Development of a NOx Verification Protocol and Actual Testing of Onboard Idle Reduction Technologies

New Technology Research and Development Program
N-42

Submitted to:
Houston Advanced Research Center

Submitted by:
Texas Transportation Institute

Submitted: August 2011
Revised: January 2012

Texas Transportation Institute
The Texas A&M University System
College Station, Texas

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Recently, many states, cities, and regions in the United States have adopted and started to implement anti-idling regulations for heavy duty vehicles. Long-haul truck fleets have mandated rest periods for drivers, during which the trucks are often kept idling, and are therefore a major source of truck idling emissions. These emissions not only have adverse effects on air quality and human health in surrounding areas, but also affect the truck driver's health due to infiltration of emissions into the truck cabin. Truck idling also results in fuel consumption and greenhouse gas emissions, which can also be reduced through reduction of truck idling.

Consequently, many long-haul truck companies are currently using, or are considering the use of idle reduction technology (IRT) devices, which provide an alternative means of maintaining in-cab air conditioning or heating without the need for idling a truck's main engine. There are many different IRT devices available in the market; however, no standard procedures exist by which the performance of these devices can be verified. In this project, the Texas Transportation Institute (TTI) research team developed a verification protocol, which can be used to evaluate the performance of IRT devices on a standardized basis. The performance of various IRT devices was tested according to this protocol. The results and findings from the IRT device testing are presented in this report.

There are different categories of onboard IRTs available, and the protocol developed in this research focuses on four major types: diesel-powered auxiliary power units (APUs), battery-powered APUs, direct-fired heaters (DFHs), and thermal storage cooling (TSC) units. The test protocol covers examination of the overall performance of IRT devices in terms of their ability to maintain desired cabin temperatures, the emissions of the devices (oxides of nitrogen [NOx], carbon monoxide [CO], carbon dioxide [CO_2], hydrocarbons [HC], particulate matter [PM], and Mobile Source Air Toxics [MSAT]) as well the fuel consumption, or in the case of battery-powered units, the power performance.

The following main tasks were performed for this project.

- Collection of baseline idling emissions and fuel consumption data for selected heavy-duty diesel vehicles (HDDVs).
- Development of an U.S. Environmental Protection Agency (EPA)-approved NOx Emissions Verification Protocol for onboard IRTs for HDDVs.
- Performance of NOx verification testing of selected samples from the four classes of onboard IRTs; in addition to NOx, the research team also collected information on other pollutants, fuel consumption, noise, and/or energy performance, as outlined in the protocol.
- Development of a web-based information system for use by the trucking industry and other stakeholders regarding available IRTs and their NOx emissions reduction and other benefits.

The development of the verification protocol was based on an investigation of relevant literature and resources including national testing standards and recommended practices, consultation with EPA staff, Houston Advanced Research Center (HARC) staff, and discussions with IRT device

manufacturers. The testing of the selected IRT devices was performed based on the developed protocol, and the collected test results were compared with the results from the baseline testing of idling trucks. Below is a summary of the test approach and methodology used for the collection of the baseline truck idling data, and IRTs' performance/emissions data:

- Data collection was performed under two main test conditions: under hot conditions (i.e., when the truck cab requires cooling) and cold conditions (i.e., when the truck cab requires heating). Depending on the characteristics and settings of the IRT devices, hot tests, cold tests, or both were performed, as applicable. Two diesel-powered APUs (diesel APUs) and a Truck Stop Electrification (TSE) unit were tested for both hot and cold test conditions. Two battery-powered APUs (battery APUs) were tested for the hot condition, and two DFHs were tested for the cold condition.
- IRT devices and truck air conditioning system (AC) or heating system (Heat) were set for the same target desired temperature range (73°F ± 5°F) for both hot and cold test conditions.
- Three HDDVs (one model year (MY) 2006 and two MY11 trucks) were used for the collection of baseline truck idling data under both hot and cold conditions.
- The MY06 truck, owned by the TTI (identified as Truck #1), was used for installation and testing of all tested IRT devices. The data collected for this truck under hot and cold testing conditions at a low idle (engine speed of 600 RPM) were used as the baseline for comparison of emissions and fuel consumption data collected from the IRTs, from the other trucks, and for other idle modes.
- Additional truck idling data collection was performed while the trucks were idling for conditions of varying engine speeds (low, medium, and/or high RPM) and AC or Heat modes, including both ventilation off (re-circulation of cabin air, Re-Cir mode) and ventilation on (outside air is conditioned and brought into the cab, Air-In mode).
- For battery APUs and the TSE unit, which do not consume fuel nor produce any direct emissions, only energy consumption data were collected.
- The noise performance was also tested for each IRT device, except for the TSE unit which could not be tested for noise due to the stationary installation being inside the test chamber.
- All tests except noise tests were performed inside TTI's Environmental and Emissions Research Facility (EERF), in which IRT devices and test trucks were placed in a test chamber to maintain a controlled environment in terms of the temperature and relative humidity.

The results of the testing and data analysis indicate that in general, IRT devices showed emissions benefits in terms of NOx as well as other pollutants when compared to truck idling. During the tests, while the idling trucks were able to reach and maintain the desired cabin temperature for both hot and cold test conditions, diesel APUs could do so only under hot conditions, and the TSE unit was unable to do so for both hot and cold conditions. Battery APUs and DFHs tested for only hot conditions and cold conditions, respectively, were unable to maintain a desired cabin temperature as well.

The IRT devices (except for the TSE unit) were tested for noise, and the observed noise levels were all below 70 db. In addition, infiltration testing (to determine emissions intrusion into cab) was performed for a single IRT device (a diesel APU) and for the TTI truck (Truck #1). Computational fluid dynamics (CFD) was used to simulate the pollutant distributions in the EERF and inside the cabin of the truck. It was found that the pollutant concentrations inside the cabin increased (i.e., the cabin infiltration occurred) faster for the truck engine idling than for when the APU is used.

This research project developed a verification protocol for the comprehensive evaluation of the performance of IRT devices from both a user perspective and in terms of the environmental benefits such as emissions reduction and fuel consumption reduction. No such protocol currently exists, and this allows for testing of IRT device performance on a common basis, under controlled conditions. The results from the testing of IRT devices, and comparison with data collected from idling trucks, provides an overview of the relative emissions and fuel benefits, and the performance of these devices in terms of various parameters including noise, cabin infiltration, and the ability to reach and maintain desired temperatures. The results of this research will be very useful as the use of IRT devices continues to increase among long-haul truck fleets.

Introduction

Background

The economy of the U.S. is strongly reliant on HDDVs to move a vast array of goods across the country. Currently there are close to 3 million heavy-duty trucks operating in the United States (*1*). The U.S. Department of Transportation (DOT) mandates that truck drivers rest 10 hours for every 14 hours of driving (*2*). This results in extended periods of time that drivers spend resting and sleeping in the cabs of their trucks. As a consequence, almost all long-haul truck drivers idle their vehicles for close to 10 hours per day to operate heating systems and air conditioners, generate electricity, charge their vehicle's batteries, and warm up the engines (*3,4,5*).

