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Comparison of emissions measurement between a sensor-based compact emissions meter and a standard PEMS

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Comparison of emissions measurement between a sensor-based compact emissions meter and a standard PEMS

Jordan Leatherman

Thesis 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

**Master of Science
in
Mechanical Engineering**

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Abstract

Comparison of emissions measurement between a sensor-based compact emissions meter, and a standard PEMS

The emissions produced by diesel engines are detrimental to human health, and the environment. To reduce these harmful emissions, engine manufacturers have used exhaust after treatment systems. The main objective of these after-treatment systems is to reduce exhaust emissions with minimal impact on an engines performance. The increase in emission regulations resulted in the need for a portable device to measure emissions. Portable emissions measurement systems (PEMS) are used to ensure engines comply with regulations in the real world. Although these systems are portable and can be installed on a vehicle they are bulky, expensive and time consuming to install. More recently a compact version of the PEMS based on lower cost, smaller sensors have come to market. These devices are not recognized for in-use compliance but potentially have a use for rapid testing of a larger fleet of vehicles.

The main objective of this study was to perform a sensor-based emissions measurement comparison of the oxides of nitrogen (NO_x) and particle number (PN) emissions collected between the NTK Compact Emissions Meter (NCEM) and a Horiba OBS-ONE GS with PN analyzer unit. The NCEM is a newly marketed device that measures exhaust NO_x and Oxygen (O_2) concentrations through the use of a zirconium-oxide sensor, and PN with a diffusion-charging type sensor. Using the Horiba OBS-One PEMS as the reference to the accuracy of the NCEM at different operating conditions was examined. The Horiba OBS-One PEMS is compliant with the Code of Federal (CFR) regulations, Title 40, Part-1065, Subpart J, which details in-use emissions compliance testing for a vehicle equipped with heavy-duty engines. Both units were installed on a heavy-duty on-highway Mercedes Benz Actros cab-over truck. This truck was tested over a number of different routes that included various terrain, and traffic situations. One of the test routes was created to satisfy the European Union (EU) Real Driving Emissions (RDE) characteristics. This route was repeated three times. This test route included stop and go, low speed constant flow, and highway operation. The second test route consisted of highway driving an elevation change of 400 meters to examine altitude on the analyzers. The third and final test route was a highway route with relatively constant altitude. All data sets were subsequently analyzed using linear regression, and binning technique.

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List of Abbreviations

CAA	Clean Air Act
CAFEE	Center of Alternate Fuels Engines and Emissions
CARB	California Air Resource Board
CFR	Code of Federal
CLD	Chemiluminescence
CO	Carbon Monoxide
CO ₂	Carbon dioxide
DOC	Diesel Oxidation Catalyst
DOJ	Department of Justice
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
EU	European Union
FID	Flame Ionization
FTP	Federal Test Procedure
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbons
HDD	Heavy Duty Diesel
HDDE	Heavy Duty Diesel Engine
HDDV	Heavy Duty Diesel Vehicles
HDIUT	Heavy Duty In-Use Testing
KG	Kilograms
KM	Kilometers
NCEM	NTK Compact Emissions Meter
NDIR	Non Dispersive Infrared Detection
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
NTE	Not-To-Exceed
O ₂	Oxygen
OEM	Original Equipment Manufacturers
PEMS	Portable Emissions Measurement Systems
PM	Particulate Matter
PN	Particle Number
PPM	Parts Per Million
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
THC	Total Hydrocarbons
U.S. EPA	United States Environmental Protection Agency
WVU	West Virginia University

1 Introduction and Objectives

1.1 Introduction

Diesel engines produce exhaust emissions that are detrimental to the environment. The United States Environmental Protection Agency has enacted strict regulations to decrease these harmful emissions. These strict regulations have influenced engine manufacturers to use after treatment systems to reduce emissions. In addition to these strict emissions standards, the regulations for heavy-duty vehicles also require in-use emissions testing with portable emissions measurement systems (PEMS). PEMS give engine manufacturers and research corporations a tool to examine emissions from these diesel engines while operating in the real world. Now researchers and engine manufacturers are burdened with the task of testing large truck fleets. The need for a more compact and portable emissions measurement tool is necessary.

1.2 Objective

The objective of this study was to compare the oxides of nitrogen (NO_x) and particle number (PN) measured by the NTK compact emissions meter (NCEM); and the Horiba OBS-ONE. The accuracy measured by the sensors attached to the NCEM were compared to the analyzers attached to the Horiba OBS-ONE. This accuracy and repeatability would then be used to determine if the NCEM could be used as a tool to determine compliance with emissions standards.

2 Background Knowledge

2.1 Portable Emissions Measurement Systems

PEMS were invented to compare real-world driving emissions to laboratory based engine dynamometer emissions for heavy-duty engines. PEMS are compact enough install in the back of automobiles and truck cabs, however they provide accurate means to demonstrate compliance with emission standards. PEMS units are very important for their major role in emissions research and regulations certification [1]. They bring a different aspect to emissions testing that dynamometer and stationary equipment do not allow. Laboratory based emissions measurement systems use a dynamometer that allows for alike testing, if a certain testing program is used. PEMS allow for the use of emissions testing equipment during real-time driving conditions [2]. These conditions can vary in ever changing traffic conditions such as, urban, rural, highway routes. Geographic changes can be observed by terrain changes that vary from mountain terrain, to flat land. Even weather conditions can be factored into real driving conditions. PEMS have the ability to measure a much wider variety of gases and compounds when compared to other compact measurement systems, such as the NCEM. Many PEMS have the capability to measure particulate matter (PM), particle number (PN), carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbons (THC), and oxides of nitrogen (NO_x) [3]. They have the capability to record air-to fuel ratio, exhaust flow rate, atmospheric temperature, humidity, pressure, and location using global positioning systems (GPS) [3]. These units have a few disadvantages, the first being the upfront investment associated with purchasing a PEMS. Another disadvantage associated with PEMS is the amount of support equipment needed in order to operate them correctly. This support equipment is large gas bottles which are needed for zero span checks. Another disadvantage with PEMS units is the required set-up times and subsequent downtime of the vehicle. A benefit associated with PEMS is the ability to measure real-time emissions data with laboratory accuracy. Another benefit to the newer PEMS is that they have the ability to have an optional On Board Diagnostic (OBD) interface unit [1]. This allows for PEMS to be able to record data from the engine

control unit (ECU) attached to the vehicle. This allows for an easier user-interface and more options when it comes to analyzing data.

2.2 Particulate Matter

Particulate Matter (PM), is a mixture of emission particles that are present in the air, they are detrimental to the human health. These particles are found in many different sizes, and can be composed of thousands of different chemicals and compounds [4]. This is one of the most harmful diesel emissions. Most of these particles react with one another in the atmosphere; some examples of these are a product of chemicals such as oxides of nitrogen, and oxides of sulfur [4]. These are mainly emitted from industry facilities, and engine powered vehicle such as automobiles, heavy-duty trucks, and marine vessels. When compared to other fuel engines, diesel has always had relatively the highest of PM emissions [5]. That is the cause for the massive push to check and reduce diesel emissions.

Particle matter can be split into two size categories; the larger category is composed of particles generally 10 micrometers and smaller in diameter [4]. This is referred to PM10. The smaller of the two categories is the finer particles that are generally 2.5 micrometers and smaller in diameter [4]. They are labeled as PM2.5. These particles are inhalable by human beings, they are the most dangerous to human beings because they remain deep in your respiratory system, and have the possibility to enter the bloodstream [4]. While in the United States of America, we have become more worried with how these have been redirected through the introduction that occurred in 1997 when new air quality standards were introduced [6]. These new standards only are for elements or particles that are smaller than 2.5 μm (PM) and with the new standards for elements and particles that are below 10 μm (PM). They are responsible for the air pollution that causes reduced visibility [7].

2.3 Particle Number

One of the emission parameters investigated in this study was PN. PN has been gaining attention due to its ability to characterize harmful emissions even further. PN is based on the amount of particles instead of the mass of the particulate matter (PM). The measurement is recorded by number of particles per volumetric flow rate. The most

commonly used label is number of particles per cubic centimeters ($\frac{\#}{cm^3}$). This measurement quality is used to better understand the solid emissions [7]. PN emissions can be increased by a variety of different factors. The PN is increased in the exhaust when the in-cylinder temperatures are reduced. This results in a higher formation of soot, which is PM but affects PN [7]. Diesel particulate filters (DPF) are used to filter out the soot particles. They can be composed of thousands of different chemicals and compounds [8]. The emissions particles can be large enough for the human eye to see, but in most cases can be microscopic [9]. The health effects of the small fine particles have the potential to be much more harmful than the larger ones, due to the fact of the particles being so fine that they are able to basically slip pass the human body's respiratory system filtration. The European Union (EU) in recent years has introduced emissions limits for PN. A PN dimension method is established by the platform that was implemented for the basis for the EU particle number emission restrictions [10]. They have seen great inconsistencies, due to a variation in testing and measurement strategies. The EU has a calculated protocol that requires for reliable classification of the PN limits, these limits were then adopted by the EU PN emission regulations [10]. The United States Environmental Protection Agency (EPA) has yet to follow suit on regulations based on PN for emission limits [9]. The EPA has enforced strict emissions limits on the PM emissions, the current limit is 0.01 grams per brake horsepower – hour (g/bhp-hr), but there is no PN emissions limit in current use.

2.3 Oxides of Nitrogen

One of the other major exhaust species, Oxides of Nitrogen (NO_x), was investigated in this study. NO_x is a common term used to cover a wide variety of gaseous emissions. The NO_x compounds are nitrous oxide (N₂O), nitric oxide (NO), dinitrogen dioxide (N₂O₂), dinitrogen trioxide (N₂O₃), nitrogen dioxide (NO₂), dinitrogen tetroxide (N₂O₄), and dinitrogen pentoxide (N₂O₅) [11]. NO_x is considered as one of the major emissions gases that flow out of internal combustion engines [12]. They are responsible for a large portion of smog development in the earth's atmosphere [13]. Higher NO_x concentrations are formed from a variety of causes. The vehicle is equipped with after-treatment systems that limit and reduce the amount of NO_x. The after treatment system that aids in the reduction of NO_x is the selective reduction catalyst (SCR). The SCR is

responsible for reducing the NO_x levels by injecting a urea solution into the exhaust stream. The urea when heated turns into ammonia (NH_3). This urea starts a chemical reaction which transforms NO_x into N_2 , water (H_2O), and trace amounts of carbon dioxide (CO_2). The issue with the SCR is that there is a residual amount of NH_3 remaining in the exhaust. This amount of unreacted NH_3 can result in what is consider NH_3 slip. NH_3 slip is the result of an incomplete chemical reaction between the NO_x particles, and the NH_3 [11]. This causes an amount of unreacted NH_3 to proceed through the exhaust downstream. NH_3 could form into ammonium sulfates, and these can corrode, or hinder after treatment compounds downstream [11]. Another issue is that the potential for emissions of NH_3 gases is always possible.

