that the maximum boost pressure is regulated in turbocharger system in order to protect the engine and the turbocharger components. Thus,

effect of wastegate system on the boost pressure can potentially alter the model developed from a vehicle without a wastegate system.

Figure 51. Direct flow rate comparison between directly measured exhaust flow rate versus corrected exhaust flow model rate from Vehicle 2.

A linear regression is performed between the EFM flow rate and the corrected exhaust model flow as shown in Figure 52 for Vehicle 2. The regression produced an R^2 of 0.901. Although, there are over and under estimation of the exhaust flow due to the technology difference in turbocharger system of Vehicle 2, the variability from the corrected exhaust flow model is found to be still within the 15% through most of the engine operation range. Variance above 25% between the directly measured exhaust flow and the estimated exhaust flow is contributed to combination of over estimating the EGR flow rate and different turbocharger technology.

Figure 52. Regression analysis of directly measured exhaust flow and corrected exhaust flow model as intake air flow plus fuel flow from Vehicle 2.

5.3 Results of Accuracy and Measurement Variability of On-board NO_x Sensors

Accuracy and measurement variability analysis of on-board NO_x sensors are performed. Figure 53 shows the NO_x concentrations measured by the FTIR, new and aged on-board NO_x over a HHDDT and UDDS cycles. Moreover, on-board NO_x sensors are kept on all times, even during low aftertreatment temperature in order to evaluate on-board NO_x measurements during these conditions. No mechanical failure is observed from these sensors during low aftertreatment temperature conditions. Also, the aged on-board NO_x sensors which was taken from a HDD vehicle with 60,000 miles is found to be performing well compared to the FTIR and new on-board NO_x sensor measurements.

Figure 53. Direct flow comparison between FTIR, old and new on-board NO_x sensors.

Figure 54 and 55 show the measurement variability of a new on-board NO_x sensor compared with FTIR NO_x concentrations over three repeats of UDDS and HHDDT cycles on chassis dynamometer testing, respectively. Measured NO_x concentrations are segregated into NO_x concentration bins and averaged over each concentration bin respect to NO_x concentrations from FTIR measurement. Measurement accuracy of on-board NO_x sensor is found to be mostly within 10% with respect to FTIR in concentration levels between 25 and 250 ppm range.

Measurement accuracy of an on-board NO_x sensor is found to be higher within 10 to 25% with respect to FTIR in concentration levels between 250 and 400 ppm range. Measurement variability of the on-board NO_x at concentration levels of 250 to 400 ppm is found higher compared to the measurement variability observed during NO_x concentration measurement level between 25 to 200 ppm. Deviations between the FTIR and on-board NO_x sensors at higher concentration levels (250-400 ppm) is attributed the different phenomena of the sample in the heated line and filter while on-board NO_x sensors have only small dead volume for sampling.

At very low NO_x concentration levels of 0 to 8 ppm, significant deviation up to 80% difference between on-board NO_x and FTIR measurements is observed. However, still a good measurement accuracy is observed from on-board NO_x sensors measurement at fairly low NO_x concentration levels of 8 to 25 ppm as shown in small figures inside of Figure 54 and 55.

Figure 54. Measurement accuracy and variability of on-board NO_x sensors observed during chassis dynamometer testing over UDDS cycle.

Figure 55. Measurement accuracy and variability of on-board NO_x sensors observed during chassis dynamometer testing over HHDDT cycle.

Additionally, effect of interferences gases CH_4 , CO and NH_3 on on-board NO_x sensors is investigated. In-use data from 800 hours of on-road operation with FTIR measurement system from HDD vehicles on freeway and urban routes during cross-Cali study is used to evaluate cross sensitivity of on-board NO_x sensors towards CH_4 , CO and NH_3 . Figure 56 shows CH_4 concentrations measured during on-road operation. It is found that 90% of the CH_4 concentrations are observed within 5 ppm and at this level of CH_4 concentrations, no cross-sensitivity of NO_x sensors associated with CH_4 is observed. However, a study demonstrated the influence of CH_4 on on-board NO_x sensors accuracy, but during this study NO_x sensors were exposed to high levels of CH_4 concentrations, 400 ppm, in a controlled environment [57]. On-road data collected during cross-Cali study demonstrates that 400 ppm concentration levels of CH_4 cannot be seen during real-world HDD vehicle operation. Similarly, CO concentration levels seen from in-use data collected in cross-Cali study are shown in Figure 57. It is found that 95% of the CO concentrations are observed within 10 ppm and at this level of CO concentrations, no cross-sensitivity of NO_x sensors associated with CO is detected.