A typical long-haul truck is on the road for an estimated 250 to 300 days per year, resulting in an average annual idling duration of 2,100 hours per truck (*6,7,8*). At an idling emissions rate of approximately 135 grams of NOx per hour, it is estimated that more than 2,000 tons of NOx is emitted every day in the U.S. due to extended idling. In addition to emissions, extended idling also results in a considerable waste of fuel and can cause wear on the truck engines. At an idling fuel consumption rate of one gallon per hour, it can be shown that more than 13 million gallons of fuel are wasted on a daily basis nationwide due to extended idling (*1*).

Texas is a very important state with regard to goods movement using trucks. There are 184,000 HDDVs registered in the state of Texas. Of this group, 32,000 are Class 8 trucks with a weight in excess of 33,000 lb. These trucks are typically long-haul vehicles with sleeper cabs. A TTI study found that the vehicle miles traveled (VMT) by heavy-duty trucks in Texas far exceeds what can be produced by the number of Texas-registered trucks. This indicates that there is considerable truck traffic in Texas from out-of-state and out-of-country locations. Specifically, HDDVs account for approximately 11 percent of all VMT on Texas roadways.

Based on the Texas Department of Transportation's (TxDOT) 2006 Highway Performance Monitoring System (HPMS) traffic data, the 35 nonattainment (NA) and early action compact (EAC) counties account for 70 percent of the VMT in Texas. In addition, the largest of the HDDVs, those weighing in excess of 60,000 lb gross vehicle weight rating (GVWR), account for 70 percent of all HDDV VMT (*9*).

The total number of HDDVs idling in Texas was estimated at 230,000, resulting in over 150 tons of NOx and more than 1.1 million gallons of fuel wasted daily due to extended idling (*1*). The daily numbers for the 35 counties in Texas that have air quality challenges (NA, near-nonattainment [NNA]/EAC areas) are estimated at 105 tons of NOx emitted and 700,000 gallons of fuel wasted per day due to extended idling and proportioned based on VMT numbers.

TTI performed a study for TxDOT examining extended idling emissions at truck stops as a proportion of the total Class 8b emissions (*10*). Table 1 shows that for the major ozone nonattainment areas in Texas, this percentage is close to 3 percent in 2005 and it more than doubles in 2012. This shows that the proportion of extended idling is gaining considerable importance as part of the total mobile source emissions inventory and that implementing any type of measures to reduce these emissions would be a significant contribution.

Table 1: Proportion of Extended Idling Emissions of Mobile Source Emissions

Nonattainment Area	2005 Proportion	2012 Proportion
Dallas-Fort Worth	2.0%	4.4%
Houston-Galveston	3.0%	7.7%
Beaumont-Port Arthur	3.2%	7.3%

Several methods have been developed to reduce extended truck idling. These methods can be divided into stationary and mobile technologies (*11*). The former refers to stationary equipment that can connect/disconnect from the truck when in use, and the latter refers to equipment that is installed onboard the truck. Both these types of equipment reduce the need for extended idling. The focus of this research is on onboard technologies which are mobile, so that they are location-independent, relatively low fixed capital cost (less than $10,000), and their low fuel consumption rates makes their rate of return very attractive (usually less than 2 years). These technologies can be divided into the following categories.

- *Diesel-Powered Auxiliary Power Units (Diesel APUs)*: A diesel APU is comprised of a small diesel generator, and an auxiliary air conditioning system (AC) and heating system (Heat). Diesel APUs may also provide power for in-cab appliances, the truck's main battery charging, and engine block heaters.
- *Battery-Powered APUs (Battery APUs)*: Similar to diesel APUs, but instead of a generator, a battery pack provides the power. The battery pack is charged during normal truck operation taking the electricity from truck's electrical circuit.
- *Direct-Fired Heaters*: These systems can be used to heat up both the sleeper cabin and the engine. DFHs do not provide air conditioning, power for appliances, or charging the truck's batteries.
- *Thermal Storage Cooling Units*: A TSC unit consists of a phase-change material that stores cooling energy transferred from the vehicle air conditioning system while the vehicle is operating. TSCs can only provide cooling to the sleeper compartment. A small amount of electrical power is required to operate the fans.
- *Fuel Cell (FC) Units:* A FC unit produces electricity by oxidizing a fuel. A FC unit works by using a catalytic conversion (oxidation) of a fuel, in this case diesel fuel of the truck, using the electrolyte material in a fuel cell to produce electricity (*12*). The produced electricity, then, is used to power an AC or a Heat.

It is estimated that approximately 10 percent of trucks in the U.S. have APUs (*13*). Because the government does not regulate onboard IRTs, there is very limited information on the emissions and energy performance of current commercially available onboard IRTs.

Project Need

Long duration idling is not included in current emissions inventory calculations. Guidance from the EPA shows that the maximum allowable credit for reductions from long-duration truck idling emissions is 3.4 percent of the total annual average daily Class 8 truck emissions (*14*). As shown in Table 1, the 3.4 percent can easily be exceeded at truck stops alone and that the exceedences will continue to accelerate into the future. EPA's new generation emissions factor model—Motor Vehicle Emission Simulator (MOVES)—incorporates long-duration idling into its modeling procedures (*15*). However, to obtain State Implementation Plan (SIP) credits for IRTs in MOVES, the air quality agency must base its claims and assumptions on robust methodologies and protocols. Such protocols do not currently exist. This study provides a verification protocol along with robust emissions factors for the most important onboard IRTs. It paves the way for nonattainment areas to obtain credit beyond the current 3.4 percent cap and to have the relevant information and protocols to be used in conjunction with MOVES to obtain appropriate credit for onboard IRTs.

Approximately 30 states in the US currently have anti-idling legislation implemented, when defined as states in which at least one city or county has its own active idling regulation(s) (*16*). In Texas, there is a seasonal 5-minute idling rule for some areas (*1*). Anti-idling rules such as the seasonal 5-minute idling rule will necessitate the broad use of onboard IRTs. The rules will also place a large emphasis on understanding idling emissions, fuel consumption and other performance criteria of IRTs compared to those of trucks. The trucking industry realizes that it must adopt alternatives to idling to avoid anti-idling law fines as well as to reduce fuel costs while maintaining the comfort and well-being of its employees.

The U.S. EPA, state DOTs, and air quality agencies frequently receive inquiries from the trucking industry seeking objective, unbiased information about IRTs. Today, there are over 40 technologies to choose from, with more options constantly becoming available. However, there is a lack of basic understanding and knowledge of how these technologies perform,. Some sectors of the trucking industry are reluctant to adopt these alternatives due to the lack of basic information and objective data on the performance of IRT devices. The data collected during this study address this issue by testing the various IRTs under highly-controlled and repeatable conditions.

This study focuses on the development and application of a test protocol for NOx emissions. However, at the same time other pollutants such as PM, HC, CO, and CO_2 will also be assessed along with fuel consumption and other relevant performance criteria such as noise and energy usage. These data will not only assist the trucking industry with selecting the appropriate devices, but they will assist air quality agencies in supporting those technologies and potentially obtaining emissions credits for their implementation.

Project Approach

Overall Approach

This project developed a NOx verification protocol for testing IRT devices. In addition, the developed protocol, while focused on NOx emissions, measures other pollutant emissions such as CO, HC, PM, and CO_2, as well as fuel consumption. Also, other parameters such as noise, energy, and overall performance of the devices were added in the protocol.

