

A Work-Based Window Method for Calculating In-Use Brake-Specific NO_x Emissions of Heavy-Duty Diesel Engines

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ABSTRACT

A work-based window method has been developed to calculate in-use brake-specific oxides of nitrogen (NO_x) emissions for all engine speeds and engine loads. During an in-use test, engine speed and engine torque are read from the engine's electronic control unit, and along with time, are used to determine instantaneous engine power. Instantaneous work is calculated using this power and the time differential in the data collection. Work is then summed until the target amount of work is accumulated. The emissions levels are then calculated for that window of work. It was determined that a work window equal to the theoretical Federal Test Procedure (FTP) cycle work best provides a means of comparison to the FTP certification standard. Also, a failure criterion has been established based on the average amount of power generated in the work window and the amount of time required to achieve the target work window to determine if a particular work window is valid.

Data collected during Phase IV of West Virginia University's in-use testing program were used to show that the work window method produces in-use brake-specific NO_x values similar to the 30 second Not-To-Exceed (NTE) window method, which was applicable at the time of testing, and the continuous NTE window method over different highway and urban test routes for a variety of engine configurations.

INTRODUCTION

Heavy-duty diesel engines (HDDEs) are currently certified in an engine dynamometer test cell over defined test cycles, such as the Federal Test Procedure (FTP) or the Supplemental Emissions Test (SET). The Federal Test Procedure for HDDEs is a transient engine dynamometer cycle with setpoints based on engine speed and engine torque. In order for the cycle to be representative, the setpoints are normalized based on the engine's lug curve. For engine certification, the cycle is completed twice, with the first test being a cold start and the second being a hot start. A 20 minute soak period separates the two tests. Emissions are collected

continuously throughout each cycle, and a weighted average is used to determine a composite brake-specific result for the cycles using constituent mass and individual cycle work. The composite result is based on 1/7 of the results of the cold test and 6/7 of the results of the hot test.

The SET, also known as the European Stationary Cycle (ESC) or the Organisation Internationale des Constructeurs d'Automobiles (OICA) cycle, is a 13 mode steady-state engine dynamometer cycle that is 28 minutes in length. It was adopted by the US EPA for engine certification after the 1998 Consent Decrees between the settling heavy-duty diesel engine manufacturers, the United States Department of Justice, the United States Environmental Protection Agency (US EPA), and the California Air Resources Board were established. Setpoints for this cycle are based on the engine's lug curve. The speed n_{lo} is defined as the engine speed below rated speed at which full load power is 50% of the maximum power of the engine. The speed n_{hi} is defined as the engine speed above rated speed at which full load power is 70% of maximum power of the engine. The speeds A, B, and C are based on the following equations:

$$\begin{aligned} A &= 0.25 \times (n_{hi} - n_{lo}) + n_{lo} \\ B &= 0.50 \times (n_{hi} - n_{lo}) + n_{lo} \\ C &= 0.75 \times (n_{hi} - n_{lo}) + n_{lo} \end{aligned}$$

Equation 1

At each speed, the engine is run at loads of 25%, 50%, 75%, and 100% of full load torque at that speed. The SET also contains a mode at the low idle speed. Each mode has a weighting factor associated with it. Emissions are sampled at the end of each mode after a stabilization period.

Strict guidelines for engine certification testing are set by the federal government, and are outlined in 40 CFR Part 86 Subpart N, and more recently in 40 CFR Part 1065 [1, 2]. In addition to certification testing, HDDEs are

subjected to in-use testing where gaseous emissions levels cannot exceed a defined percentage of the engine's Family Emission Limit (FEL). For the engines used in this experiment, an additional 0.5 g/bhp-hr (0.7 g/kW-hr) was allowed for instrument and analyzer inaccuracies. As instrument and analyzer technology continues to improve, it is thought that this addition will decrease or disappear. In 2005, the US EPA, California Air Resources Board, and the Engine Manufacturers Association (EMA) sponsored the gaseous emissions measurement allowance program to study inaccuracies present in portable emissions measurement systems (PEMS). Results released in early 2007 showed an allowance of 0.45 g/bhp-hr for oxides of nitrogen (NO_x), 0.02 g/bhp-hr for non-methane hydrocarbons (NMHC), and 0.5 g/bhp-hr for carbon monoxide (CO) [3]. HDDEs are required to meet these limits when operating in the Not-To-Exceed (NTE) zone, which is defined by 40 CFR §86.1370-2007 [1]. In an in-use test, emissions are calculated when an engine is operating in the NTE zone for a continuous time period of at least 30 seconds in length. When this type of engine operation occurs, the engine is said to be operating in an NTE window.