Figure 56. CH₄ concentrations measured during in-use emissions HDD vehicle testing.

Figure 57. CO concentrations measured during in-use emissions HDD vehicle testing.

The on-board NO_x sensors are known to be very sensitive to NH_3 presence. Many studies have studied the cross-sensitivity of NH_3 on ZrO_2 based NO_x sensors. However, in these studies NH_3 interference on ZrO_2 based NO_x sensors observed when NH_3 concentration above 200 ppm [57], [75]. Nevertheless, Figure 58 shows NH_3 concentrations measured during on-road operation is found to be within 10 ppm of NH_3 concentrations 95% of the time. Thus, on-road data collected during cross-California study proves that 200 ppm concentration levels of NH_3 can hardly be seen during real-world HDD vehicle operation as shown in Figure 58. Yet, it is possible to have faulty aftertreatment system where high NH_3 slip can occur, thus, it is possible to detect higher NH_3 levels in case of a faulty aftertreatment system such as NH_3 dosing system used to inject NH_3 to the SCR.

Figure 58. NH₃ concentrations measured during in-use emissions HDD vehicle testing.

Evaluation of on-board NO_x sensors along with the developed exhaust flow model is performed to calculate in-use bsNO_x emissions from Vehicle 1. Moreover, a comparison of in-use NO_x emission rates measured by PEMS-Semtech, FTIR and on-board NO_x sensors are compared. In-use NO_x emissions rate are under revised in-use regulatory protocols which were 10 seconds of NTE duration time, torque and power thresholds reduced to 10%, removal of aftertreatment temperature in order to capture in-use NO_x emissions from broaden area under the NTE control area. Figure 59 shows the difference in bsNO_x emissions for each NTE event occurred during entire test. The average NTE bsNO_x emissions rate from on-board NO_x sensor, FTIR and PEMS-Semtech during freeway operation is found to be 0.091, 0.094 and 0.109 g/bhp-hr, respectively. The average NTE bsNO_x error between the FTIR using EFM as the exhaust flow rate, on-board NO_x sensor using exhaust flow model developed is found to be 11.4%. Furthermore, the average NTE bsNO_x error between the PEMS-Semtech using EFM as the exhaust flow rate, on-board NO_x sensor using exhaust flow model developed is found to be 18.3%. Overall, it can be concluded

that on-board NO_x sensors are capable of monitoring in-use NO_x emissions while applying NTE in-use emission protocol.

6 CHAPTER VI-CONCLUSIONS

The main objective of this research was to assess the measurement thresholds of in on-board NO_x sensors to evaluate real-time NO_x emissions rate and show that on-board NO_x sensors can be successfully used in development of a cost-effective in-use NO_x emissions monitoring methodology using revised in-use emissions regulatory protocols (NTE and WBW) that can be easily used to screen off-cycle NO_x emission rates from a large number of HDD vehicles.

This research presented detailed analysis of two different approaches for in-use emissions evaluation, namely US-NTE and EU-WBW protocols for HDD vehicles and necessary revision for both methods to improve the evaluation of HDD vehicle's in-use emissions are needed to evaluate in-use NO_x emission from low-load vehicle operation. It was found that the current NTE methodology makes use of a small portion of the data approximately 10 to 30% for both urban and freeway type operation which leads to a poor evaluation of in-use emissions from HDD vehicles. NTE methodology can be a powerful procedure to evaluate in-use emissions from HDD vehicles with revision. Reducing NTE duration time significantly increases the number of NTE events. For this purpose, NTE duration time can be changed from 30 to 10 seconds. Results from the NTE analysis prove that even with 10 seconds of NTE duration time, in-use bsNO_x emissions from all vehicles are below the level of 1.5 times of the USEPA 2010 emissions standard. Moreover, it is found out that to increase NTE control area, torque and power thresholds must be altered simultaneously and revised thresholds for both parameter can potentially be reduced from 30 to 10% to evaluate in-use NO_x emissions from low-load operation. To evaluate in-use NO_x emissions from high speed, freeway type operation, torque and power threshold can be reduced from 30 to 20%. Aftertreatment temperature exclusion plays a key role for the evaluation of in-use bsNO_x emissions. Results from the NTE analysis, which do not include aftertreatment exclusion, show some of valid NTE events have up to six times higher in-use bs-NO_x emissions than the average in-use bsNO_x emissions rates obtained from the NTE analysis where aftertreatment temperature exclusion is applied. Outcomes from the sensitivity analysis of WBW methodology exhibits similar observations obtained from the NTE sensitivity analysis. It is found out that 20% power thresholds exclude data from low-load operation. Thus, lowering

the power threshold to 10% can potentially improve the evaluation of in-use NO_x emissions from low-load, urban type operation. 20% power threshold seems reasonable to evaluate off-cycle NO_x emissions from high-load, freeway type operation as seen that vehicles sustain loads above 20% most of the time during freeway operation.