3 Literature Review

3.1 Regulation History

The first federal legislation that enacted research on air pollution was the Air Pollution Control Act of 1955. This act increased funding for research into air pollution. The act also funded the discovery of sources of air pollution [6]. The Clean Air Act of 1963 was introduced to limit the amount of air pollution in the United States of America. The act was effective at providing research to monitor and minimize the amount of pollution in the air. In 1967 the United States Congress enacted the Air Quality movement. This act's sole purpose was to provide more in-depth research on emission control techniques. That same year the state of California was the very first state to enforce vehicle emissions. In 1970 Congress passed another more stringent Clean Air Act, this act gave the Environmental Protection Agency the power to regulate emissions from a large majority of vehicles [6]. The National Emission Standards for Hazardous Air Pollutants was established as well because of the 1970 CAA [6]. In 1974 federal regulations on heavy-duty emissions began in the United States [6]. In 1977 Amendments were added to the Clean Air Act of 1970, these amendments included revising some areas of the National Ambient Air Quality Standards [6]. The latest amendments to the Clean Air Act of 1970, was the most recent which were established in 1990. These amendments included increase monitoring and emissions enforcement. It created a program to establish control techniques of 189 toxic pollutants [6]. The Clean Air Act was proposed to regulate the levels of vehicle emissions. In the 1990s the EPA discovered that many heavy-duty diesel manufacturers were using computer programs to conceal elevated engine emissions. The engine manufacturers who were involved represented over "95%" of the HD diesel engine market [14]. This resulted in a large amount of imposed regulations on these engine manufacturers. One of the regulations was that these engines had to meet a certain emission standard during in-use operation. It also introduced the need for PEMS.

3.2 Current Emissions Standards in the United States

The US and California have various emissions standards for compression ignition engines that are used in heavy duty vehicles. These standards apply to all compression ignition engines, including dual fuel diesel, natural gas, and other compression ignition fuels. For the United States and the state of California, heavy duty diesel vehicles are not required to be chassis certified. They only require the engines to be certified. These certifications include basic standards that are listed as specific tests that were performed and the emission levels based on g/bhp*hr. A PEMS units is used to collect gaseous and particulate matter emissions to perform this compliance test. The method is based on the engine operating within set boundaries of a control area which is on the engine map. Certain engine and after treatment boundary conditions are set as the lower threshold in order to consider a valid NTE data point. Another stipulation to make sure the event is a valid NTE test is that the engine operation must have a duration of greater than or equal to 30 seconds. In order for the engine to pass the compliance test the vehicle pass ratio must be greater than or equal to 0.90 [15]–[17]. The current federal standard for PM emissions from heavy-duty engines is 0.01g/bhp-hr, and 0.20 g/bhp*hr for NO_x emissions. The EPA also require diesel fuel standards that limit the amount of sulfur content allowable in the fuel. The current sulfur content limit is 15 ppm. The EPA regulates sulfur content in diesel fuel in way to combat sulfur oxides (SO_x), which are a health concern for humans and the environment.

3.3 Real Driving Emissions Requirements

The requirements for RDE tests are as follows, the data acquisition device must record at minimum of 1 hertz[18]. The percentage of the total divided trip distance is 34% urban, 33% rural, and 33% highway. The route must be continuous, no breaks. The speed thresholds are urban must be less than 60 km/h, the rural must be between 60-90 km/h, and the highway must be greater than 90 km/h[18]. The maximum vehicle speed achieved during the test route is 145 km/h. The average urban speed that must include stops are traffic signals, must be between 15-30 km/h. When the vehicle approaches to a complete stop, it must be less than 1km/h. All urban stops must add up to at least 10% of the time of

the urban portion of the test route[18]. The urban portion must contain stop portions that have a time duration of at least 10 seconds or longer. The highway speed must have a 5-minute time duration where the speed is greater than 110 km/h. The entire route must be between 90-120 minutes in duration. The elevation change between the start and end point must be less than 100 m. The minimum total distance of each single mode must be greater than 16 km. The vehicle speed must be compared between the ECU and the GPS unit on the PEMS unit. The test route can not include any off-road portions, and must be performed during a single workday[18]. Combining data to ‘fill-in’ missing data from a different route is not allowed, and cold start must be recorded but dissuaded during emissions data analysis. All of these rules are combined from information from a variety of sources, all combined in source [18].

3.4 University of California, Riverside PEMS Comparison

In recent years PEMS has been used to measure emissions from light duty, heavy duty and construction vehicles [19]. The goal of using PEMS is to reproduce functioning of equipment used in the laboratory. PEMS that are fully 1065 complaint consist of companies such as AVL, Horiba, and Sensors Inc. The 1065 compliant PEMS units are boxy, bulky and very costly. The 1065 compliant PEMS components are also very multifaceted to use during the set up and operation of the components [19]. There has been a stress on the necessity to collect “in-use emissions from a wider range of operating vehicles” in the past few years [19]. In recent years’ people have become more interested in mini PEMS because they are cost effective, smaller and still deliver dependable emissions amounts. Mini PEMS can be used by the government agencies, engine and vehicle manufactures so that they can recognize any matters that can potentially be bad. Yang et al. found that Maha established a “PEMS that can measure NO_x, CO₂, and PM” [19]. A few other manufactures have also established PEMS units that are reliable as well.

The goal of this study was to relate the 1065 compliant PEMS and a current generation mini PEMS that were both mounted onto a 2012 Chevrolet Silverado 2500HD Duramax. The Chevrolet Silverado was re-fueled at the same service station throughout the study. They drove the Chevrolet Silverado for two days and used three different driving routes in Los Angeles, California. The three driving routes represent highway, local and

downtown driving in Los Angeles, California [19]. The mini PEMS used in the Yang et al. study was an NTK NCEM which measures PN, NO_x, O₂, PM mass as well as Air/fuel ratio [19]. The NCEM model has direct sensors that measure instead of dilution sampling. This results in having no time delay and the receptiveness can be measured in real-time. The system can be set up in about less than 10 minutes, and weighs about 12 kg. The unit can be powered through a DC12/24 V battery for a vehicle [19]. The NO_x sensor will identify NO_x through the capacity of O₂ ions by the disconnection of NO_x in the N₂ and O₂ detection chamber. This was intended to trap the layer before the gases are able to spread to the detection lot of the component [19]. The results that the University of California compiled are somewhat close, within 3 percent for the highway and LA downtown test routes. This was for the NO_x emissions for both machines, the A.V.L. MOVE and the NCEM emissions meter. The other routes which included the local and the idle/creep were relatively higher. These routes results were within 10 % of each other. For the Total PM results, the faired rather large in percent difference. When compared to the results between the two machines, the differences ranged from -31 % to 109 %. The highest being the LA downtown route. For the PN emissions, the results again were slightly different, the emissions meter machine was slightly higher than that of the 1065 Complaint machine across all speed variations. The University of California Riverside was able to come to the conclusion that while the NCEM was able to read relatively close number when compared to the 1065 compliant, it still should only be used for screening tool, or a monitoring tool. The 1065 compliant machine was much more accurate in all tests, when compared to that of the emissions meter. The local route NO_x readings for the emissions meter and the 1065 complaint respectively is 4.44 g/mi for the emissions meter and 4.07 for the 1065 complaint. That is recordings for the local routes, this route represented the second largest percent difference in NO_x readings at a percent (%) of 9.20. The highway and LA downtown test routes showed much lower percent differences, with the highway average being -2.90 % and the LA downtown being 2.70 %. The greatest percent difference was recording on the idle and creep test, which represented a reading of -9.40 %. Some of the error that might have been there is that the UCER only performed one of those tests, so the sample size was small. The Local average total PM for the emissions meter unit was 0.18 mg/mi, and for the 1065 complaint unit was 0.25, this resulted in a -31.10 % difference. The Highway total pm

recording resulted in a slightly less percent difference, reading -17.20 percent. The LA downtown total pm had the highest percent difference, coming in at 109 %. And the idle and creep reported a total pm percent difference of -24.30 %. The PN results for the local test average are as followed, 8.49×10^{11} # per mile for the mini PEMS, and 4.81×10^{10} # per mile for the 1065 complaint. This resulted in a percent difference of 178.5553 percent. The results for the highway average are 4.82×10^{11} # per mile for the mini PEMS, and the 1065 complaint PEMS recording 2.77×10^{10} # per mile. These averages resulted in a percent difference of 199.77 %. The LA downtown resulted in an average of 2.11×10^{12} # per mile for the mini PEMS, and 3.76×10^{10} # per mile for the 1065 complaint machine. These values resulted in a percent difference of 193.26 %. The last test route, which was the idle and creep, recorded the following values. The emissions meter had a result of 3.87×10^{12} # per mile, and 7.62×10^{10} # per mile for the 1065 complaint PEMS unit. The difference between the study conducted by University of California and the study in this paper is the vehicles used, the data analysis, and the routes in which the study were conducted.

3.5 Comparison of PEMS with Laboratory Grade Equipment

In Europe, the European Union created a list of emission limits for all new vehicles being produced. These emission limits have defined what adequate limits are to be considered for those vehicles being produced and sold. Such pollutants of these standards are CO, HC, NO_x, particle matter, and particle number [20]. Researchers had to verify the validity of compliance through various procedures to ensure certification standards. These certification standards include performance driving routes that have been attached to a chassis dynamometer in a meticulous laboratory where research can be conducted [20]. In the European Union they created the new Worldwide Harmonized Light Vehicle Test Procedure in which they base the driving standards of collection of emissions on real driving situations. The PEMS must include portable analyzers, exhaust mass flow meters (EFM), weather station, and a GPS [20]. The European Union (EU) also regulates the trip requirements for testing, for example the maximum and minimum length of trip, distance, speed, boundary conditions, altitude (maximums and minimums) as well as [20]. Conditions must also include in the real driving situations urban, suburban, rural and highway types of driving conditions. The measurements of PEMS have improved over the

years and will continue to rise in the coming years for the European Union's regulations [20]. These PEMS units are very robust and reliable to use on vehicles that are driven on roads [20]. In a study that was conducted by the Joint Research Centre (JRC) they found areas of uncertainty in the exhaust flow meter, gas analyzers and drift. Since that research was collected they created a conformity factor which only allows a certain amount of the maximum emission levels of all vehicles on the roads today. That study even compared PEMS with some laboratory equipment during a test to assure that the proper setup and configurations were correct [20]. Varella, et. al found that very few studies have been conducted on the differences of PEMS and laboratory equipment [20]. The two PEMS units were compared to laboratory size analyzers, some were connected to tailpipe, some situations a dilution tunnel was used, and some were bagged emissions. For the tailpipe emissions, the NO_x emissions measured from the PEMS units were within 5% for 20ppm and higher levels of concentration. The lower the concentrations went the higher the percent error rose. For 7 ppm, the error percent was 15%, and they recorded measurements as low as 1ppm, and it had a corresponding percent error of 30%. These results show that current PEMS units have the ability to provide portability with good accuracy when compared to a lab based unit [20]. The study conducted by Roberto, and colleagues, was conducted on two light duty vehicles, one which was compression ignition, and the other spark ignited. This study was based on comparing various PEMS units to laboratory-based equipment. The study in this paper, was based on comparing one of the units used by Roberto to a new NCEM PEMS unit.