In-use emissions can be collected while the vehicle functions during its in-use operation using a PEMS. The most readily available instruments for in-use, on-road emissions testing are "garage-grade" repair multigas analyzers. However, these instruments are often designed for steady-state tests and ambient air quality measurements or for testing gasoline-fueled and spark-ignited engine emissions. Often the design of these instruments does not allow for the capturing of transient events of an engine. The technology used is customarily based on pricing, rather than the accuracy of the measurement, as these analyzers are designed for inspection and maintenance (I/M) procedures rather than compliance testing. Several systems have been developed in the past by various research organizations and commercial companies to measure engine emissions during in-field or on-road operation. These systems are comprised of components that are comparable to the laboratory-grade equipment used in the engine and chassis dynamometer certification and/or verification testing. However, any system that is developed for in-use, on-road, on-board testing must be lightweight and portable for installation and testing purposes, while still maintaining the qualitative measurements of laboratory instruments. An important advantage of using an on-board system for emissions testing is that the system helps to eliminate the need for an expensive, instrumented testing facility. Installation of a PEMS on a vehicle takes a small amount of time when compared to the time spent installing an engine on an engine dynamometer test bed or a vehicle on a chassis dynamometer. Emissions can be reported in various methods, such as distance-specific (g/mile, g/km), work-specific (g/bhp-hr, g/kW-hr), or time-specific (g/s) measurements.

When using a PEMS device for emissions testing, the vehicle is driven through representative routes on roads

or highways, rather than through a prescribed representative cycle in the test cell. Although the FTP and UDDS (Urban Dynamometer Driving Schedule) cycles are still commonly used for engine and chassis dynamometer testing, it has been shown that these tests are not representative of how vehicles are currently driven on the highway. These tests were developed by studying vehicles during their in-use operation. The cycles were then created to mimic the average operation of these vehicles. Due to vehicle transmission and axle ratios, the average equivalent vehicle speed of the FTP test varies from vehicle to vehicle. The average speed of the UDDS test is also 19 mph (30 km/h) while the maximum speed is 58 mph (93 km/h) [4].

Today, most interstate highways throughout the United States, which carry a large amount of heavy-duty diesel-fueled vehicles, have a posted speed limit of 65 mph (105 km/h) or 70 mph (113 km/h). Therefore, it is necessary to devise a new procedure for testing brake-specific mass emissions from these vehicles. An on-board PEMS is best suited for this application. West Virginia University (WVU) was employed by the six settling HDDE manufacturers to assess mobile emissions measurement technology and integrate a system to record engine emissions during a vehicle's in-use, on-road operation. WVU has incorporated then-current technology into an on-road emissions measurement system, known as the Mobile Emissions Measurement System (MEMS). This system meets the requirements of measuring emissions of an engine while it is operated in the vehicle during its in-use operation. The development and testing of MEMS was divided into four phases. Phase I consisted of evaluating current available technology to determine if any system was capable of fulfilling the requirements of a PEMS. If no such systems were found, then a new system was to be integrated. Phase II involved developing routes in accordance with the requirements of the Consent Decrees to test heavy-duty diesel-powered vehicles with a PEMS during their in-use, on-road operations [5-10]. The actual testing of vehicles was included in Phases III and IV of the project using predetermined test routes (see Supporting Information – Test Routes) that were used for all test vehicles, regardless of their configuration.

METHODOLOGY

MEMS OVERVIEW

During all tests over all routes, data were collected using WVU's MEMS. MEMS consists of three major subsystems: the emissions measurement system, the exhaust flow measurement system, and the data acquisition system.

The emissions measurement system of MEMS, shown in Figure 1, is housed in a stainless steel enclosure. The main components of the system are a heated line, a heated filter, a nitrogen dioxide (NO₂) converter, a Horiba MEXA 7000 Ox analyzer, a pump, a

pressure regulator, a chiller, and a Horiba BE-140 AD multigas analyzer.