A common exhaust flow model based on estimated intake flow, fuel flow and a regression model to consider EGR flow is developed for HDD vehicles equipped with an EGR system as a part of this research. The variability from the corrected exhaust flow model accounting EGR rate is found to be within the 15% through most of the engine operation range. 8% reduction is achieved compared to the exhaust flow model associated with air intake flow plus fuel flow. The overall results suggest that information on EGR flow rate is needed in order to have more accurate exhaust flow model. It was also found that turbo systems of a vehicle play a critical role for exhaust flow modeling. Thus, an exhaust flow model can be more improved if the model can incorporate different turbo technologies and EGR flow rate.

A quantification of in-use NO_x emission rates, measurement accuracy and variability from on-board NO_x sensors are assessed. The best measurement accuracy of an on-board NO_x sensor was found to be mostly within 10% with respect to FTIR concentration levels between 25 and 200 ppm and the measurement variability of the on-board NO_x at concentration levels of 25 to 200 ppm was found to be within 5% respect to FTIR NO_x concentrations. At very low NO_x concentration levels of 0 to 8 ppm, significant deviation up to 80% difference between on-board NO_x and FTIR measurements is observed. However, still a good measurement accuracy from on-board NO_x sensors measurement at fairly low NO_x concentration levels of 8 to 25 ppm was found within 20%. However, with upcoming low-NO_x standards, measurement accuracy and variability of on-board NO_x sensors were found to be questionable. Further improvements are needed in on-board NO_x sensor accuracy if they are intended to be utilized in monitoring at or below 0.02 g/bhp-hr bsNO_x emissions.

The cross-sensitivity of NH₃ on ZRO₂ based on-board NO_x is investigated during real-world vehicle operation. Studies have shown that NH₃ interference on ZRO₂ based NO_x sensors observed when NH₃ concentration above 200 ppm [58], [75]. Nevertheless, in this research, NH₃ concentrations measured during on-road operation is found to be within 10 ppm of NH₃

concentrations 95% of the time. Thus, and no obvious interference from NH_3 was detected on on-board NO_x sensors.

Evaluation of on-board NO_x sensors along with the developed exhaust flow model is performed to calculate in-use bsNO_x emissions within the revised NTE in-use regulatory protocol. The average NTE bsNO_x emissions rate from on-board NO_x sensor, FTIR and PEMS-Semtech during freeway operation is found to be 0.091, 0.094 and 0.109 g/bhp-hr, respectively. The average NTE bsNO_x error between the FTIR using EFM as the exhaust flow rate, on-board NO_x sensor using exhaust flow model developed is found to be 11.4%. Furthermore, the average NTE bsNO_x error between the PEMS-Semtech using EFM as the exhaust flow rate, on-board NO_x sensor using exhaust flow model developed is found to be 18.3%. Overall, it can be concluded that on-board NO_x sensors are capable of monitoring in-use NO_x emissions while applying NTE in-use emission protocol within reasonable agreement.