In order to accomplish the goal of the project, the TTI research team collected and examined existing information on IRT performance and the testing procedures. Additionally, the team investigated current standards that could be related to the testing procedures of emissions and performance of IRT devices. After collecting all the relevant information, the research team developed a testing protocol that covered all the necessary aspects for testing of IRT devices. The development of the protocol also involved multiple consultations with EPA staff and with the manufacturers of IRT devices. Once the protocol had been developed, the team tested multiple devices in order to verify the protocol while also gathering important information on the performance of the various IRT devices.

This research project was divided into four main tasks: Development of an Understanding of HDDV Idling Emissions, Development of a Verification Protocol for Onboard Idle Reduction Technologies, Performance of NOx Verification Testing of Selected Onboard Idle Reduction Technologies, and Development of a Web-Based Information System. Each task is described below.

Task 1 Development of an Understanding of HDDV Idling Emissions

This task involved the examination of previous studies related to emissions of HDDV during idling and of IRT devices. With the collected information, the research team was able to better understand not only the idling emissions of HDDVs, but also emissions of alternative options (IRTs), and to identify gaps in knowledge and areas for further investigation necessary for developing the protocol.

Task 2 Development of a Verification Protocol for Onboard Idle Reduction Technologies

This task involved the development of the actual testing protocol. In addition to the information collected and examined during the Task 1, the research team also investigated relevant testing procedures, standards, recommended practices, and any documents that contained relevant information for testing of IRT devices. The other elements involved in the testing, such as testing equipment specifications, were also examined. This task also included consultation with EPA and HARC staff and IRT manufacturers.

Task 3 Performance of NOx Verification Testing of Selected Onboard Idle Reduction Technologies

In this task, actual testing of selected IRT devices was performed as per the developed protocol. After developing the protocol in Task 2, the research team, with consultation with EPA staff, selected IRT devices for actual testing. Each selected device was transported to the TTI's EERF in Bryan, Texas. The testing was conducted under controlled environmental conditions (temperature and/or relative humidity). The selected IRT devices were installed on a HDDV truck owned by TTI and tested following the developed testing protocol. Each device was then removed from the truck after being tested so that the next device could be tested in the same manner. Also, testing of the truck and two additional trucks was performed for comparison purposes.

Task 4 Development of a Web-Based Information System

This task involved the development of a web-based information system to enable a wide range of stakeholders to access the information collected from the testing of the IRT devices. This website, located on a TTI-hosted server, will include all relevant information on the devices that are tested under the protocol at the EERF, including emissions, fuel consumption, and ability to maintain desired cab temperature. The website will be located at http://ttiairquality.tamu.edu/eerftesting/. All results of any future testing conducted under the testing protocol can also be added to the system.

Facilities and Equipment

The following section describes the equipment used for the testing of the IRT devices and trucks.

Test Chamber

TTI's Environmental and Emissions Research Facility is located at Texas A&M University's Riverside Campus in Bryan, Texas. The EERF includes an environmentally controlled test chamber with dimensions of 75 ft long × 23 ft wide × 22 ft high. The chamber can control both temperature and humidity. It also has a solar lighting array to simulate solar loading and fans to simulate wind chill effects. The chamber can control temperatures from −40°C to 55°C for the purposes of testing IRT devices. These features are key components of the IRT verification protocol. Figure 1 shows a picture of the test chamber.

Figure 1: TTI's EERF Test Chamber

SEMTECH-DS

The SEMTECH-DS is a portable emissions measurement system (PEMS), which complies with EPA's Code of Federal Regulations (CFR) Title 40 Part 1065 (so-called, 40 CFR 1065) emissions testing and is used for emissions testing of the IRT devices and the trucks. It consists of a set of gas analyzers to measure gaseous emissions of NOx (both nitrogen oxide [NO] and nitrogen dioxide [NO_2]), HC, CO, CO_2, and oxygen (O_2) in the exhaust. The SEMTECH-DS is used in conjunction with the SEMTECH electronic flow meter (EFM), which measures the vehicle exhaust flow rate. This allows for the calculation of exhaust mass emissions from all measured gasses. Figure 2 shows the SEMTECH-DS and flow meter installed on a truck during testing.

Figure 2: SEMTECH-DS and EFM

Dekati Mass Monitor

The DMM 230-A (DMM) is a real time PM measuring instrument for vehicular emissions testing. The DMM provides second-by-second analysis of the PM concentrations from the vehicle exhaust, providing both total PM mass measurements and particle mass size distribution of the particles up to 1.5µm in 6 size bins. The DMM is used in conjunction with TTI's microdilution system to measure the diluted exhaust directly from the IRT devices being testing. Figure 3 shows the DMM.

Figure 3: Dekati Mass Monitor

Microdilution Sampling System

TTI uses its microdilution sampling system (MSS), a sampling system using a partial-flow-dilution (PFD) as stated in 40 CFR 1065 to sample MSAT cartridges as well as to provide exhaust samples to the DMM. The exhaust is transferred through a heated line to the MSS from a probe in the outlet of the SEMTECH EFM. The MSS uses two Dekati diluters and a Dekati air heater to dilute the raw sample from the exhaust sample. Figure 4 shows this system.