Figure 1. MEMS Emissions Measurement System Installed in a Test Vehicle

The Horiba MEXA-720 NO_x is a zirconium oxide based sensor capable of reporting NO_x and oxygen (O₂) concentrations in the exhaust sample. The principle of operation is based on the diffusion of oxygen ions through dual platinum coated zirconium oxide chambers when heated to a high temperature of approximately 700 °C. The amount of current required to maintain a constant voltage across the second chamber as the oxygen ions are pumped out of that chamber is proportional to the NO concentration in the sample [11]. Although the MEXA-720 NO_x is supposed to be capable of reporting a total NO_x concentration measurement without an NO₂ to NO converter, MEMS uses a converter to ensure an accurate total NO_x measurement [12]. A zirconium oxide sensor is also known to be sensitive to ammonia (NH₃). However, ammonia concentrations in exhaust during this study were at or near zero, as none of the engines were equipped with NO_x aftertreatment systems, such as Selective Catalytic Reduction (SCR), which may use an ammonia solution as a reducing agent.

The Horiba BE-140 AD multigas analyzer uses non-dispersive infrared (NDIR) absorbance technology to determine carbon monoxide (CO) concentrations in the exhaust [13]. The analyzer is also capable of measuring HC and CO, but its capabilities are limited. The CO concentrations in raw diesel exhaust are too low (typically less than 100 ppm) for the resolution of this analyzer to report accurately. The analyzer was designed for inspection and maintenance use on gasoline engines, which may have CO concentrations as high as 20% during rich engine operation [14]. Since the analyzer is not heated, and water is removed prior to the sample entering the analyzer, HC results can be skewed due to the heavy hydrocarbons found in diesel exhaust that can condense along with the water vapor in the sample. Also, an NDIR-based hydrocarbon analyzer has a poor response to hydrocarbon compounds other

than n-alkanes when compared to a flame ionization detector (FID) [15]. Therefore, the BE-140 AD analyzer is used to report only CO₂ measurements to allow for a carbon balance calculation for quality control and quality assurance purposes.

To determine mass rate emissions, MEMS uses a differential pressure device inserted into a length of exhaust piping that is mounted in the exhaust system of the vehicle to measure exhaust flow rate. The Annubar®, by Dieterich Standard, Inc., is a multi-port averaging device that works on the Bernoulli principle [16]. The diamond shape of the device creates an area of large pressure upstream and a low pressure downstream. A pressure transducer accurately measures this differential pressure. Along with the temperature and absolute pressure of the exhaust gas and the pipe diameter, and a variety of parameters associated with the Annubar®, the exhaust flow rate can be calculated. The exhaust flow rate measurement system mounted on a transit bus is shown in Figure 2.



Figure 2. MEMS Exhaust Flow Rate Measurement System Installed on a Test Vehicle

Signals from the emissions measurement system, the flow measurement system, the ambient box, the engine control unit, and the global positioning system are input into the data acquisition system of MEMS. The data acquisition system of MEMS, shown in Figure 3, is housed in a separate stainless steel enclosure than the emissions measurement system due to the sensitivity of its components. The enclosure contains data acquisition cards and various data converters.

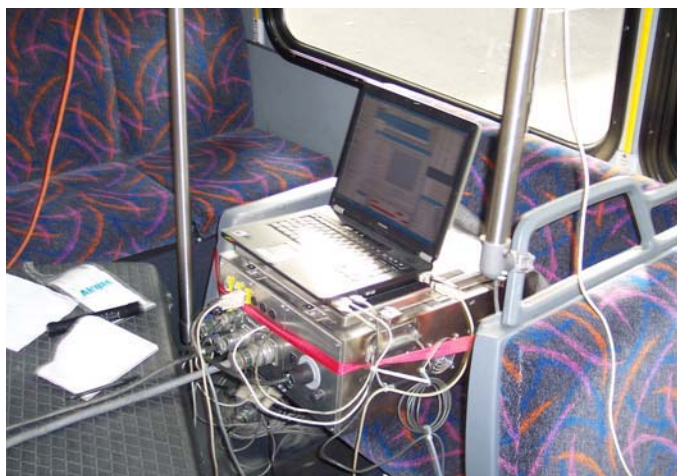


Figure 3. MEMS Data Acquisition System Installed in a Test Vehicle

Parameters such as engine speed and engine torque are read from the engine control unit to determine engine power and brake-specific emissions. Other engine information such as, but not limited to, coolant temperature, oil temperature, oil pressure, inlet manifold temperature, and boost pressure may also be read from the engine control unit. Proprietary information, such as fuel injection timing, may also be read from the engine control unit by sending a message to the engine control unit via a communication adapter and reading a returned message [17]. For most engines, engine information was read using SAE Surface Vehicle Recommended Practices J1587 and/or J1939 protocols [18, 19].