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8 APPENDICES

A. Summary of the Statistical Model Developed to Predict Correction Factor K

B. Details on the results from sensitivity analysis of NTE methodology of Vehicle 1 and 2

Route Vehicle #	Boundary Conditions	# of NTE	NTE Duration [sec]			bsNOx [g/bhp-hr]			Aftertreatment Temperature [°C]			Work [bhp-hr]			Power [%]		
			mean	max	min	mean	max	min	mean	max	min	mean	max	min	mean	max	min
URBAN VEHICLE 1	Base, 30 sec	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Base, 20 sec	1	26.0	26	26	0.020	0.020	0.020	262.6	262.6	262.6	1.89	1.89	1.89	56.5	56.5	56.5
	Base, 10 sec	3	18.7	26	11	0.015	0.020	0.006	251.9	258.8	262.6	0.72	1.89	1.89	56.2	60.8	51.2
	Base, Torque 10%, Power 10%, 10 sec	6	20.3	34	10	0.068	0.320	0.000	257.0	262.4	252.2	0.06	0.23	0.00	39.7	57.0	22.6
	Base, Torque 10%, Power 10%, No aftertreatment Temperature	37	21.2	53	10	0.687	5.793	0.000	216.9	262.4	177.0	1.07	4.61	0.20	37.9	92.9	14.4
URBAN VEHICLE 2	Base, 30 sec	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Base, 20 sec	2	27.0	27	27	0.011	0.017	0.004	281.3	286.6	276.1	1.84	1.94	1.73	51.5	54.4	48.7
	Base, 10 sec	19	14.3	27	10	0.027	0.158	0.002	275.6	286.9	254.2	1.04	1.94	0.62	56.0	87.1	42.4
	Base, Torque 10%, Power 10%, 10 sec	21	20.6	46	10	0.026	0.158	0.000	276.9	294.9	254.2	1.34	3.17	0.37	48.8	81.0	27.8
	Base, Torque 10%, Power 10%, No aftertreatment Temperature	37	18.4	46	10	0.165	1.049	0.000	242.4	294.9	139.9	1.16	3.17	0.37	47.7	85.1	24.0
FREEWAY VEHICLE 1	Base, 30 sec	4	36.0	49	30	0.094	0.126	0.052	288.1	297.3	277.9	2.74	4.79	1.82	57.1	76.2	44.3
	Base, 20 sec	7	30.9	49	20	0.074	0.126	0.005	302.7	336.9	277.9	2.33	4.79	1.44	58.4	84.5	44.3
	Base, 10 sec	18	19.4	49	10	0.055	0.145	0.005	303.7	336.9	277.9	1.36	4.79	0.57	52.0	84.5	36.8
	Base, Torque 10%, Power 10%, 10 sec	36	21.5	64	10	0.062	0.281	0.007	298.6	335.3	253.9	1.23	6.01	0.30	42.3	73.2	23.1
	Base, Torque 10%, Power 10%, No aftertreatment Temperature	42	22.0	111	10	0.069	0.281	0.007	293.3	335.3	215.0	0.38	0.88	0.15	42.9	90.5	23.1
FREEWAY VEHICLE 2	Base, 30 sec	27	69.7	247	30	0.094	0.186	0.030	317.6	352.7	254.8	5.55	16.87	1.77	61.2	88.8	38.6
	Base, 20 sec	45	51.4	247	20	0.095	0.186	0.030	307.8	352.7	254.6	3.99	16.87	1.16	57.4	88.8	38.1
	Base, 10 sec	73	36.8	247	10	0.101	0.202	0.030	301.5	352.7	254.2	2.79	16.87	0.52	54.4	88.8	38.1
	Base, Torque 10%, Power 10%, 10 sec	74	52.5	582	10	0.105	0.245	0.047	297.5	352.5	253.8	3.42	34.17	0.36	45.4	88.8	23.5
	Base, Torque 10%, Power 10%, No aftertreatment Temperature	102	45.3	582	10	0.148	2.044	0.047	276.9	352.5	105.2	2.87	34.17	0.36	43.5	88.8	22.9