3.6 Experiences and Results with different PEMS

The vehicle that was used for research by Czerwinski, Zimmerli, Comte, and Bütler was a rented 2014 Seat Leon 1.4 TSI with approximately 20,800 kilometers (km) on it. When testing the vehicle the driver drove about 2,000 km [18]. Summer gasoline was used from the Swiss Marker, with no change in the lube oil. Some of the tests that were run by Czerwinski, et al. were accomplished using a 4WD-chassis dynamometer [18]. The controlled variable is the dilution ratio from the CVS-dilution tunnel, and it is controlled by the CO₂ analysis [18]. From the tests that were completed on the test vehicle, the researchers were able to know that the OBM Mark IV has no flowmeter for the

measurement of the exhaust flow. This is allowed because it can calculate from the on-board data, which makes it more easy to use and adapts better to the vehicle [18]. Czerwinski, et al. performed three tests that were used on a chassis dynamometer. In the first round of tests each was completed with a cold start of 20-25 degrees C the second round of tests were completed with a warm engine start. Each route has at least 3 minutes of constant speed going 80 km/h while being in 4th gear [18]. Several types of road were used for testing with each test lasting for 1 hour on roads such as urban, rural and highways. The RDE routes used in this study all met the requirements for Euro 6c regulations. In conclusion, the PEMS units that were used recorded greater CO₂ data than that of the laboratory grade equipment. The NO_x that was measured had great differences present between the units.

3.7 NO_x Sensors Cross Sensitivity

According to Frobert, Raux, Yann and Jeudy here is a need to decrease the amount of greenhouse gases that escape into the atmosphere as well as constraint the amount of local pollutants that escape [21]. New technologies have been created to combat these harmful effects to our environment through using newer internal combustion engine developments [21]. These new technologies include having direct high-pressure injections, variable valve timing, actuation as well as advanced exhaust gas recirculation and more efficient after treatment systems. While using these features one must have absolute and accurate control on diagnosis strategies [21]. According to Frobert et al. when using NO_x after treatment with the selective catalytic reduction for using lean engines it is obligatory that at least one NO_x sensor when doing the control and analysis. NO_x sensors were created from zirconia-based potentiometric oxygen sensors. This type of sensor has a double cavity and mixed potential [21]. One disadvantage is that it is an issue to distinguish the dissimilar apparatuses of gas mixtures. Although, planar potentiometric sensors are currently being developed. These sensors are much more modest and delicate for temperature differences and exhaust gas flow changes [21].

According to Frobert, et al. NGK recently created their own technology, which includes amperometric sensors that have multi-electrodes in the system. Each of these are divided into three cavities which the first references the contact with the air, the second,

measures the cavity that has been developed for O₂ sensors, and the third, allows a second cavity to be developed for O₂ removal and NO sensors [21]. According to Frobert et al. the declines that are left are then transformed in the dispersal barrier, which are then found around the exhaust gas and first cavity. In this section the NO₂ is theoretically, to be altered to NO in the first and second cavities. Afterwards the NO is then theoretically to be decreased while in the second cavity when the O₂- is being thrust out [21]. During this phase the NO_x sensor can be utilized as an ammonia sensor. This allows for device feedback when relating to a NO_x approximation. While the ammonia is supposed to be oxidized when in the first cavity due to an advanced functioning temperature of >600 °C and the reacting properties of the zirconia [21].

According to Frobert et al. the all tests that have been executed with sensors come from the same generation and have related histories. The tests also include diesel engine with a diesel particulate filter free exhaust line with approximately 200 hours on it. There is also no aging or poisoning because it is a brand-new system being used [21].

Frobert et al. found that when considering the exhaust gas temperature, it is often the first thing that is studied. The furnace temperature consists of having three different sensors with temperature differences. The temperature differences consist of 150, 250, and 350 °C. When each temperature is tested it has 5 concentrations of NO or NO₂ that are being tested as well. Ammonia can somewhat have an influence on the gas temperature, especially at 150 °C [21]. Higher gas temperatures were needed for the tests completed by Frobert et al. because the sensor requires higher temperatures for the furnace to work [21]. For the experiments conducted with Frobert et al. they used petite reply times, snappy accurateness and robust reliability [21].

The NO_x sensor can be seen to record a value from 5 to 15 % greater when vaporized water is introduced into the gas mixture [21]. The value associated with a NO_x sensor is typically 15 to 20% lower than that what would be recorded by a CLD technology unit. When adding NH₃ into the mixture gas the NO_x sensor shows to be extremely sensitive to the NH₃ amount [21]. In today's society, NO_x sensors are an important part of life for exhaust systems. The research has shown that NO_x has allowed for less NO₂ to be released because of the NO being released into the two cavities. Exhaust gases have had a

significant impact on water and oxygen as they relate to NO_x measurement [21]. When the circumstances are great with the impact of H₂O and O₂, the impact is much lower for ethanol, aldehydes, and NO. Of course an perfect number is required to obtain for the NO_x and NH₃ [21].

3.8 Influence of Altitude on NO_x Concentration Levels

China has various areas of plains and mountains which include a wide variety of altitude variations. Some altitudes are as high as 2,000 meters and as low as 1,000 meters [22]. The temperature variations also fluctuate in the above plains and mountains as well as the O₂ content. The air intake differs as well as the air-fuel ratio which allows for alterations to occur in the cylinders and fuel consumption [22]. The altitude is taken into account when PEMS is being tested. During this process the highest altitude allowed for testing is 2,400 meters. The OBD and PEMS are great methods to use in RDE testing situations [22]. The OBD detection allows for the sensors to be monitored so that the driver can be aware of the status of the equipment during testing [22]. A signal will light up to show any malfunctions that could allow for high emissions to be collected. These OBD ideas are being used in the United States, EU, China, India, and Brazil [22]. In this current study the primary focus has been on the altitude and temperature of when doing RDE in higher altitudes. This study also collects NO_x, fuel, and how the vehicle operates during RDE while also testing the OBD. This also allows for comparison between the test vehicles based on specific formulas [22].

The study used three diesel trucks that were equipped with OBD and was tested during an RDE route. Each of the vehicles were the same make and model. The mileage was approximately less than 110,000 km on them [22]. The NO_x emissions and fuel consumption during the tests were measured at various speeds. The trucks were listed as A, B, and C. The benchmark was set to be Truck B for the analysis of difference [22]. The errors and fuel consumption rates have been within $\pm 3.5\%$ between the vehicles. The trucks were set to full load condition during the real driving portion. The cities that were used for testing with the different altitudes were Jinan, Chifeng, and Lhasa [22]. Those altitudes ranged between $<1,000$ m to 4,000 m. The tests that were conducted included altitudes that would normally be found in parts of China [22]. During the testing the

temperature also played a role. The temperatures that were collected ranged between -10° C~ 10° C, 10° C - 20° C and 20° C- 35° C [22]. The tests were also completed during the same time frame which was 8:00-17:00 over the course of three days [22]. The conclusions from this study show that altitude has influence on the NO_x emission rate[22]. For altitudes ranging from 3000- 4000 m resulted in lower NO_x emissions[22]. This is because the lower in-cylinder temperatures associated with a decreasing intake air amount[22].

4 Test Route

The vehicle was tested over a duration of 8 weeks. The tests were conducted through the use of 3 driving routes, a real driving emissions (RDE) route, which included three different types of terrain. The figure 43, located in the appendix, shows a map of the RDE route. The second route was referred to as Tavannes, which was a village in the large mountains. The figure 42, located in the appendix, shows a map of the Tavannes test route. The third route was referred to as Highway loop, this was a flat highway route. The figure 44, located in the appendix, shows a map of the Highway route. The first driving portion of the RDE was designed to replicate urban driving. The second was designed to represent a rural driving, and the third was designed to replicate a highway driving experience. The overall total distance traveled was 95.9 km, with a total test duration of 1 hour, 53 minutes, and 12 seconds. The first driving portion was designed to replicate urban driving. The distance traveled for the first portion was 25.1 km, with an average speed of 27.6 km/h. The duration of this portion was 54 minutes, and 35 seconds. The second was designed to represent a rural driving, the distance traveled was equal to 35.4 km, with a duration of 33 minutes and 29 seconds. The average speed for the rural portion was 63.4 km/h. The third was designed to represent a highway driving. The distance traveled was equivalent to 35.3 km, with a duration of 25 minutes and 7 seconds. The average speed of this portion was 84.4 km/h. The Tavannes route included steep inclines at highway speeds. The Tavannes route had a duration of about 44.8 minutes. The third route, also known as the highway loop included flat highway driving experiences. The entire route was supposed to simulate consist speed, flat terrain.

5 Equipment Setup

The equipment setup included the NTK Compact Emissions Meter, and the Horiba OBS-ONE GS with PN unit. The power system for this setup is two 24-volt deep cycle batteries configured in a parallel circuit. Each pair of batteries lasted about 4 hours per pair. The batteries provided consist uninterrupted power supply for the duration of half the testing day.

5.1 Horiba OBS-One

5.1.1 General System Description

The PEMS that will be focused on in this study is the Horiba OBS-ONE. This company has been designing and manufacturing vehicle emissions and testing equipment for decades. The Horiba OBS-One is one of the most advanced PEMS available on the market. It can be used in certification of CFR 1065 Regulations, and Euro VI regulations [3]. It has the ability to perform cert testing for PEMS, it can measure NO_x, PM, PN, CO, CO₂, and THC. OBS-ONE PM unit is the industry-leading on-board PM measurement system. The Horiba unit included the PN unit, as well as the PM addition. This unit has specifications listed in the Table 17: Horiba OBS-One Specifications Chart [18] located in the appendix. The OBS-ONE records data at a rate of 10 hertz. This unit is supported as an OBD interface unit. There is a picture of the unit used in testing below in figure 1. This pictures shows the gaseous emission measurement unit (GS), and the PN measurement unit.

Figure 1: Horiba OBS-ONE

5.1.2 Measurement Principles

5.1.2.1 Particle Number

PN is measured through the use of a condensation particle counter (CPC). The Figure 2: Condensation Particle Counter [24] shows a diagram of how the CPC measures particle number. The emissions particles enter through the inlet, as they proceed through the tube, they increase in size, collected butanol. At the end of the device, a laser, and the photodiode is used to measure the particles. A disadvantage of this measurement principle is since this device particle measurement programme (PMP), it has a size measurement cut off of 23 nanometers [18]. An advantage of this measurement principle is that it conditions the particles as they enter the device. Making it less likely for the emissions to read unrelated substances. For the PN the 23 nanometers to 1000 nanometers, and $0-5 \times 10^7$ particles per cm^3 [23].

Figure 2: Condensation Particle Counter [24]

5.1.2.2 Oxides of Nitrogen

The OBS-One uses a process called chemiluminescence (CLD) to measure the amount of NO_x in the emissions. In Figure 3 it shows a diagram of how the measurement tool operates. The CLD detector uses a chemical reaction to aid in the detection of exhaust emissions. The process is known for the emission of light that occurs as a result of a chemical reaction. The reaction that occurs is between NO and ozone particle; when this reaction takes place it produces light [25]. The photons that are produced are used to measure in a photo multiplier tube. The output signal is related to the NO concentration that is present in the emission sample. The total NO_x can also be measured by a CLD instrument. The sample is sent through a heating element, where the NO_2 is exposed to high temperature, then it decomposes to NO and O_2 . This entire reaction is incredibly fast, this means that the instrumentation is very sensitive, and responsive. The disadvantage of this measurement type when compared to the direct mount NO_x sensor found on the NCEM is that the emission gases must travel through a tube to the unit. The range on the sensor is 0-100 to 0-3000 parts per million (PPM).