Nearly all of the software used for MEMS was written and developed by personnel at West Virginia University. The software programs are written in Microsoft Visual Basic to be used on a Windows PC [20]. Some of the engine control unit information can be collected using commercially available software [21].

The data acquisition code contained both calibration and data collection features. Prior to installation of the system on the test vehicle, the program was used to calibrate pressure transducers and thermocouples and store vehicle information. Then prior to a test, as well as after a test, the program was used to zero and span transducers and analyzers. During a test, the program recorded data from analyzers, transducers, thermocouples, a GPS, and the engine control unit.

Once an in-use test was completed, the post processing software was used to convert the data collected during the test into engineering units. The post processor time aligned data from different sources and created files that could be used to further understand and interpret the data. Files that contained raw and calculated values for each channel were created as well as summary files for each test. Data were checked at the end of each test leg as a quality control and quality assurance measure [14, 22].

NOT-TO-EXCEED REGION DEFINITION

The Not-To-Exceed (NTE) region is defined as the engine speed and torque area where engine speed is greater than the n_{15} speed and engine torque is greater than or equal to 30% of the maximum engine torque or greater than or equal to 30% of maximum engine power, whichever is greater [1]. The speed n_{15} is calculated from Equation 2.

$$n_{15} = 0.15 \times (n_{hi} - n_{lo}) + n_{lo}$$

Equation 2

The NTE region for a heavy-duty diesel engine is shown in Figure 4.

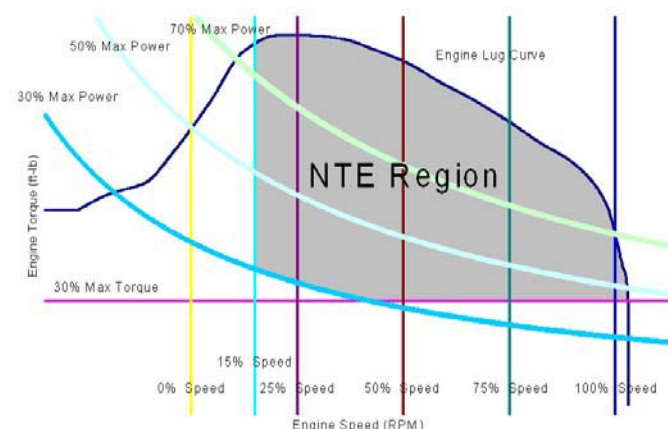


Figure 4. Not-To-Exceed Region

At the time of the testing in this study, in-use testing regulations stated that an NTE event is defined as a 30 second continuous window of engine operation within the NTE zone. If an engine operates in the NTE zone for a continuous period longer than 30 seconds, then there exist several 30 second windows of operation. For example, if an engine operates in the NTE zone for a period of 35 seconds, and 5 Hz data is collected, then there are a total of 26 30 second NTE events. More recently, heavy-duty diesel engine manufacturers have lobbied to alter the definition of an NTE event. It is believed that once an engine is operating in the NTE zone for a minimum of 30 seconds, the single event should continue until the engine is no longer operating in the NTE zone. In this method, termed a continuous NTE event, brake-specific emissions tend to be lower than those of 30 second windows due to a greater number of samples in the event and thus, better averaging. The continuous NTE method is outlined in 40 CFR §86.1912 [1].

The 30 second and continuous windows of NTE region engine operation methods of determining in-use emissions have several shortcomings. The methods do not include all ranges of engine speed and torque. Engines equipped with exhaust aftertreatment systems may be operating in the NTE zone, but not meet the requirement for exhaust gas temperature due to design

or a regeneration event. The methods also do not allow for a feasible method of measuring particulate matter emissions due to the possibility of entering and exiting the NTE region without experiencing a 30 second minimum NTE event.