C. Details on the results from sensitivity analysis of WBW methodology of Vehicle 1 and 2

Route Vehicle #	Ref Cycle Work [bhp-hr]	Power Threshold [%]	# of Windows	# of Valid Windows	Percentage of Valid Windows [%]	bsNOx [g/bhp-hr]			Aftertreatment Temperature [°C]			Power [%]		
						mean	max	min	mean	max	min	mean	max	min
URBAN VEHICLE 1	1xFTP	20%	2652	169	6.37%	0.330	0.340	0.270	232.9	239.4	229.2	26.8	29.7	20.1
	1xFTP	10%	2652	1777	67.01%	0.750	0.940	0.270	213.8	239.4	203.4	15.4	29.7	10.0
	1xFTP	0%	2652	1780	67.12%	0.750	0.940	0.270	213.8	239.4	203.4	15.3	29.7	9.8
	0.5xFTP	20%	3419	647	18.92%	0.390	0.890	0.050	233.6	248.6	207.4	24.9	37.7	20.1
	0.5xFTP	10%	3419	1887	55.19%	0.747	1.159	0.053	217.5	248.6	197.8	19.0	37.7	10.0
	0.5xFTP	0%	3419	2547	74.50%	0.711	1.158	0.053	215.2	248.6	197.8	16.3	37.7	7.0
	2.0xFTP	10%	1230	358	29.11%	0.619	0.689	0.603	215.9	216.4	213.5	14.7	16.4	12.4
	2.0xFTP	0%	1230	358	29.11%	0.619	0.689	0.603	215.9	216.4	213.5	14.7	16.4	12.4
URBAN VEHICLE 2	1xFTP	20%	1966	1535	78.08%	0.097	0.258	0.019	257.2	281.8	212.9	27.7	35.0	20.0
	1xFTP	10%	1966	1945	98.93%	0.115	0.258	0.017	252.7	281.8	208.1	24.8	35.0	10.1
	1xFTP	0%	1966	1952	99.29%	0.115	0.258	0.017	252.6	281.7	208.1	24.7	35.0	9.7
	0.5xFTP	20%	2439	1654	67.81%	0.079	0.421	0.010	262.2	284.5	193.8	28.3	42.5	20.0
	0.5xFTP	10%	2439	2061	84.50%	0.133	0.424	0.010	250.5	284.5	185.9	26.0	42.5	10.3
	0.5xFTP	0%	2439	2425	99.43%	0.162	0.458	0.010	247.5	284.5	185.9	23.3	42.5	5.9
	2.0xFTP	20%	1142	718	62.87%	0.104	0.139	0.046	251.3	268.2	235.7	25.6	28.2	20.2
	2.0xFTP	10%	1142	1128	98.77%	0.106	0.139	0.046	251.2	268.2	235.7	22.8	28.2	14.7
FREEWAY VEHICLE 1	2.0xFTP	0%	1142	1128	98.77%	0.106	0.139	0.046	251.2	268.2	235.7	22.8	28.2	14.7
	1xFTP	20%	6543	4013	61.33%	0.149	0.310	0.037	273.3	307.3	214.5	38.6	56.7	27.7
	1xFTP	10%	6543	4013	61.33%	0.149	0.310	0.037	273.3	307.3	214.5	38.6	56.7	27.7
	1xFTP	0%	6543	4013	61.33%	0.149	0.310	0.037	273.3	307.3	214.5	38.6	56.7	27.7
	0.5xFTP	20%	6896	4451	64.54%	0.168	0.437	0.039	266.8	322.8	167.8	38.8	81.1	20.0
	0.5xFTP	10%	6896	4451	64.54%	0.168	0.437	0.039	266.8	322.8	167.8	38.8	81.1	20.0
	0.5xFTP	0%	6896	4451	64.54%	0.168	0.437	0.039	266.8	322.8	167.8	38.8	81.1	20.0
	2.0xFTP	20%	5905	3366	57.00%	0.140	0.193	0.093	275.5	289.0	246.7	38.4	43.4	31.2
FREEWAY VEHICLE 2	2.0xFTP	10%	5905	3366	57.00%	0.140	0.193	0.093	275.5	289.0	246.7	38.4	43.4	31.2
	2.0xFTP	0%	5905	3366	57.00%	0.140	0.193	0.093	275.5	289.0	246.7	38.4	43.4	31.2
	1xFTP	20%	7071	7057	99.80%	0.142	0.431	0.067	283.6	350.3	190.0	40.3	72.3	21.7
	1xFTP	10%	7071	7057	99.80%	0.142	0.431	0.067	283.6	350.3	190.0	40.3	72.3	21.7
	1xFTP	0%	7071	7057	99.80%	0.142	0.431	0.067	283.6	350.3	190.0	40.3	72.3	21.7
	0.5xFTP	20%	7460	7225	96.85%	0.153	0.745	0.057	280.7	353.3	156.4	40.6	83.1	20.0
	0.5xFTP	10%	7460	7446	99.81%	0.159	0.745	0.057	279.3	353.3	152.7	40.0	83.1	17.7
	0.5xFTP	0%	7460	7446	99.81%	0.159	0.745	0.057	279.3	353.3	152.7	40.0	83.1	17.7
	2.0xFTP	20%	5976	5962	99.77%	0.124	0.272	0.077	292.1	345.1	229.2	42.0	65.7	26.5
	2.0xFTP	10%	5976	5962	99.77%	0.124	0.272	0.077	292.1	345.1	229.2	42.0	65.7	26.5
	2.0xFTP	0%	5976	5962	99.77%	0.124	0.272	0.077	292.1	345.1	229.2	42.0	65.7	26.5