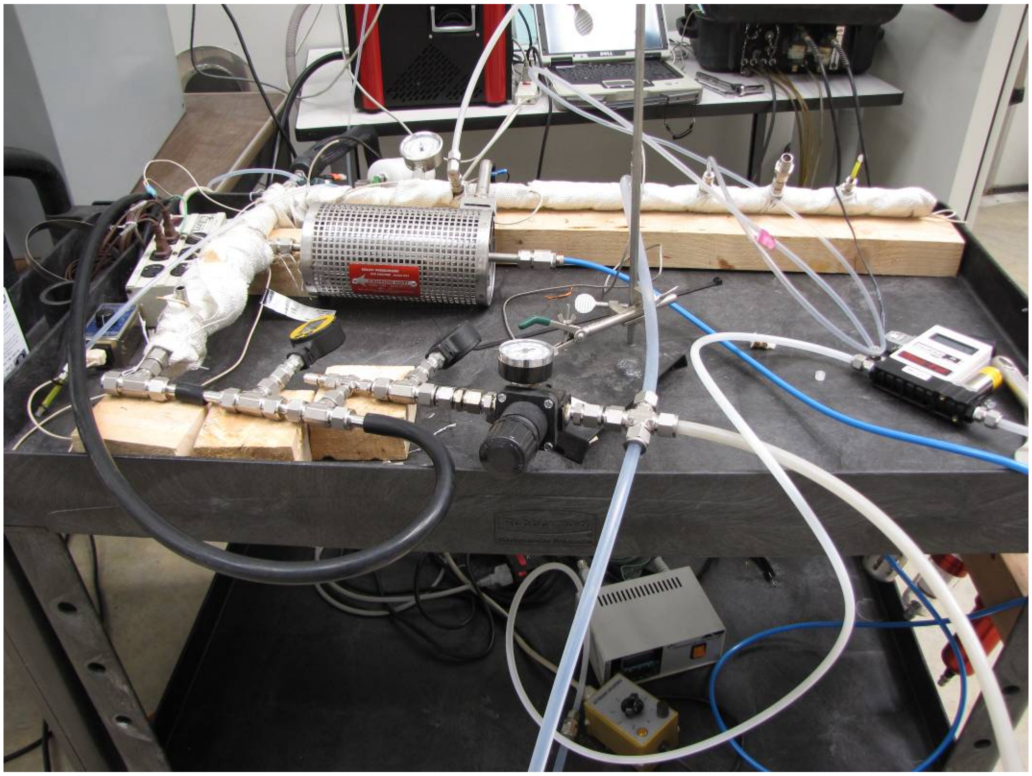


Figure 4: Microdilution Sampling System

Ambient Air Monitors

For the infiltration testing, TTI's ambient air monitoring instruments, a Model 42i gas analyzer and Model 48i manufactured by Thermo Scientific Inc., are used for measuring NOx and CO concentrations. The 42i analyzer measures NOx concentrations by using chemiluminescence technology and provides outputs for NO, NO_2, and NOx. The concentrations are recorded and reported in parts per billion (ppb) or milligrams per cubic meter (mg/m^3). The lowest detectable limit at a 60-second averaging time is 0.40 ppb, while the highest is 100 parts per million (ppm). The 48i analyzer measures CO concentrations using gas filter correlation technique. The 48i analyzer can measure concentrations up to 10,000 ppm. Figure 5 shows the 42i analyzer. The 48i analyzer has the same outside design with different analyzers inside used for measuring CO instead of NOx.

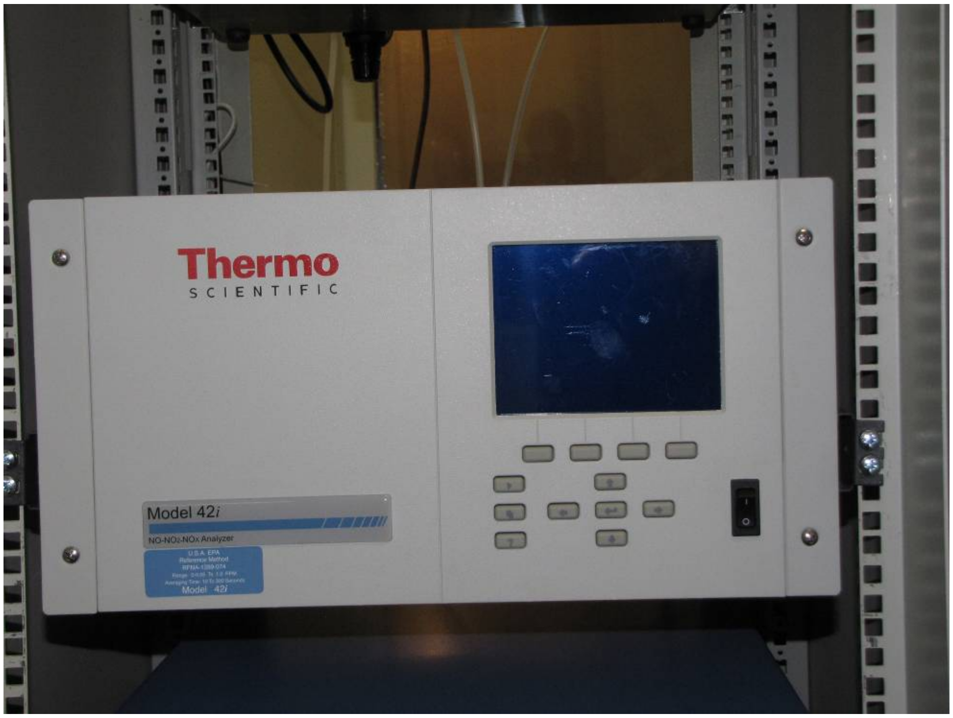


Figure 5: Thermo Scientific 42i Analyzer

State of the Practice Assessment

Truck Idling

Many studies have examined the emissions, fuel consumption, emissions infiltration, and AC and/or Heat performance of HDDV trucks while idling. Results from these studies show that HDDV idling data are significantly different depending on testing conditions. These conditions include engine speed, temperature setting, engine size, model year, fuel type, and fuel injector type. It was found that engine speed (expressed in revolutions per minute, RPM) is a major contributing factor in the variability of idling emissions. According to surveys, it was found that although 600–700 RPM was normally set as the factory default idle speed, the average idling engine speed during extended idling was 870 RPM, because the higher engine speed reduces engine vibration and engine noise and increases power for AC and electric accessories (*17*).

In 2003, another study measured five class-8 trucks under different temperatures and engine speeds (*18*). These tests were conducted inside the climate controlled chamber located at the U.S. Army's Aberdeen Test Center near Washington, D.C. The tests were conducted at high idle (1100–1200 RPM) and low idle (600–700 RPM) and at three different temperature settings. The test conditions were:

- 32°C (90°F) with the AC activated.
- −18°C (0°F) with the Heat activated.
- 18°C (65°F) with no accessories activated.

The study concluded that trucks emitted more and consumed more fuel at the higher RPM conditions. This is an important finding because, as the survey by Lutsey et al. (*17*) concluded, truckers often set idle speeds higher than a factory default to help maintain their cabs' comfort and to power accessories. The study also found that CO_2 and NOx emissions increased as the test temperature increased, while CO, HC, and PM (under 2.5 µm in size) all decreased as the temperature rose.

In a 2005 study by TTI titled *Mexican Truck Idling Emissions at the El Paso – Cuidad Juarez Border Location* (*19*), truck idling emissions were measured at the U.S.-Mexico border area. In this study, trucks were tested under different scenarios, including AC activated (AC On) and AC not activated (AC Off), and high and low RPM idling conditions. The study found that in most instances, emissions increased with higher RPMs, except for total hydrocarbon (THC) emissions. Emissions of all pollutants, with the exception of NOx, were also higher when the AC was not running, as compared to when it was on.

Lambert et al. (*20*) studied truck idling emissions in different AC modes and RPM conditions in Knoxville, TN. Each truck completed a highway pre-conditioning run to ensure that the engine and exhaust had reached operating temperature prior to testing. For all measured emissions, CO, CO_2, NOx, and THC, the values were higher as RPM increased. The study also found that the test with the AC On produced more emissions compared to the tests where the AC was not running during idling.

In a 2009 study by Gaines and Hartman (*21*), two trucks were tested with different fuel types. A 2001 truck was tested with conventional diesel fuel, containing 500 ppm sulfur. The other, a 2007 truck, was tested with ultra low sulfur diesel (ULSD) fuel, containing 15 ppm sulfur. These trucks were tested for both heating and cooling conditions. For the heating conditions, heat was provided to cabs of the trucks. For the cooling conditions, air conditioning was provided to the cabs. (No specific information on the ambient or target cabin temperature was given.) The study found that cooling conditions showed higher fuel consumption than heating tests. Between the two trucks, the newer truck with ULSD used less fuel than the older truck with conventional diesel. The older truck also produced more NOx and PM (under 10 µm in size) emissions for both the heating and cooling conditions.

Lim (*22*) presented idling emissions data with nine HDDV under various RPM and temperature conditions: high/low RPM and 0°F (Heat On), 65°F (No Load), and 90°F (AC On). For the emissions measurements, the Real-time On-road Vehicle Emissions Reporter (ROVER) developed by EPA was used. ROVER measures emissions with the engine operating and vehicle speed data from a global positioning system (GPS). The trucks emitted more NOx and CO_2 and consumed more fuel under high RPM and accessory loading than low RPM and no accessory conditions.