When analyzing how much time an engine operates in or out of the NTE region, or how many 30 second NTE events or continuous NTE events occur during a test, the amount of time an engine spends operating outside of the NTE region may become a significant portion of the test, especially during periods of low engine power output or long idle operation. Heavy-duty diesel engine manufacturers are required to broadcast an accurate estimated engine torque output via an ECU datalink for all engine operation. The following section will present an alternative method to calculating in-use brake-specific emissions for all ranges of engine operation. The method integrates emissions data over a predetermined window of work, rather than time, to obtain a brake-specific emissions result. The authors believe that this method will help in gathering engine emissions data both inside the NTE region and outside the NTE region, an area that has had limited focus during heavy-duty diesel engine in-use testing to date.

WORK WINDOW METHOD EXPLANATION

The parameters required to determine the amount of work performed by the engine during its in-use operation are ECU engine speed (N), ECU engine torque (T), and time (t). The engine speed is recorded from the ECU, as well as engine torque. In this study, data were collected at 5 Hz. Instantaneous work can be calculated for each data point in the data set. Then, beginning at each point in the data set, the instantaneous work is summed until the desired amount of work has been accumulated. This point in time is marked as i^* . This amount of accumulated work is denoted as the work window. This calculation is given in Equation 3.

$$WorkWindow(bhp \cdot hr) = \sum_{i=0}^{i^*} \left(\frac{N_i \left(\frac{rev}{min} \right) \times T_i (ft \cdot lb_f)}{\left(\frac{1 rev}{2\pi rad} \right) \left(\frac{60 sec}{1 min} \right) \left(\frac{550 ft \cdot lb_f}{1 sec \cdot bhp} \right)} \times \Delta t_i (sec) \times \left(\frac{1 hr}{3600 sec} \right) \right)$$

Equation 3

To determine raw exhaust brake-specific mass emissions, the concentration of the desired gas constituent ([X]), exhaust gas flow rate (Q), constituent density (ρ), time (Δt), and the work window are all required measurements. Each of the signals of these variables must be time aligned with one another to account for sample delays specific to the particular variable. Equation 4 shows how each of these items is used.

$$bsX \left(\frac{g}{bhp \cdot hr} \right) = \frac{\sum_{i=0}^{i^*} \left\{ \frac{[X](ppm)}{10^6} \times \rho_X \left(\frac{g}{ft^3} \right) \times \dot{Q}_i \left(\frac{ft^3}{sec} \right) \times \Delta t_i (sec) \right\}}{WorkWindow(bhp \cdot hr)}$$

Equation 4

The final important calculation in the work window method is the time duration of the work window. The window duration is calculated by summing the time increment of the data from the beginning point in the data set to the point in the data set where the target amount of work has been accumulated.

$$WindowDuration(min) = \sum_{i=0}^{i^*} \Delta t_i (sec) \times \left(\frac{1 min}{60 sec} \right)$$

Equation 5

Once the work window, the brake-specific mass concentration of an exhaust constituent, and window duration have been calculated for a point in the data set, the process is repeated beginning at the next point in the data set. This method may be thought of as a sliding window approach. The process continues until the amount of work in the “n+1” window is less than the amount of desired work. It should be noted that window duration is not fixed for a given work window.

The work window method that is presented here is similar to the non-road diesel NTE that has been previously presented by the US EPA [24, 25]. In that method, a non-road engine is tested during its normal operation for an entire day. That data is then normalized to a 6 hour day. Similar to the method presented here, a window of work equal to 10% of the total work output during the normalized day is moved throughout the data incrementing every 1% work to determine brake-specific emissions concentrations.

Each method allows for in-use brake-specific emissions of the engine to be determined for a wide-variety of engine operation. However, the tests that were used for this study were conducted in a manner that did not allow for an entire day of in-field engine operation. The authors believe that the work window method that is presented here provides a better method of determining in-use on-road emissions of an engine during a pre-determined test route than the non-road method of the US EPA.

RESULTS

Figure 5 shows bsNOx results based on the work window method compared to NTE bsNOx results for a range of work windows of 1 bhp-hr to 75 bhp-hr (0.74 kW-hr to 56 kW-hr) for a highway test of a 2003 engine of approximately 9 L displacement and 300 hp (224 kW) in a transit bus. The 1 bhp-hr (0.74 kW-hr) work window produces high bsNOx results at various points throughout the test. For small work windows, periods of high engine speed and torque may produce periods of higher bsNOx. As the work window interval grows