Figure 3: Chemiluminescence Detector[26]

5.2 NTK Compact Emissions Meter

5.2.1 General System Description

The emissions meter that will be focused on in this study is the NTK Compact Emissions Meter. It is manufactured by NGK/NTK. This company has been designing and manufacturing sensors and automotive parts for ages. The NCEM is an ultra-portable and simple emissions measurement instrument. It has the ability to measure exhaust gas composition, particularly NO_x , O_2 , PM and PN. It is different from the OBS-One because it is not capable of certification. Since this inability, the instrument could be considered a meter. It has limited measurement capabilities when compared to the Horiba OBS-One. The NCEM is more useful as an emissions monitoring meter. They have great portability, and the ease of use is second to none. They are very lightweight and very small. They can be used in lab monitoring and real-world driving tests. They also require short wait times, and have a very user-friendly interface. NTK has the ability to operate on vehicle power, and will not greatly load the engine. Currently in addition to the exhaust gases measurement ability they have the ability to measure Air/Fuel Ratio. These emissions meters have the ability to also interface with the OBD-II, and a Global Position Sensor. This is beneficial because the engine data information and sensor data can be sampled simultaneously. The Global Position Sensor is used to track terrain changes and traffic situation. The NCEM is equipped with an on-board LCD screen that displays the real-time measurements. Data can be easily reviewed on computer via NTK software package NCEM viewer. The

specifications are listed in the chart below. It was equipped with the NO_x module, and the PM/PN module. The NCEM records data at a rate of 1 hertz. In figure 4 below, there is a picture of the NCEM used in this study [27].

Figure 4: NTK Compact Emissions Meter

5.2.2 Measurement Principles

5.2.2.1 Particle Number

NTK compact emissions meter utilizes pipe direct measurement for its PN emissions data collection. It utilizes the same technology found in a Pegasor PPS-M. The Figure 5: NCEM PN Sensor Diagram [28] shows how the sensor operates. The first step is clean air is forced past a positivity charged element, where it becomes a positive charge ion. While this is occurring an emissions sample is introduced, these two specimens interact at the location labeled the ejector throat. At this time, the soot particles and positively charged ions mate. An important thing to note here is the larger the soot particle, the more charge it will pick up. After the positively charged ions attach to the soot particles they are then sent by a positively charged ion trap, this trap is designed to repel unattached ions, so they attach to the negatively charger or grounded shell (green). The soot particles will not attach to either and will proceed out of the chamber. The measurement is calculated by a wire that is attached to the positive charge element at the beginning, and a wire that is attached to the grounded shell. The difference of these two elements result in the amount of soot particles. This method is called escaping current method [21]. A disadvantage

associated with this measurement method is there is no conditioning of the particles, so this could result in condensed water vapor, or volatile particles being measured. Another disadvantage associated with this principle is that the user must know the size distribution of particles before the test can begin. This ensures that the proper particle size is being analyzed [21]. The range for the PN is 0 to $1.0 \times 10^8 \text{ \#/cm}^3$. The PN has the ability to read particle sizes below 23 nanometers.

Figure 5: NCEM PN Sensor Diagram [28]

5.2.2.1 Oxides of Nitrogen

The NCEM's sensor feature a zirconium oxide (ZrO_2) sensor that has the ability to measure oxygen (O_2) and NO_x . The Figure 6: Zirconium Oxide Sensor Diagram [30] shows a diagram of the sensor. It is equipped with a two chamber design where one chamber is used for each gas measurement [29]. The ZrO_2 sensor detects oxides of nitrogen by first measuring ions of O_2 that were created by the detachment of NO_x particles into O_2 and N_2 . This reaction and measurement all occurred in the detection chamber. The design utilized for this sensor turns NO_2 molecules into NO and O_2 molecules. This process is performed in a layer that traps the gases before they reach the detection portion of the sensor. An advantage seen is that this direct mount sensor is superior in a sense that the gaseous emission is measured directly in the tailpipe. This differs from the OBS in a way that the OBS has tubing that transports the emission sample back to the unit inside of the cab of the vehicle. For NO_x the NCEM has a range of 0 to 1500 ppm.

Figure 6: Zirconium Oxide Sensor Diagram [30]

5.3 Test Vehicle

The tests were performed on a 2015 Mercedes Benz Actros 1848LS 4X2 F13. This truck is equipped with an inline 6-cylinder engine with a displacement of 12.8 liters. This truck has a power output of 354 kilowatts (kW). It had an odometer reading of 118,000 km. This truck and trailer combination had a combined test weight of 31425 kilograms (kg). This vehicle is equipped with advanced after treatment technologies such as

Exhaust gas recirculation (EGR), diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and a selective catalyst reduction (SCR). The gas sensors, and collection lines were connected to an exhaust tip, the Horiba OBS-ONE and the NTK Compact Emissions Meter was attached simultaneously. Pictures of the truck and exhaust system used in this study can be found in the appendix, Figure 45, Figure 46, and Figure 47. A more in-depth truck specifications of the truck used in this study can be found in the appendix.

6 Results and Discussion

6.1 Overview of Data

The Data consisted of three routes, a Real Driving Emissions Route, a highway with elevation terrain, and a highway with flat terrain. The data was analyzed using several different methods. The first method was a raw comparison that compared the NO_x recorded from the NCEM vs that of the reference unit the Horiba OBS-ONE. Then the Real Driving Emissions route was broken up into 4 portions. The first being the cold start portion which had a duration of 500 seconds. The second being the urban portion which consisted of 25.1 km. The third portion had a duration of time that corresponded to that of 60.5 km. And then the fourth and final was from the 60.5 km to the end of the route. There were some time deviations between each test route, which was to be expected. After this there was binning of certain ppm levels. The first being the 10 ppm levels, while using the OBS as the reference, the NCEM was recorded and analyzed based on its percent error at certain ppm levels. This also was performed for the 20 ppm levels. The next data set that was analyzed was that from the RDE routes for the PN data. This included a very simple analysis that consisted of a raw data comparison of the NCEM to the reference unit the Horiba OBS-One.

6.2 Comparison of NO_x PEMS Data

6.2.1 Real Driving Emissions Route - Urban/Rural/Highway Operation

This section covers the NO_x emission analysis performed on all three RDE routes, these routes consisted of four portions. The first portion which had a duration of 500 seconds was considered the cold start portion. The second portion which lasted until the distance traveled reached a value of 25.1 km, this portion was called the urban portion. The third portion which included data from the end of the second portion to a distance of 60.5 km, was considered the rural portion. The last portion of the RDE test route, was called the highway portion it consisted of the data after 60.5 km had been traveled. Figure 43 in the appendix can be used as a reference.

6.2.1.1 Overall RDE Route NO_x Emissions Comparison

The Figure 7 below shows the report data on a raw NO_x gaseous emissions with the corresponding vehicle speed that was collected for the RDE route 2 from both PEMS units, the red is NCEM, and the blue is the OBS-ONE, and the Green is the vehicle speed. The second RDE route was used as a visual representation because of the R² values associated with the regression plots. The route consisted of four different types of driving, the first 500 seconds is considered a cold start simulation, this usually produces high NO_x emissions. Next is the urban type of driving environment, this simulates a heavy traffic, stop and go traffic situations. The next portion of the trip consisted of a rural driving simulation. The last portion of the trip the highway portion, produced a low concentration of NO_x. Between the four different test portions, the cold start resulted in the highest, NO_x concentrations, due to the after-treatment system being cold. The highest value seen in this portion was equal to 632 ppm. The next highest level of NO_x concentrations can be seen during the urban portion; this can be attributed to the stop-n-start traffic situations that resulted in changing load conditions. The highest value seen in the urban portion was equal to 392 ppm. The next highest level of NO_x concentrations seen in this test route was associated with the rural portion, the highest concentration seen in this portion is equal to 267 ppm. The lowest concentration of NO_x seen during this entire test can be associated with the highway portion. The highest concentration seen in this portion is equal to 83 ppm. This low concentration of NO_x can be attributed to a highway speed, and the SCRs' ability to operate at optimum temperatures.

Figure 7: RDE 2 NO_x Raw Data with Vehicle Speed

The Figure 8 below shows the report data on a linear regression plot of NO_x gaseous emissions collected for the RDE trip 2 from both PEMS units. The corresponding R²-value to this linear regression is 0.96742. This is the second highest R² value recorded for all three RDE test routes. The lowest being RDE route 1 equal to 0.9524. And the highest being the RDE 3, which was equal to 0.96865. An overall trend that can be seen with the linear regression is that at higher NO_x concentrations, the NCEM measured higher values. In example, the NCEM read a value of 486 ppm, while the OBS read a value of 363.6 ppm. Another example while the NCEM measured a value of 535 ppm, OBS read a value of 407.9 ppm. For these instances, there is a percentage error equal to 33.66 %, and 31.16 %, respectively. This might be associated with the different location of the NO_x measurement equipment. For the NCEM the NO_x measurement is a direct mount sensor, for the OBS, the gas emission sample must be routed to the unit.

Figure 8: Linear Regression for RDE 2 NO_x Overall

Table 1: Overall RDE NO_x R² Values

RDE 1	0.95444
RDE 2	0.96744
RDE 3	0.96865

The Figure 9 below shows the report data on a QQ plot of the raw NO_x gaseous emissions collected for the RDE trip 2 from both PEMS units. The red line is the linear comparison line, the closer the blue marks are to the line they more comparable the data. The Quantile-Quantile (QQ) plot displays the linearity of the two sensors, as the increase

in NO_x concentration. Some points at on the graph will show a representation of the data. A QQ plot is a plot that displays the quantiles of one data set to the quantiles of a second data set [31]. At the 100 ppm concentration level, the NCEM measured 93 ppm, while the OBS measured 100.19 ppm. At the 200 ppm concentration level, the NCEM measured 188 ppm, and the OBS measured 199.73 ppm. At the 400 ppm level, the NCEM measured 440 ppm, and the OBS measured 393.28 ppm. At the 600 ppm level, the NCEM measured 625, while the OBS measured 599 ppm. The corresponding percent error with these values are -7.17 % for the 100 ppm concentration, -1.9454 % for the 200 ppm concentration, 11.879 % for the 400 ppm concentration, and the percent error 600 ppm concentration is 4.341 %.

As shown in the trend provided by the values, at the higher NO_x concentrations the NCEM measured higher values.

Figure 9: RDE 2 NO_x QQ Plot

6.2.1.4 Cold Start

The cold start portion of the RDE routes is used to display the NO_x that is produced while an engine is in its warmup session. This portion of the test route had a duration of

500 seconds for the beginning of the test route. Cold start procedures typically produce elevated NO_x concentrations due to the fact that the emissions suppression system has not had the time to properly heat up to peak operating temperatures. The graph below Figure 10 displays the raw data of the NO_x concentration levels in relationship with the vehicle speed.