A 2007 study by Zietsman et al. (*23*) looked at different emissions rates of Mexican-Domiciled trucks (trucks based out of Mexico) using various alternative fuels, both during idling as well as in-use. The study looked at three separate fuels: ULSD, a 20 percent biodiesel blended fuel (B20), and a diesel fuel sourced from PEMEX, Mexico's state-owned oil company. The PEMEX diesel fuel was a regular diesel with containing a maximum of 500 ppm sulfur. The study looked at 10 trucks using two testing conditions, low idle (600–700 RPM) and high idle (approximately 1200 RPM). The study's results showed that B20 and PEMEX fuels decreased the NOx, HC, and CO emissions. The fuel types did not have any effect on the CO_2 emissions, although since 20 percent of the B20 fuel came from a renewable resource it could be considered to be an emissions benefit.

The emissions can be affected by other factors in addition to RPM, AC load, and fuel type. A study conducted by Khan et al. (*24*) found that the fuel injection type can also affect emissions. An HDDV with an Electronic Fuel Injection (EFI) system emitted less CO, HC, and PM under idling conditions than a Mechanical Fuel Injection (MFI) system. However, the NOx emissions rates were higher for EFI systems when compared to MFI systems.

IRT Devices

When compared to research on truck idling, fewer studies have examined the performance of IRT devices. Lee et al. (*25*) tested a diesel-powered APU installed on a HDDV class 8b truck. They tested the emissions and fuel consumption under two conditions: HDDV idling with 600 RPM with almost no additional load condition, and APUs with full load (AC or Heat set at maximum speed) condition with the truck off. It was found that CO, NOx, THC, and PM emissions were all much lower for the APU as compared to the truck idling scenario. However the fuel consumption and CO_2 emissions were higher during APU operations.

Lim (*22*) measured the idling emissions from a diesel-powered APU (2000 Pony Pack) and a DFH (Model D1LC) and compared their NOx and CO_2 emissions with those from several trucks while idling. Both the APU and the DFH significantly reduced the emissions and fuel consumption. Furthermore, the degree of the reduction was greater for the DFH than the APU for heating. APU emissions during the heating operation were lower than those for cooling.

A Department of Energy (DOE) report (*26*) showed test results of different IRTs. One APU, manufactured by MorElectric, reduced the overall idling time of the truck by 13.8 percent and improved the fuel consumption of the truck by 0.33 MPG when compared to trucks without the APU installed. The study also tested a Webasto Airtop 200 DFH and found that it reduced idle time by 17 percent and improved fuel economy by 0.126 MPG (*26*).

What is clear from the past studies is that there is no comprehensive data on how different IRT devices will perform when tested and compared on the same test vehicle under repeatable conditions. The development of the NOx verification protocol, and testing performed according to it, will help to identify the true benefit that is gained from the different IRT devices.

Development of a Verification Protocol for On-Board Idle Reduction Technologies

This task developed an EPA-approved verification test protocol for onboard IRT comprising of diesel APUs, battery APUs, direct-fired heaters, and thermal storage cooling units. Once approved and implemented the protocol would allow for the performance of the IRT devices to be tested using standardized methods that are repeatable for current and future devices. This will allow all interested parties, including the EPA, trucking industry, and others to gather unbiased information on the performance of such devices.

Protocol Development

The proposed verification protocol for onboard IRT addresses four key elements of these technologies—emissions, fuel consumption, noise, and energy performance. The draft protocol developed as part of this study is based on national testing standards/recommended practices such as Society of Automotive Engineers (SAE), Technology and Maintenance Council (TMC), and CFR. Table 2 shows some specific testing standards that were consulted to develop the draft testing protocol.

Table 2: Standards Consulted in Development if Verification Protocol

Measure	Standard Consulted
Emissions	CFR-40, 1065
Noise	SAE J336
	SAE J1096
Fuel Consumption	SAE J1321
Energy Performance	TMC RP 432
	SAE J1503

In addition to the standards industry partners, the EPA, and HARC were consulted as part of the development process. The testing phase was used to ensure that the protocol was practical and was the best way to test the devices. The testing phase led to numerous changes that were incorporated into the final draft version of the protocol (see Appendix A). The protocol contains the following nine sections.

Section 1: Introduction

This section details the scope of the protocol and includes important descriptions and definitions that are used throughout the protocol. It also describes the forms that must be filled out, by both the testing applicant and testing organization, for each test that is conducted.

Section 2: Measurement Instruments and Equipment

This section describes the requirements for the instruments and equipment that are used to collect data during testing. This includes emissions, fuel consumption, noise, energy, and wind measurements.

Section 3: Test Application

This section deals with the application process that an IRT manufacturer must complete prior to participating in the verification testing.

Section 4: Test Preparations
This section details the preparations that the applicant must go through prior to testing. It also highlights the preparations of the IRT device that must occur prior to testing. It also describes the requirements of the testing facility.

Section 5: General Testing Configurations
This section discusses setup requirements for each test. It covers aspects such as fuel and engine fluids required for a test, installation of the IRT device on the test vehicle, service loading during a test, environmental testing conditions, how to measure the temperature inside the cab, number of tests, duration of tests, and how the cabin of the test vehicle is to be tested.

Section 6: Fuel Consumption Measurement
This section focuses on the measurement of the fuel consumption. This measurement is not required for the battery APUs or TSC units because they do not consume fuel during their operations.

Section 7: Emissions Measurement
This section details the steps needed to perform the emissions measurements during testing. Like the fuel consumption measurements, this section is not required for those IRT devices that do not consume fuel.

Section 8: Noise Measurement
This section details the noise measurement test. This test, unlike the other measurement categories, must be carried out separately from the other tests. The noise test cannot be conducted inside a test chamber because noise can reflect off the walls of the chamber and be picked up by the monitoring device. The protocol discusses the requirements for a location to conduct the noise measurements.

Section 9: Energy Performance Measurement
The final section of the protocol deals with the energy performance of the IRT devices. Any device that connects to the truck battery, even those that run off of diesel or other fuel, must have this section of testing conducted. This ensures that any amount of power drawn from the truck battery is captured during the test.

Updates to the Verification Protocol

The initial version of the protocol, after being discussed with various parties including the EPA and vendors of IRT devices, was used to conduct the testing of the selected IRT devices. After the testing was completed the project team made some minor modifications to the protocol. In order to properly complete the testing it was found that a few items in the protocol needed to be changed slightly to ensure that all devices were properly tested. The changes were prompted by the different features of the devices, many of which were unexpected during the initial protocol development. All the changes have been implemented into the final version of the protocol attached in Appendix A.

Testing Methodology

This section describes test methodology used for the test actual testing of IRT devices and trucks.

IRT Testing

For the IRT testing, emissions, fuel consumption, noise levels, and AC and/or Heat performance data of selected IRT devices were collected under the test conditions shown in Table 3. Each type of data collection is briefly summarized here:

- *Emissions*: The gaseous tailpipe emissions (NOx, CO, CO_2, and THC) were measured using the SEMTECH-DS, PM emissions were measured using the DMM. In addition, MSAT samples were taken to measure key air toxics, formaldehyde (CH_2O) and acetaldehyde (CH_3CHO).
- *Fuel consumption*: The fuel consumption was measured using the carbon balance method embedded in the software of the SEMTECH-DS.
- *Performance:* The performance of the AC or Heat for each of the test scenarios was measured as the profile of the truck cabin's temperature during the test.
- *Noise:* The noise was measured inside the cab using a sound meter (SoundPro DL manufactured by Quest Technologies) during a separate test procedure that replicates conditions used to acquire the other data.