Figure 10: RDE 2 NO_x Cold Start Raw Data with Vehicle Speed

The measured NO_x concentrations during the cold start procedure of the second RDE test route are displayed in Figure 11 pictured below. The corresponding R² value associated with this graph is equal to 0.97165. This value is the second highest of the three RDE test routes. RDE 1 had a value of 0.96003, and RDE 3 had a value of 0.97903. The trend on this graph is similar to that seen on the overall RDE 2 graph shown in *figure 7*. At the 100 ppm concentration level, the NCEM measured a value of 102 ppm, while the OBS measured a value of 107.9 ppm. At the 300 ppm concentration level, the NCEM measured a value of 430 ppm, while the OBS measured a value of 292.4 ppm. At the 400 ppm concentration level, the NCEM measured a value of 535 ppm, while the OBS recorded a concentration of 407.9 ppm. The corresponding percent errors associated with these

differences are, -5.468 % for the 100 ppm concentration level. For the 300 ppm concentration level, the percent error was equal to 47.06 %. For the 400 ppm concentration level, the percent error was equal to 31.16 %. The trend is showing as the NO_x concentrations increase, so does the percent error between the sensors.

Figure 11: Linear Regression for RDE 2 NO_x Cold Start

Table 2: : RDE Cold Start NO_x R² Values

RDE 1	0.96003
RDE 2	0.97165
RDE 3	0.97903

6.2.1.5 Urban Portion

The urban portion of the RDE routes is used to display the NO_x that is produced while a vehicle is in stop and go traffic situations. This portion of the test route had a distance of 25.1 km, there was not a time associated with this test portion because of the different traffic situations, and the traffic control devices. Urban driving situations typically produce elevated NO_x concentrations due to the constant stop and start driving simulation. This constant changes in load result in changing NO_x emissions. The graph below Figure 12 displays the raw data of the NO_x concentration levels in relationship with the vehicle speed.

Figure 12: RDE 2 Urban NO_x Raw Data with Vehicle Speed

The measured NO_x concentrations during the urban portion of the second RDE test route are displayed in Figure 13 pictured below. The corresponding R² value associated with this graph is equal to 0.95419. This value is the highest of the three RDE test routes. RDE 1 had a value of 0.86994, and RDE 3 had a value of 0.87167. The trend on this graph is similar to that seen on the overall RDE 2 graph shown in Figure 7. The urban portion of

the test route does not produce NO_x concentrations as elevated as the cold start portion. At the 100 ppm concentration level, the NCEM measured a value of 83 ppm, while the OBS measured a value of 101.8 ppm. At the 200 ppm concentration level, the NCEM measured a value of 172.5 ppm, while the OBS measured a value of 191.4 ppm. At the 400 ppm concentration level, the NCEM measured a value of 467.5 ppm, while the OBS recorded a concentration of 393.3 ppm. The corresponding percent errors associated with these differences are, -18.468 % for the 100 ppm concentration level. For the 200 ppm concentration level, the percent error was equal to -9.875 %. For the 400 ppm concentration level, the percent error was equal to 18.87 %. The trend is showing as the NO_x concentrations increase, so does the percent error between the sensors. Another trend that is shown with this data, is as the NO_x concentrations decrease, so does the percent error between the sensors.

Figure 13: Linear Regression for RDE 2 NO_x Urban

Table 3: RDE Urban NO_x R² Values

RDE 1	0.86994
RDE 2	0.95419
RDE 3	0.87167

6.2.1.6 Rural Portion

The rural portion of the RDE routes is used to display the NO_x that is produced while a vehicle is in a rural setting, meaning consist flow of traffic, but at lower top speeds from highway. This portion of the test route had a distance of 35.4 km, there was not a time associated with this test portion because of the different traffic situations, and the traffic control devices. Rural driving situations typically produce low NO_x concentrations due to the constant speed, compared to the highway portion the rural, is lower speed, and there still are stop and start situations, but they are limited when compared to the urban portion. This changes in load will result in elevated NO_x emissions. The graph below Figure 14 displays the raw data of the NO_x concentration levels in relationship with the vehicle speed.

Figure 14: RDE 2 Rural NO_x Raw Data with Vehicle Speed

The measured NO_x concentrations during the rural portion of the second RDE test route are displayed in Figure 15 pictured below. The corresponding R² value associated with this graph is equal to 0.95419. This value is the second highest of the three RDE test routes. RDE 1 had a value of 0.92926, and RDE 3 had a value of 0.96209. The trend on this graph is similar to that seen on the overall RDE 2 graph shown in Figure 7. The rural portion of the test route typically does not produce elevated NO_x concentrations. This is due to the constant speed, and the load not dramatically changing during the test. As shown on the graph, during a 0 ppm NO_x concentrations, it is recorded negative NO_x concentrations. At the 50 ppm concentration level, the NCEM measured a value of 68 ppm, while the OBS measured a value of 50.67 ppm. At the 100 ppm concentration level, the NCEM measured a value of 119 ppm, while the OBS recorded a concentration of 105.1 ppm. The corresponding percent errors associated with the differences are, 34.20 % for the 50 ppm concentration level. For the 100 ppm concentration level, the percent error was equal to -13.225 %. The trend is showing if at low NO_x concentrations, the NCEM measures elevated values when compared to the OBS measurement. Another trend that is shown with this data, is as the negative NO_x concentrations.

Figure 15: Linear Regression RDE 2 NO_x Rural

Table 4: RDE Rural NO_x R² Values

RDE 1	0.92926
RDE 2	0.9541
RDE 3	0.96205

6.2.1.7 Highway Portion

The highway portion of the RDE routes is used to display the NO_x that is produced while a vehicle is on highway, at highway speeds, it is supposed to represent high constant speed, without any stop and goes. This portion of the test route had a distance of 35.3 km,

there was not a time associated with this test portion because of the different traffic situations, and congestion that would be encounter on highways. Highway driving situations typically produce the lowest NO_x concentrations due to the constant speed. The graph below Figure 16 displays the raw data of the NO_x concentration levels in relationship with the vehicle speed.

Figure 16: RDE 2 Highway Raw Data with Vehicle Speed

The measured NO_x concentrations during the highway portion of the second RDE test route are displayed in Figure 17 pictured below. The corresponding R² value associated with this graph is equal to 0.96092. This value is the second highest of the three RDE test routes. RDE 1 had a value of 0.92107, and RDE 3 had a value of 0.90777. The trend on this graph is similar to that seen on the overall RDE 2 graph shown in Figure 7. The highway portion of the test route typically produces the lowest NO_x concentrations. This is due to the constant high speed, and the load not dramatically changing during the test. During the highway test the NO_x concentration levels ranged from -9.5 ppm to 48 ppm. The negative NO_x concentrations can be seen in the test route, mainly recorded by the

NCEM sensors. As shown on the graph, during a 0 ppm NO_x concentrations, it is recorded negative NO_x concentrations. For this portion the test route the NCEM measured values that were elevated or lowered concentrations. At the 10 ppm concentration level, for one data point the NCEM measured a value of 10 ppm, while the OBS measured a value of 10.91 ppm. For another data point the NCEM measured a value of 12 ppm, while the OBS measured a value of 10.36 ppm. At the 30 ppm concentration level, the NCEM measured a value of 31.5 ppm, while the OBS recorded a concentration of 29.95 ppm. For another data point the NCEM measured a value of 24.5 ppm, while the OBS measured a value of 29.86 ppm. These data points do not display repeatability. The corresponding percent errors associated with the differences are, -8.34 % for the first 10 ppm concentration level data point. For the second 10 ppm concentration level data point, the percent error was equal to 15.83 %. For the first 30 ppm concentration level data point, the percent error was equal to 5.17%, and for the second 30 ppm concentration level data point the percent error was equal to -17.92%. The trend is showing at low NO_x concentrations, the NCEM displays variations in measured values, when compared to like values measured from the OBS. Negative NO_x concentrations are measured the NCEM during this test route.

Figure 17: Linear Regression for RDE 2 NO_x Highway

Table 5: RDE Highway NO_x R² Values

RDE 1	0.92107
RDE 2	0.96089
RDE 3	0.90774

6.2.1.8 NO_x Concentration Binning - 10 ppm Bin Size

The 10 ppm bin data analysis was set up to analyze data from a 10 ppm increment. This analysis averaged the NO_x concentrations within a range of 0-10 ppm, 10-20 ppm, and etc. This technique of data analysis is used to take the average, and in some instances reduce outliers in the data set. In Figure 18 below, the data was recorded during the second test route RDE route. This data was used because of its higher R² values on the regression plots associated with this test route. The R² value of RDE 2 is equal to 0.97562. RDE 1 has an R²-value of 0.94602, for the 10 ppm increment binning technique. For RDE 3, the associated R² value equals 0.96796. At the 100 ppm concentration level, the NCEM

measured a value of 92.35 ppm, while the OBS measured a value of 105.5 ppm. At the 200 ppm concentration level, the NCEM measured a value of 223.2 ppm, while the OBS recorded a concentration of 204.2 ppm. At the 400 ppm concentration level, the NCEM measured a value of 467.5 ppm, while the OBS recorded a concentration of 393.3 ppm. The corresponding percent errors associated with the differences are, -12.464 % for the 100 ppm concentration level data point. For the 200 ppm concentration level data point, the percent error was equal to 9.305 %. For the first 400 ppm concentration level data point, the percent error was equal to 18.87 %. The trend is showing a repeated trend throughout this analysis, as the NO_x concentrations, the NCEM measured values were elevated when compared to the OBS. The percent error increased as the NO_x concentrations increased.

Figure 18: Linear Regression for RDE 2 NO_x Concentration Binning - 10 ppm Bins

Table 6: RDE NO_x 10 ppm Bins R² Values

RDE 1	0.94605
RDE 2	0.97562
RDE 3	0.96796

The 10 ppm bin data analysis was set up to analyze data in a 10 ppm average increment. Figure 19 show the error percentage that is calculated in these three 10 ppm binning graphs. The RDE routes all showed a maximum of $\pm 23\%$ error, and a minimum of 0 % error. All three RDE test routes display similar results, but there are some differences. The RDE 1 test shows a more negative percent error, which shows that the NCEM was reading lower values than the reference unit the OBS. The RDE 2 test repeats this trend, but the RDE 3 test shows more positive percent errors, which tells us that the NCEM is reading higher NO_x concentrations than the OBS.

Figure 19:Error Percentage for RDE 2 NO_x Concentration Binning - 10 ppm Bins

6.2.1.10 NO_x Concentration Binning - 20 ppm Bin Size

The 20 ppm bin data analysis was set up to analyze data from a 20 ppm increment. This analysis averaged the NO_x concentrations within a range of 0-20 ppm, 20-40 ppm, and etc. This technique of data analysis is used to take the average, and in some instances reduce outliers in the data set. In Figure 20 below, the data was recorded during the second test route RDE route. This data was used because of its higher R² values on the regression plots associated with this test route. The R² value of RDE 2 is equal to 0.98921. RDE 1 has an R²-value of 0.96582, for the 20 ppm increment binning technique. For RDE 3, the associated R² value equals 0.98701. At the 100 ppm concentration level, the NCEM measured a value of 96.95 ppm, while the OBS measured a value of 109.8 ppm. At the 300 ppm concentration level, the NCEM measured a value of 299 ppm, while the OBS recorded a concentration of 310.3 ppm. At the 500 ppm concentration level, the NCEM measured a value of 513 ppm, while the OBS recorded a concentration of 514.7 ppm. The corresponding percent errors associated with the differences are, -11.702 % for the 100 ppm concentration level data point. For the 300 ppm concentration level data point, the percent error was equal to -3.642 %. For the first 500 ppm concentration level data point, the percent error was equal to -0.3303 %. The trend is showing a repeated trend is repeated across all three data sets. When binned in 20 ppm intervals the data points start to trend toward a linear relationship.

Figure 20: Linear Regression for RDE 2 NO_x Concentration Binning - 20 ppm Bins

Table 7: RDE NO_x 20 ppm Bins R² Values

RDE 1	0.94587
RDE 2	0.98921
RDE 3	0.98701

The 20 ppm bin data analysis was set up to analyze data in a 20 ppm average increment. Figure 21 shows the error percentage that is displayed in these three binning graphs. The RDE routes all showed a maximum of 25 % error, and a minimum of 0% error. For the 20 ppm error percentage there were some differences between each individual test route. For RDE 1 and RDE 2 the test results displayed an increase in the number of negative error percentages, which explains that the NCEM was reading lower values than the OBS. RDE 2 test route both displayed a range of -15 % to 25 % error percentages. The largest range of data can be seen on RDE 2.

Figure 21: Error Percentage for RDE 2 NO_x Concentration Binning - 20 ppm Bins

6.2.2 Tavannes Route - Highway Operation with Grade

The Tavannes test route performed in a higher altitude. There are many different elevation changes, that are associated with this route. The first important trend to observe is whether or not the altitude effects the NO_x concentration levels emitted from this truck during operation. This test route began with a warm start which resulted in elevated NO_x concentrations. This trip included what would be considered as highway speeds mixed with moderate to severe inclines that resulted in heavy load situations. The elevation changes also result in high load changes which can result in higher NO_x concentration levels. Figure 42 in the appendix can be used as a reference.

6.2.2.1 Overall Tavannes Route NO_x Emissions Comparison

The Figure 22 below shows the test data on a raw NO_x gaseous emissions with the corresponding vehicle speed that was collected for the Tavannes test route 1 from both PEMS units, the red is NCEM, and the blue is the OBS-ONE, and the green is the vehicle speed. As displayed below, the first 250 seconds resulted in higher NO_x emissions because of the associated start up routine. This duration of start-up operation was considerably less than what was observed in the RDE routes. The graphs a correlation between elevated NO_x concentrations during vehicle acceleration. However, it can be observed that during constant speed, the NO_x concentrations were decreased.

Figure 22:Tavannes 1 NO_x Raw Data with Vehicle Speed

The Figure 23 below shows the report data on a QQ plot of the raw NO_x gaseous emissions collected for the Tavannes test route 1 from both PEMS units. The QQ plot displays the linearity of the two sensors, but as the NO_x concentration level increases there is a deviation from the linearity. Some points at on the graph will show a representation of the data. At the 100 ppm concentration level, the NCEM measured 122 ppm, while the OBS measured 108.49 ppm. At the 200 ppm concentration level, the NCEM measured 182.5 ppm, and the OBS measured 202.4632 ppm. At the 400 ppm level, the NCEM measured 461.5 ppm, and the OBS measured 396.52 ppm. The corresponding percent error with these values are 3.235 % for the 100 ppm concentration, -9.8597 % for the 200 ppm concentration, 16.4 % for the 400 ppm concentration. As shown in the trend provided by the values, at the higher NO_x concentrations the NCEM measured higher values.

Figure 23: Tavannes 1 NO_x QQ Plot

The Figure 24 below shows the report data on a linear regression plot of NO_x gaseous emissions collected for the first Tavannes test route from both PEMS units. The corresponding R²-value to this linear regression is 0.96276. This is the highest R² value recorded for both Tavannes test routes. The lowest being Tavannes route 2 which was equal to 0.94284. An overall trend that can be seen with the linear regression is that at higher NO_x concentrations, the NCEM measured higher values. In example, the NCEM read a value of 208.5 ppm, while the OBS read a value of 198.2 ppm. Another example while the NCEM measured a value of 418.5 ppm, OBS read a value of 396.5 ppm. For these instances, there is a percentage error equal to 5.196 %, and 5.548 %, respectively. This might be associated with the different location of the NO_x measurement equipment. For the NCEM the NO_x measurement is a direct mount sensor, for the OBS, the gas emission sample must be routed to the unit.

Figure 24: Linear Regression for Tavannes 1 NO_x Overall

Table 8: Overall Tavannes NO_x R² Values

Tavannes 1	0.96276
Tavannes 2	0.95116

6.2.2.3 NO_x Concentration Binning - 10 ppm Bin Size

The 10 ppm bin data analysis was set up to analyze data from a 10 ppm increment. This analysis averaged the NO_x concentrations within a range of 0-10 ppm, 10-20 ppm, and etc. This technique of data analysis is used to take the average, and in some instances reduce outliers in the data set. In Figure 25 below, the data was recorded during the second test route RDE route. This data was used because of its higher R² values on the regression

plots associated with this test route. The R^2 value of RDE 2 is equal to 0.97562. Tavannes 2 has an R^2 -value of 0.93836, for the 10 ppm increment binning technique. At the 100 ppm concentration level, the NCEM measured a value of 91.79 ppm, while the OBS measured a value of 104.5 ppm. At the 200 ppm concentration level, the NCEM measured a value of 191 ppm, while the OBS recorded a concentration of 197.6 ppm. At the 400 ppm concentration level, the NCEM measured a value of 397.7 ppm, while the OBS recorded a concentration of 393.7 ppm. The corresponding percent errors associated with the differences are, -12.163 % for the 100 ppm concentration level data point. For the 200 ppm concentration level data point, the percent error was equal to -3.340 %. For the first 400 ppm concentration level data point, the percent error was equal to 1.016 %. The trend is displayed in this data point analysis is that the lower NO_x concentration is associated with correlation between the sensors.

Figure 25: Linear Regression Tavannes 1 NO_x Concentration Binning - 10 ppm Bins

Table 9: Tavannes NOx 10 ppm Bins R² Values

Tavannes 1	0.96779
Tavannes 2	0.93836

The 10 ppm bin data analysis was set up to analyze data in a 10 ppm average increment. Figure 26 show the error percentage that is shown in the 10 ppm binning of this dataset. The error percentage displays the NCEMs data points error offset when compared to the OBS data points. The Tavannes 1 route had a maximum percent error of 28 %, and a minimum of 0% error. The Tavannes 1 test route displays a maximum range of -28% to 28%. The negative error percentage shows the NCEM is recording lower concentration levels than the reference unit, and the positive error percentage shows the NCEM is recording higher concentrations than the OBS.

Figure 26: Error Percentage Tavannes 1 NO_x Concentration Binning – 10 ppm Bins

6.2.2.4 NO_x Concentration Binning - 20 ppm Bin Size

The 20 ppm increment binning technique was used again for the Tavannes routes. The Figure 27 below shows the 20 ppm binning. For the first Tavannes route, the R^2 value is 0.97634, this was highest R^2 value for the both of the Tavannes test routes. For the Tavannes 2 route, the R^2 value associated with this graph is 0.94286. The average R^2 value between the Tavannes 20 PPM binning graphs is equal to 0.9596. When compared to the 10 ppm binning, the 20 ppm takes a larger range of data points and takes the average. At the 100 ppm concentration level, the NCEM measured a value of 94.79 ppm, while the OBS measured a value of 107.7 ppm. At the 200 ppm concentration level, the NCEM measured a value of 207.9 ppm, while the OBS recorded a concentration of 210.7 ppm. At the 500 ppm concentration level, the NCEM measured a value of 502 ppm, while the OBS recorded a concentration of 485.6 ppm. The corresponding percent errors associated with the differences are, -11.987 % for the 100 ppm concentration level data point. For the 200 ppm concentration level data point, the percent error was equal to -1.3289 %. For the first 500 ppm concentration level data point, the percent error was equal to 3.377 %. The trend is displayed in this data point analysis is that the lower NO_x concentration is associated with correlation between the sensors.

Figure 27: Linear Regression Tavannes 1 NO_x Concentration Binning - 20 ppm Bins

Table 10: Tavannes NO_x 20 ppm Bins R² Values

Tavannes 1	0.97634
Tavannes 2	0.94286

The 20 ppm bin error percentage shows the NCEMs error when compared to the same point associated to the OBS ONE. Figure 28 shows the error percentage that is calculated in the associated binning graph. The Tavannes routes showed a maximum range of -25 % and a minimum of 1 % error. The Tavannes test route 20 ppm error percentage displays a variation in error percentages, this correlation shows that the NCEM was

measuring elevated and lowered data points, when compared to the OBS. The data shows the OBS reads higher NO_x levels at lower NO_x concentrations.

Figure 28: Error Percentage Tavannes 1 NO_x Concentration Binning - 20 ppm Bins

6.2.3 Highway Loop - Highway Operation on Flat Terrain

The Highway loop route consisted of constant highway speeds. The engine when started was warm during both highway test routes. These constant high speed resulted in lower NO_x concentrations. Figure 44 in the appendix can be used as a reference.

6.2.3.1 Overall Highway Loop Route NO_x Emissions Comparison

The Figure 29 below shows the report data on a raw NO_x gaseous emissions with the corresponding vehicle speed that was collected for the highway 2 from both PEMS units, the red is NCEM, and the blue is the OBS-ONE, and the green is the vehicle speed. The vehicle speed is correlated with the NO_x concentrations, the duration of the constant highway speeds showed low NO_x concentrations. The first 250 seconds of this test is

similar to the Tavannes route, with respect to the warm start-up routine. Throughout this test route negative NO_x concentration levels can be seen on the graph.

Figure 29: Highway 2 NO_x Raw Data with Vehicle Speed

The Figure 30 below shows the report data on a QQ plot of the raw NO_x gaseous emissions collected for the highway 2 from both PEMS units. The red line is the linear comparison line, the closer the blue marks are to the line they more comparable the data. The QQ plot displays the linearity of the two sensors, as the increase in NO_x concentration. Some points at on the graph will show a representation of the data. At the 100 ppm concentration level, the NCEM measured 79.5 ppm, while the OBS measured 96.23 ppm. At the 200 ppm concentration level, the NCEM measured 179 ppm, and the OBS measured 200.29 ppm. At the 600 ppm level, the NCEM measured 780.5 ppm, and the OBS measured 619.0447 ppm. The corresponding percent error with these values are -17.29 % for the 100 ppm concentration, -10.6296 % for the 200 ppm concentration, -26.0814 % for the 600 ppm concentration. As shown in the trend provided by the values, at the higher NO_x concentrations the NCEM measured higher values.

Figure 30: Highway 2 NO_x QQ Plot

The Figure 31 below shows the report data on a linear regression plot of NO_x gaseous emissions collected for the second highway test route from both PEMS units. The corresponding R^2 -value to this linear regression is 0.97227. This is the highest R^2 value recorded for both highway test routes. The lowest being highway route 1 which was equal to 0.93313. An overall trend that can be seen with the linear regression is that at higher NO_x concentrations, the NCEM measured higher values. In example, the NCEM read a value of 101 ppm, while the OBS read a value of 104.7 ppm. Another example while the NCEM measured a value of 546 ppm, OBS read a value of 546 ppm. For these instances, there is a percentage error equal to -3.5339 %, and 0 %, respectively. For the highway test route, there was a linear relationship. Both units' sensors measured negative NO_x.