As shown in Table 3, IRT devices were tested either under the hot condition only, cold condition only, or both hot and cold conditions depending on the operational nature of the devices. Then, the collected data were analyzed to characterize the emissions, fuel consumption, and performance of the AC or Heat for the IRT devices being tested.

Table 3: IRT Device Test Condition

IRT Type	Test Condition	
	Hot Condition	**Cold Condition**
Diesel APU	37.8°C (100°F)	−17.8°C (0 °F)
Battery APU	37.8°C (100°F)	Test not applicable
DFH	Test not applicable	−17.8°C (0 °F)
TSE	37.8°C (100°F)	−17.8°C (0 °F)

The temperature conditions were set after discussion with EPA staff based on the national testing standards/recommended practices mentioned in the previous section. However, these conditions need to be reinvestigated because some IRTs could not operate properly for these conditions as discussed in Test Result section.

The testing procedure began with the selection of IRT devices for the testing. During the protocol development task, numerous IRT manufacturers were contacted to participate in the development of the protocol as well as the testing. Interested companies were asked to submit a voluntary statement of intent to participate. These technologies were presented to EPA staff as possible candidates for testing. EPA staff randomly selected IRTs from the different categories to be tested, among the pool of submissions received. The following IRT categories were selected to participate in the testing process.

- Two Diesel Powered APUs.
- Two Battery Powered APUs.
- Two Direct Fired Heaters.
- One TSE Device.

Once the IRT device vendors were selected, they were contacted by TTI and scheduled for testing. Each IRT device test lasted approximately one week, from installation on the test truck to removal of the unit. The test week began with the installation of the device on the truck during Day 1. Each manufacturer that was selected to participate in the testing was invited to visit the facility during the week of testing. Each manufacturer was also requested to install its device on the test vehicle. This ensured that each device was installed correctly to the manufacturer's specifications. Since no installation was required for the TSE device, the vendor for that technology did not conduct a site visit.

After the installation, the device was checked to ensure that it was working properly prior to performing the test. Each device would then be tested on Days 2 through 4 of its testing cycle. After the device had completed its testing cycle, it was removed from the test truck. The installation of the IRT devices was performed in a manner that resulted in minimal damage to the test trucks when the devices were removed. Therefore, in some cases, minor modifications to standard installation practices were required; for example, using straps instead of bolts to secure the device. However, no changes to the installation were made that would affect device operation and performance, and all such installation was performed with the manufacturer's approval.

After installation of the IRT device, the test truck was place inside the EERF and fitted with a SEMTECH EFM though which emissions samples were withdrawn to the test instruments described previously. Figure 6 shows a picture of the equipment setup for a test on an APU. The sample of the exhaust was passed, via heated lines, outside the chamber through a port in the side of the chamber. This allowed for the testing equipment to remain outside the test chamber during the harsh testing conditions.

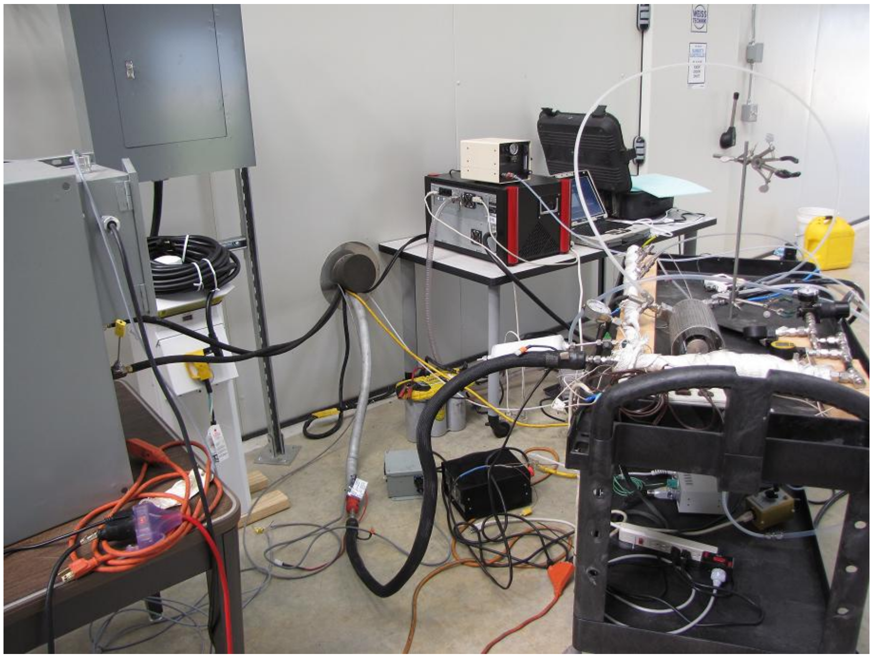


Figure 6: Testing Equipment Set Up for Test

Once the device and all the testing equipment were installed, the IRT was tested following the procedures in the developed testing protocol. After the testing was completed the IRT devices were removed from the truck. Information on the APU engines is shown below.

- APU 1.
    - 2 Cylinder Engine.
    - Displacement: 0.507 liters.
- APU 2.
    - 3 Cylinder Engine.

Truck Idling Testing

In addition to testing of the IRT devices, three trucks were also selected for testing for comparison of IRT operations versus truck idling. These trucks include a MY06 truck, a MY11 truck with a selective catalytic reduction (SCR) system, and a MY11 truck with an advanced exhaust gas recirculation (EGR) instead of an SCR system. The following is a detailed description of the selected trucks:

- Truck 1 (TTI 06): This is a MY06 truck owned by TTI. In addition to being used for baseline testing, it was also used to test the selected IRTs (all the IRTs were installed on this truck).
    - 2006 Freightliner.
    - Model: Columbia CL120.
    - Engine: Cat C15.
    - Rated power: 475 HP.
    - Displacement: 15 L.
    - Emissions control devices: none. Engine is compliant with 2004 EPA standards for on-road HD engines.
- Truck 2 (MY11 #1): This is a MY11 truck with an SCR system for NOx control.
    - 2011 Kenworth.

  - Model: W900.
  - Engine: Cummins ISX15 500.
  - Rated power: 500 HP.
  - Displacement: 15 L.
  - Emissions Control Device(s): EGR, SCR, and diesel particulate filter (DPF). Engine is compliant with 2010 EPA PM standards and 0.30 g/bhp-hr for NOx
- Truck 3 (MY11 #2): This is a MY11 truck with an advanced EGR system for NOx control.
  - 2011 International.
  - Model: GDT 430B.
  - Engine: Navistar Maxxforce.
  - Rated power: 430 HP.
  - Displacement: 12.4 L.
  - Emissions Control Device: advance EGR and DPF. Engine is compliant with 2010 EPA PM standards and 0.50 g/bhp-hr for NOx.

For truck testing, idling emissions, fuel consumption, and AC performance, data collection from each of the selected trucks was conducted in the same manner as that described in the previous section. The test trucks were tested under different temperatures, ventilation modes, and idle speed conditions (low speed idle at the engine speed of 600 RPM, medium speed idle at 900 RPM, and high speed idle at 1200 RPM with regard to AC and Heat. Not all the possible idling speeds, temperatures, and load combinations are applicable to actual use, and Table 4 shows a summary of the testing combinations used. The collected data were then analyzed to characterize the emissions, fuel consumption, and performance of the AC or Heat for the truck being tested.