Figure 31: Linear Regression for Highway 2 NO_x Overall

Table 11: Overall Highway NO_x R² Values

Highway 1	0.93313
Highway 2	0.97227

6.2.3.3 NO_x Concentration Binning - 10 ppm Bin Size

The 10 ppm bin data analysis was set up to analyze data from a 10 ppm increment. This analysis averaged the NO_x concentrations within a range of 0-10 ppm, 10-20 ppm, and etc. This technique of data analysis is used to take the average, and in some instances reduce outliers in the data set. In Figure 32 below, the data was recorded during the second test route highway route. This data was used because of its higher R² values on the

regression plots associated with this test route. The R^2 value of highway 2 is equal to 0.9566. Highway 1 has an R^2 -value of 0.85369, for the 10 ppm increment binning technique. At the 100 ppm concentration level, the NCEM measured a value of 102.5 ppm, while the OBS measured a value of 106.5 ppm. At the 200 ppm concentration level, the NCEM measured a value of 186.7 ppm, while the OBS recorded a concentration of 205 ppm. At the 400 ppm concentration level, the NCEM measured a value of 405.5 ppm, while the OBS recorded a concentration of 396.6 ppm. The corresponding percent errors associated with the differences are, -3.755 % for the 100 ppm concentration level data point. For the 200 ppm concentration level data point, the percent error was equal to -8.9268 %. For the first 400 ppm concentration level data point, the percent error was equal to 2.2441 %. The 100 ppm binning technique showed a linear relationship between both sensors.

Figure 32: Linear Regression Highway 2 NO_x Concentration Binning - 10 ppm Bins

Table 12: Highway NO_x 10 ppm Bins R² Values

Highway 1	0.85369
Highway 2	0.9566

The 10 ppm bin error percentage data analysis was set up to analyze data in a 10 ppm average increment. Figure 33 show the error percentage that is calculated for the 10 ppm binning of the second highway test route. The highway 1 and 2 error percentage graphs show a correlation between error percentage and NO_x concentration. The range on the graph below is -20 % to 28 %. With a data point that measured within 1 % of the OBS.

Figure 33: Error Percentage Highway 2 NO_x Concentration Binning - 10 ppm Bins

6.2.3.4 NO_x Concentration Binning - 20 ppm Bin Size

The 20 ppm bin data analysis was set up to analyze data from a 20 ppm increment. This analysis averaged the NO_x concentrations within a range of 0-20 ppm, 20-40 ppm, and etc. This technique of data analysis is used to take the average, and in some instances reduce outliers in the data set. In Figure 34 below, the data was recorded during the second test route highway route. This data was used because of its higher R² values on the regression plots associated with this test route. The R² value of highway 2 is equal to 0.94872. Highway 1 has an R²-value of 0.88136, for the 20 ppm increment binning technique. At the 100 ppm concentration level, the NCEM measured a value of 104.4 ppm, while the OBS measured a value of 109.9 ppm. At the 200 ppm concentration level, the NCEM measured a value of 162.2 ppm, while the OBS recorded a concentration of 189.7 ppm. At the 400 ppm concentration level, the NCEM measured a value of 368.1 ppm, while the OBS recorded a concentration of 404 ppm. The corresponding percent errors associated with the differences are, -5.0045 % for the 100 ppm concentration level data point. For the 200 ppm concentration level data point, the percent error was equal to -14.4966 %. For the first 400 ppm concentration level data point, the percent error was equal to -8.8861 %. The 20 ppm binning technique showed a linear relationship between both sensors.

Figure 34: Linear Regression Highway 2 NO_x Concentration Binning - 20 ppm Bins

Table 13: Highway NO_x 20 ppm Bin R² Values

Highway 1	0.88136
Highway 2	0.94872

The 20 ppm binning error percentage data analysis was set up to analyze data error in a 20 ppm average increment. Figure 35 displays the error percentage that is calculated for the highway 2 test route. The highway 2 route showed an error percentages range of -17.3 % to 23.1 %. With the majority of the data points trending towards a negative error percentage. This trend shows that the NCEM was reading lower NO_x concentrations than the reference unit.

Figure 35: Error Percentage Highway 2 NO_x Concentration Binning - 20 ppm Bins

6.3 Comparison of PN Concentration Measurements

6.3.1 Real Driving Emissions Routes

This section covers the PN emissions analysis performed on all three RDE routes, these routes consisted of four portions. The first portion which had a duration of 500 seconds was considered the cold start portion. The second portion which lasted until the distance traveled reached a value of 25.1 km, this portion was called the urban portion. The third portion which included data from the end of the second portion to a distance of 60.5 km, was considered the rural portion. The last portion of the RDE test route, was called the highway portion it consisted of the data after 60.5 km had been traveled.

6.3.1.1 Overall RDE 1 Route PN Comparison Analysis

For the first RDE test route, Figure 36 shows the data that was collected over the duration of the entire test route. The first 500 seconds of this test was the cold start portion,

during this time interval the NCEM measured elevated NO_x concentration levels. For one data point, the NCEM recorded a value of $7.78 \times 10^6 \frac{\#}{\text{cm}^3}$, while the corresponding OBS value recorded a value of $4.01 \times 10^6 \frac{\#}{\text{cm}^3}$. This is equal to a percent error equal to -94.01 %. This was just one example of how inaccurate this dataset was. The NCEM would measure elevated values when compared to the OBS. The reason for this is because the OBS has a measurement cut-off point. The NCEM can measure down to 5 nm, while the OBS cannot measure below 23 nm.

Figure 36: RDE 1 PN Raw Data with Vehicle Speed

For the first RDE test route, Figure 37 below shows the linear regression plot of the data collected over the duration of the test route. The R^2 value associated with this graph is equal to 0.58044. This low R^2 value shows that the data shows little to no correlation. RDE 2 had an R^2 value equal to 0.93648, and the RDE 3 data R^2 value equaled 0.92743. These two graphs shown great correlation, they can be referenced in the appendix figures

95 and 97. The NCEM read a value of $2.66 \times 10^5 \frac{\#}{cm^3}$, while the OBS read a value of $0 \frac{\#}{cm^3}$. An example of correlation is the NCEM measured a value of $4.98 \times 10^6 \frac{\#}{cm^3}$, OBS read a value of $3.807 \times 10^6 \frac{\#}{cm^3}$. The percentage error equal to -30.81 %. This might be associated with the different location of the NO_x measurement equipment. For the NCEM the NO_x measurement is a direct mount sensor, for the OBS, the gas emission sample must be routed to the unit.

Figure 37: Linear Regression for RDE 1 PN Overall

Table 14: RDE PN R² Values

RDE 1	0.58044
RDE 2	0.93648
RDE 3	0.92743

6.3.2 Tavannes Routes - Highway Operation with Grade

The Tavannes test route was performed at a higher altitude. There are many different elevation changes, that are associated with this route. The first important trend to observe is whether or not the altitude effects the PN concentration levels emitted from this truck during operation. This test route began with a warm start which resulted in elevated NO_x concentrations. This trip included what would be considered as highway speeds mixed with moderate to severe inclines that resulted in heavy load situations. The elevation changes also result in high load changes which can result in higher PN concentration levels.

6.3.2.2 Overall Tavannes 2 Route PN Comparison Analysis

For the second Tavannes test route, Figure 38 below shows the linear regression plot of the data collected over the duration of the test route. The NCEM measured higher levels of PN concentration when compared to the OBS. Similar to the Tavannes 1 the spikes in the data, is most likely due to acceleration and deceleration, although in this data set it is less prevalent. The NCEM is much more sensitive to PN concentration spikes due to its ability to measure lower particle sizes.

Figure 38:Tavannes 2 PN Raw Data with Vehicle Speed

For the second Tavannes test route, Figure 39 below shows the linear regression plot of the data collected over the duration of the test route. The R^2 value associated with figure 39 is equal to 0.66314. The R^2 value associated with the Tavannes 1 route is equal to 0.60186. The average of the both R^2 values is equal to 0.626625. Although this R^2 value is lower than usual it still shows that there is a correlation of the data, and more data analysis should be performed. An in depth data point analysis is not necessary on this figure, the NCEM was measurement elevated PN concentrations due to the sensors ability to measure smaller particle sizes.

Figure 39: Linear Regression for Tavannes 2 PN Overall

Table 15: Tavannes PN R^2 Values

Tavannes 1	0.60186
Tavannes 2	0.66429

6.3.3 Highway Loop - Highway Operation on Flat Terrain

6.3.3.1 Overall Highway Loop 1 Route PN Comparison Analysis

For the first highway route, Figure 40 below shows the data collected over the duration of the test route. The highway test route showed some correlation in the raw data chart, but the NCEM still continues to read higher PN concentration levels. These data

point spikes can be due to the DPF regenerating, because the truck is sensing steady state operation at high heat, and so the soot is being burnt off, spikes can be seen in PN data. Another explanation for these spikes is the truck acceleration which is consisted with high PN concentration spikes.

Figure 40: Highway 1 PN Raw Data with Vehicle Speed

For the first highway test route, Figure 41 below shows the linear regression plot of the data collected over the duration of the test route. The R^2 value associated with this graph is equal to 0.8186. This is the highest R^2 value of the two highway PN tests. The R^2 value associated with highway 2 is equal to 0.7864.

Figure 41: Linear Regression for Highway 1 PN Overall

Table 16: Highway PN R^2 Values

Highway 1	0.8186
Highway 2	0.78569

7 Conclusions and Future Work

7.1 Conclusions

This study was conducted to compare the accuracy and repeatability of the sensors and analyzers associated with the NCEM, and the OBS-One. For the NO_x portion of this study the following results were concluded. During the NO_x data analysis, the RDE routes produced the highest R^2 value of 0.96865, this was recorded during the overall test of the third RDE route. With this R^2 value, it shows that the ZrO_2 sensor attached to the NCEM does have the ability to measure NO_x levels comparable to that recorded by the CLD analyzer attached to OBS-One. The reasoning behind this conclusion is because of the high R^2 value that was revealed during the linear regression analysis. During the Tavannes test route, the highest R^2 value was present during the first route. The R^2 value associated with the Tavannes 1 is equal to 0.96276. This reinforces the conclusion that the NCEM sensor has the ability to record the values comparable to the OBS-One. The highway recorded the highest R^2 value during the entire study, it was equal to, 0.97227. The R^2 value results display that across the three different test routes the NCEM was capable of measuring NO_x concentration levels relative to the OBS-One.

The binning technique used in this study allowed for easier comparison of the two data sets from the PEMS units. The 10 ppm increment binning allowed for a smaller population of data to be averaged and analyzed in a narrow spectrum with more data points. The 20 ppm increment binning allowed for a larger population of data to be averaged and analyzed in a broader spectrum with less data points. The error percentages were then used to analyzed the data with their respective binning interval. When comparing the error percentages associated with 10 ppm and 20 ppm, a comparison is used to compare a smaller population average vs a larger population average. The binning allowed for smaller intervals of data to be analyzed. The NCEM showed equal variance when compared to the OBS-One.

For the PN concentrations the following conclusions can be made about the results. In the RDE 1 test route, during the cold start, the NCEM was reading extremely high values compared to the OBS-One. For example, the highest data spike had a NCEM data point value of $7.78 * 10^6$ for PN concentration. The corresponding OBS-One data point value recorded a value of $4.01 * 10^6$. That is a 45 % error percentage. The cold start portion of the RD. Another instance where outliers were frequent was in the PN concentration for the highway test routes. One conclusion is that maybe these were occurring because the truck is sensing steady state operation at high heat, and so the soot is being burnt off. When the soot is being burnt off that is often associated in a large amount of particle emissions.