Table 4: Truck Testing Combinations

Chamber Set Point (°C)	Idle Speed	Load Type*
−17.8 (0°F)	low	Heat/Re-Cir mode
−17.8 (0°F)	low	Heat/Air-In mode
−17.8 (0°F)	med	Heat/Re-Cir mode
−17.8 (0°F)	high	Heat/Re-Cir mode
−17.8 (0°F)	low	None
37.8 (100°F)	low	AC/Re-Cir mode
37.8 (100°F)	low	AC/Air-In mode
37.8 (100°F)	med	AC/Re-Cir mode
37.8 (100°F)	high	AC/Re-Cir mode
37.8 (100°F)	low	None
22.8 (73°F)	low	None
22.8 (73°F)	med	None
22.8 (73°F)	high	None

** **Load type definitions - Heat:** truck's heating system used; **AC:** truck's air conditioning system used; **Re-Cir:** ventilation off (cabin air is on re-circulation; **Air-In:** ventilation on (outside air is brought into the cabin).*

Infiltration Testing

Using CFD modeling tool, the TTI research team characterized the pollutant dispersion and infiltration. For the infiltration tests, time-dependent temperature and pollutant emission data were recorded. Pollutant concentration inside the cabin was also measured to assess the infiltration of the pollutant species. Then, CFD tools were used to simulate the steady-state flow field and transient dispersion of gas-phase pollutants in two test conditions: one for Truck #1 and the other for a diesel APU. CFD modeling approach, first applied as a supplement of the experimental study, has been used to save money and time in research and has proven to be a useful tool. Typically, a CFD simulation needs to be validated with experimental data for locations where physical measurements are available (*27*). Then the simulation can be used for analyzing the vector and scalar fields in the entire simulated space. In recent years, CFD modeling has been widely used to analyze and predict flow field (*28, 29, 30*), temperature distribution (*31*, *32*), and mass transfer including pollutant dispersion (*33, 34 35*, *36, 37*, *38*). Yang (*36*) used CFD simulation to predict contaminant dispersion in a climate chamber when flow field was kept unchanged. Detailed test methodology is provided in the following sections.

Test Conditions

Two different test conditions were simulated with CFD in this study, an APU test condition and Truck #1 engine idle (TRUCK) test condition, as shown in Table 5. For the APU test, only the APU was operating, and air circulation in the cabin was driven by the APU. In the TRUCK test, the truck engine was idling, and air circulation in the cabin was driven by the AC of truck #1. For the TRUCK test, the exhaust from truck #1 was transported out of the EERF through a duct, so that only emissions from the engine block were released into the chamber. During the TRUCK test, the engine cooling air entered the engine compartment from the front of the truck, and flowed downward underneath the engine carrying the pollutants emitted from the engine block (crankcase emissions). In either test conditions, the fans attached to the chamber ceiling shown in Figure 7 circulated the air inside the EERF, assisting dispersion of the pollutants.

Table 5: Status of Major Devices in APU or TRUCK Test Conditions

Operation Condition	APU Test	TRUCK Test
Fans (chamber fans)	On	On
APU	On	Off
Truck Engine	Off	On
Truck AC	Off	On

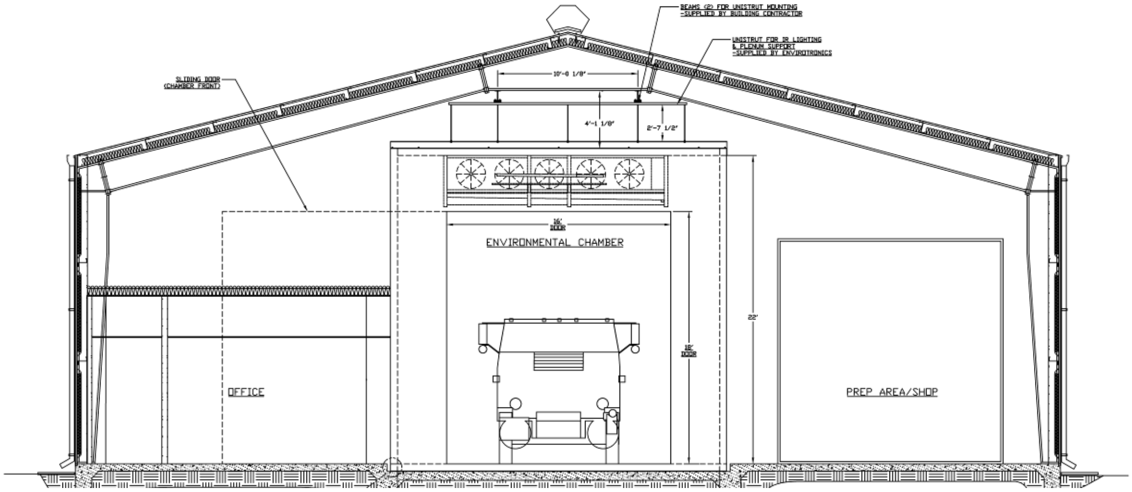


Figure 7: TTI Environmental Chamber (Middle Section Looking West)

Configurations of the EERF, Truck, and Truck Cabin

Figure 7 shows a cross-sectional view of the EERF. Inside the EERF, five identical fans (each with a diameter of 0.76 m), was attached to the ceiling to provide air circulation inside the environmental chamber. The total air flow provided by the fans was 11.66 m^3/s towards the east of the chamber. One solar light assembly was located on west of the fans. Two exits were located on the north wall of the chamber to be used as the air outlet for the pollutants emitted. A pressure-actuated vent was located on the ceiling to ensure the chamber pressure would not reach a dangerously high level.

Truck #1 was placed inside the environmental chamber for the infiltration test as shown in Figure 8. The external dimensions of the cabin were 5.18 m × 2.43 m × 4.11 m (length × width × height). The cabin was divided into two parts: the driving section and the sleeper section, with the internal dimensions of 1.22 m × 2.06 m × 2.13 m and 1.52 m × 2.18 m × 2.13 m (length × width × height), respectively. For the APU test, the cooling air was coming from four inlets (each with a diameter of 0.05 m) on the lateral walls of the cabin and the vent was located on the back wall of the sleeper cab as shown in Figure 9. For the TRUCK test, the AC of the truck was on, and six air flow inlets were located on the cabin walls as shown in Figure 9; five on the front wall (driving panel), and one on the wall just above the sleeping bed in the rear part of cab).