The following conclusions can be made about the comparison study performed in this study.

For NO_x concentration levels

1. The NCEM's ZrO₂ sensor measured elevated NO_x concentration levels when compared to the OBS-One. Some reasons for this elevated measurement is due to the direct mount sensor found on the NCEM, compared to the OBS-One having to collect and transport the sample a measurable distance before being analyzed.
2. The NCEM's ZrO₂ sensor measured small spikes of negative NO_x concentration levels.
3. The negative error percentage calculated during the 10 ppm and 20 ppm binning technique concludes the NCEM ZrO₂ measures elevated NO_x concentrations compared to the OBS-One.

For PN concentration levels

1. The NCEM's diffusion charging PN sensor measured elevated PN concentrations during the entire study when compared to the OBS-One. This is because the NCEM's PN sensor has the capability to measure smaller particle sizes when compared to the OBS-One. The NCEM measures below 23 nm, which is the OBS-One cutoff for the CPC PN measurement tool.

From the results, and through data analysis it can be concluded that the NCEM has the capability to be used as a scanning tool, but not as a standard PEMS unit. This conclusion is on the basis of sensors, and measurement capabilities.

7.2 Future Work

The results and associated conclusions presented in this study were based on concentration levels from a variety of different test routes. Future work could include a mass rate calculation that includes ECU data, and tabulated with the NCEM data. The ECU data would have to be utilized due to the fact that the NCEM does not have exhaust flow rate measurement capabilities. This would prove for an easier comparison between other studies that conducted similar experiments.

8 Bibliography

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9 Appendix

Figure 42: Tavannes Test Route

Figure 43: RDE Test Route

Figure 44: Highway Test Route

Table 17: Horiba OBS-One Specifications Chart [18]

	LDV Type		HDV Type	
	OBS-ONE GS01	OBS-ONE GS02	OBS-ONE GS11	OBS-ONE GS12
CO	x	x	x	x
CO ₂	x	x	x	x
NO/NO _x *1	x		x	
NO, NO _x , NO ₂ *2		x		x
THC			x	x
Exhaust Flow Rate	x	x	x	x
Power Requirements	DC 22-28V			
Power Consumption (@stable state) *3	Approx. 0.2 kW		Approx. 0.45 kW	
Dimensions *4	350 (W) x 470 (D) x 330 (H) mm		350 (W) x 470 (D) x 470 (H) mm	
Weight (Main Unit)	32 kg		45 kg	
Battery *5 *6	Deep-route, sealed lead battery of DC 24 V, 35 Ah (5 hour rate), Operation time : Approx. 3 hours		Deep-route, sealed lead battery of DC 24 V, 100 Ah (5 hour rate), Operation time : Approx. 4.5 hours	
Operating Conditions	Temperature : -10 to 40 deg.C,*6 Relative humidity : less than 80%, Altitude : 0 to 2000 m above sea level			

Table 18: Horiba OBS-One Measurement Principles of Gaseous Emissions [18]

	Measurement Principle	Measurement Range
CO	Heated NDIR	0-0.5 to 0-10 vol %
CO ₂	Heated NDIR	0-0.5 to 0-20 vol%
NO / NO _x	Heated CLD	0-100 to 0-3000 ppm
NO, NO _x , NO ₂	Heated-dual CLD	0-100 to 0-3000 ppm
THC	Heated FID	0-100 to 0-10000 ppmC
Sampling Method	Wet Measurement	
Exhaust Flow Rate *7	Pitot Flow Meter	0-0.2 to 0-65.0 m ³ /min
Standard Signal Measurements	Exhaust Temperature Exhaust Pressure Atmospheric Temperature Atmospheric Humidity GPS Signal Speed	

Table 19: Horiba OBS-One PN unit specifications [19]

Measuring Principles	Condensation particle counter (CPC)
Particle Diameter	23-1,000nm
Measuring Range	0-5x10 ⁷ particles/ cm ³
Power Supply	DC 24 V
Power Consumption (MAX)	Approx. 0.25 kW
Mass	Approx. 18kg
Operating Condition	Temperature: -10 – 40 °C Altitude: 0 to 2000 m above sea level Relative humidity: less than 80%
Condensation fluid	Isopropyl alcohol a special grade reagent (99.5%) correspond
Option	Outer cover for mounting outside the vehicle using a hitch carrier

Table 20: NCEM Specifications [22]

Item	Specifications
Electric Supply Source	AC 100 to 240 V or DC 12 to 28 V *1
Power Consumption	AC: about 400 VA (Max Act. Power) *2 DC: about 300 VA (Max Act. Power)
External Dimensions	348 (W) x 283 (D) x 284 (H) mm *3
Main Unit Weight	About 9.5 kg *4
Usage Environment	Ambient Temperature: -10 to 40 °C Humidity: Relative humidity of 85% or less Absolute Humidity of less than 30 g/m ³
External I/F	CAN (Complies with ISO11898) USB (PC Connection) OBD2 (ISO15765, SAEJ1979) GPS Analog Input (1 Channel)

Table 21: NCEM Module Specifications [22]

Module	Weight	Power Consumption	Output Signal	
			Signal Name	Range
NO _x /O ₂	About 0.7 kg	About 21 VA	NO _x	0 to 1500 ppm
		About 56 VA	O ₂	0 to 21 %
AFR (O ₂)	About 0.7 kg	About 21 VA	O ₂	0 to 21 %
		About 56 VA	A/F	9 to 20
PM/PN	About 1.9 kg	About 13 VA	PM	0 to 1500 ppm
			PN	0 to 1.0x10 ⁸ #/cm ³
PM/PN EX	About 2.9 kg	About 50 VA	PM	0 to 300 mg/m ³
			PN	0 to 1.0 x 10 ⁹ #/cm ³

Figure 45: Mercedes Benz Actros

Figure 46: Mercedes Benz Actros

Figure 47: Mercedes Benz Actros

Figure 48: Truck Exhaust Tip, Sensor Layout

Table 22: Mercedes Benz Actros Specifications Chart

Manufacturer	Mercedes-Benz
Model	Actros 1848 LS 4x2 F13
VIN	WDB9634031L922238
MY	2015
Cabin Type	Day Cab, Cab-Over
Engine Manufacturer	Mercedes-Benz
Engine Model	OM 471
Configuration	In-line 6 cyl.
Displacement	12.8
Power	354kW (476hp)
Torque	2300Nm
Engine Technology Features	
Engine SN	471900 C0 129232
Emission Standards	Euro VI
Emission Control	EGR, DOC, DPF, urea-SCR
Transmission	G 281-12/14, 93-1, 0
Number of Gears	
Axle Ratio	2.611
Axle Configuration	4x2
Curb Weight	8160 kg
Odometer	118,000 [km]

Figure 49: RDE 1 NO_x Raw Data with Vehicle Speed

Figure 50: Linear Regression for RDE 1 NO_x Overall

Figure 51: RDE 3 NO_x Raw Data with Vehicle Speed

Figure 52: Linear Regression for RDE 3 NO_x Overall

Figure 53: RDE 1 Cold Start NO_x Raw Data with Vehicle Speed

Figure 54: Linear Regression for RDE 1 Cold Start NO_x

Figure 55: RDE 3 NO_x Cold Start Raw Data with Vehicle Speed

Figure 56: Linear Regression for RDE 3 Cold Start NO_x

Figure 57: RDE 1 NO_x Urban Raw Data with Vehicle Speed

Figure 58: Linear Regression for RDE 1 NO_x Urban

Figure 59: RDE 3 NO_x Urban Raw Data with Vehicle Speed

Figure 60: Linear Regression for RDE 3 NO_x Urban

Figure 61: RDE 1 NO_x Rural Raw Data with Vehicle Speed

Figure 62: Linear Regression for RDE 1 NO_x Rural

Figure 63: RDE 3 NO_x Rural Raw Data with Vehicle Speed

Figure 64: Linear Regression for RDE 3 NO_x Rural

Figure 65: RDE 1 NO_x Raw Data with Vehicle Speed

Figure 66: Linear Regression for RDE 1 NO_x Highway

Figure 67: RDE 3 NO_x Highway Raw Data with Vehicle Speed

Figure 68: Linear Regression for RDE 3 NO_x Highway

Figure 69: Linear Regression for RDE 1 NO_x Concentration Binning - 10 ppm Bins

Figure 70: Linear Regression for RDE 3 NO_x Concentration Binning - 10 ppm Bins

Figure 71: Error Percentage for RDE 1 NO_x Concentration Binning - 10 ppm Bins

Figure 72: Error Percentage for RDE 3 NO_x Concentration Binning - 10 ppm Bins

Figure 73: Linear Regression for RDE 1 NO_x Concentration Binning - 20 ppm Bins

Figure 74: Linear Regression for RDE 3 NO_x Concentration Binning - 20 ppm Bins

Figure 75: Error Percentage for RDE 1 NO_x Concentration Binning - 20 ppm Bins

Figure 76: Error Percentage for RDE 3 NO_x Concentration Binning - 20 ppm Bins

Table 23: RDE R-squared values

	R ² Values		
	RDE 1	RDE 2	RDE 3
Overall	0.9524	0.9674	0.9687
Cold Start	0.96006	0.97165	0.97903
Urban	0.86994	0.95419	0.87167
Rural	0.92926	0.95422	0.96209
Highway	0.92107	0.96092	0.90777
10 ppm	0.94602	0.97562	0.96796
20 ppm	0.96582	0.98921	0.98701

Figure 77: Tavannes 2 NO_x Raw Data with Vehicle Speed

Figure 78: Linear Regression Tavannes 2 NO_x Overall

Figure 79: Linear Regression Tavannes 2 NO_x Concentration Binning - 10 ppm Bins

Figure 80: Error Percentage Tavannes 2 NO_x Concentration Binning - 10 ppm Bins

Figure 81: Linear Regression Tavannes 2 NO_x Concentration Binning - 20 ppm Bins

Figure 82: Error Percentage Tavannes 2 NO_x Concentration Binning - 20 ppm Bins

Figure 83: Highway 1 NO_x Raw Data with Vehicle Speed

Figure 84: Linear Regression for Highway 1 NO_x Overall

Figure 85: Linear Regression Highway 1 NO_x Concentration Binning - 10 ppm Bins

Figure 86: Error Percentage Highway 1 NO_x Concentration Binning - 10 ppm Bins

Figure 87: Linear Regression Highway 1 NO_x Concentration Binning - 20 ppm Bins

Figure 88: Error Percentage Highway 1 NO_x Concentration Binning - 20 ppm Bins

Figure 89: RDE 2 PN Raw Data with Vehicle Speed

Figure 90: Linear Regression for RDE 2 PN Overall

Figure 91: RDE 3 PN Raw Data with Vehicle Speed

Figure 92: Linear Regression for RDE 3 PN Overall

Figure 93: Tavannes 1 PN Raw Data with Vehicle Speed

Figure 94: Linear Regression for Tavannes 1 PN Overall

Figure 95: Highway 2 PN Raw Data with Vehicle Speed

Figure 96: Linear Regression for Highway 2 PN Overall