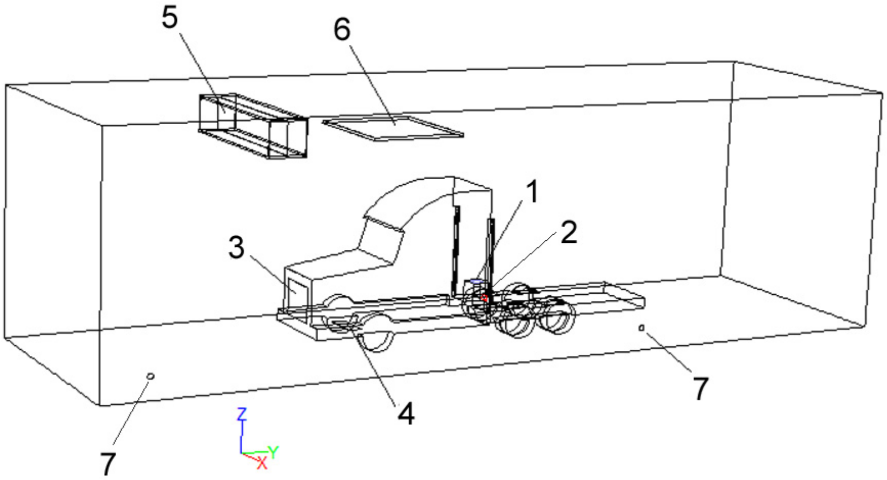


Figure 8: Geometry Model of the Environmental Chamber: (1) APU Exhaust Surface, (2) APU Intake Surface (3) Engine Cooling Air Intake Surface, (4) Engine Cooling Air Exhaust Surface, (5) Fan Interface, (6) Solar Light Assembly, (7) Exhaust Ducts (Only the One Used for the TRUCK Test Is Shown)

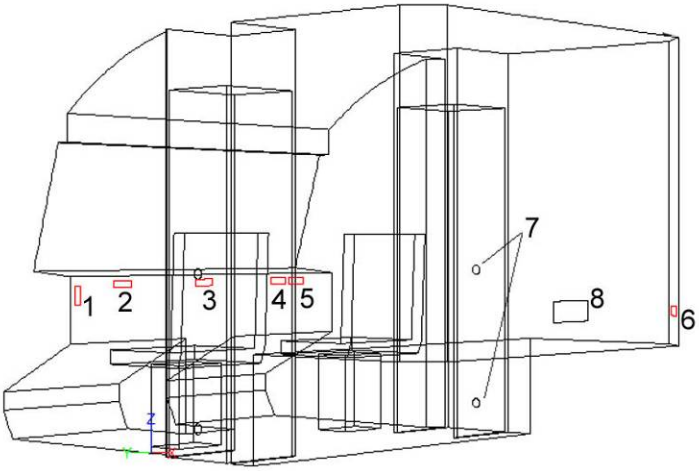


Figure 9: Geometry Model of the Truck Cabin: (1) ~ (5) Truck AC Inlets Number 1~5; (6) APU Inlets (Only One Side Is Shown); (7) Truck Inlets (Only One Side Is Shown) (8) Cabin Outlet

Pollutant Concentration Measurements

TTI's SEMTECH-DS measured emissions of the truck and the APU. TTI's 42i and 48i analyzers were used to measure NOx and CO concentrations inside the EERF and the truck cabin. NOx and CO concentrations inside the EERF were measured at three locations described in Table 6.

The concentrations at the locations were measured as an alternating manner with 5-minute duration at each location.

Table 6: Locations of the Pollutant Measurements and Measured Species

Monitor	Location
Chamber Wall Monitor	On the south lateral wall of the environmental chamber, at a height of about 2.4 m, and 7.5 m from the east end of chamber
Driver Seat Monitor	On the driver's seat
Under-Engine Monitor	Underneath the truck engine, on the floor

CFD Models

Using Gambit 2.2.30 (ANSYS, Inc., Canonsburg, PA), two separate geometric models were built, one for the EERF and the other for the truck cabin as shown in Figure 8 and Figure 9, respectively. Overall, 4.6 million cells were constructed in the EERF model, with a minimum cell volume of 1.8 x 10^{-7} m^3 (approximately the volume of a 5-mm cube), and 3.8 million cells were constructed in the cabin model with a minimum cell volume of 5.1 x 10^{-7} m^3 (approximately the volume of an 8-mm cube).

In Figure 8, the truck was placed in the center of the chamber domain at it was during the tests, the fans were modeled using a rectangular fan interface. The surface of the solar light assembly device was set to be a "wall" boundary. The two vents on the lateral wall of the chamber were set as "pressure-outlet," and all walls of the EERF and the truck were set as "walls" with an adiabatic boundary condition. The other four surfaces, the engine cooling air intake surface (the front of the truck), the engine cooling air exhaust surface (underneath the engine), the APU exhaust surface, and the APU intake surface, were assigned for different boundary conditions depending on the conditions to be simulated and are described in Table 7.

Table 7: Boundary conditions of the chamber model (surfaces shown in Figure 8)

Test conditions Simulated		APU	TRUCK
Surfaces in the Chamber Model (See Figure 8)	**1**	Velocity inlet (uniform 1.3 m/s)	Wall
	2	Pressure outlet (10^5 Pa)	Wall
	3	Wall	Outflow
	4	Wall	Velocity inlet (uniform 2.9 m/s)
	5	Fan interface: $\Delta P=13746-221.5v$	
	6	Wall	
	7	Pressure outlet (10^5 Pa)	Outflow

When modeling APU test, the APU exhaust surface was set as a velocity inlet with uniform velocity of 1.3 m/s (mass flow rate of 78 kg/h) based on actual measurement. The APU intake surface was set as the outflow boundary. In addition, the engine cooling air intake and exhaust surfaces were designated as wall boundaries because, for the APU test, the engine was off and air flows coming in or out of the engine component were negligible. On the other hand, in the modeling for TRUCK test, the engine cooling air exhaust was set as an inlet boundary with approximately the same flow rate as that through the engine cooling air intake, which was set as an outlet boundary. In this TRUCK test, the APU intake and exhaust were considered wall boundaries because the APU device was not used in this TRUCK test.

For the cabin model, all of the inlet surfaces (APU inlets for the APU test and AC inlets for the TRUCK test) were set as velocity-inlet with constant and uniform air velocities obtained from actual measurements. The measured velocity inlet speeds are shown in Table 8. The outlet surface was set as the outflow boundary.

Table 8: Boundary conditions of the cabin model (surfaces shown in Figure 9)

Test Conditions Simulated		**APU**	**TRUCK**	
Surfaces of the Cabin Model (See Figure 9)	**1**	Wall	Velocity inlet	4.1 m/s
	2			2.4 m/s
	3			2.7 m/s
	4			3.1 m/s
	5			3.1 m/s
	6			2.9 m/s
	7	Velocity inlet (1.1 m/s)	Wall	
	8	Outflow		

Simulation Approach

A two-step simulation approach was taken. First, a steady state simulation was performed to obtain the flow field. Then, a transient dispersion simulation of the gaseous pollutants was conducted. Because concentrations of the pollutants (NOx and CO) were low for the tests, only air was considered for the medium for the simulation, i.e., the assumption for the simulation was that the flow field in the chamber was independent of the pollutant concentrations.

When simulating the transient pollutant dispersion, the concentrations for all pollutants were set to be zero in the entire model at time zero. For the simulation of the APU test, a pollutant concentration at the APU exhaust surface was set as a constant value (based on actual emissions measurements) in the chamber model. Then, in the cabin model, the time-dependent concentration results obtained from the chamber model simulation were used as the pollutant concentrations at the four APU inlets. For the TRUCK test, the time-dependent pollutant concentrations measured at the engine cooling air exhaust boundary were used in the chamber model. Then, in the cabin model, the measured time-dependent concentrations were used for the concentrations at the six AC inlets (above the engine hood and near the windshield). The initial conditions used in the transient simulations for the chamber and the cabin models are shown in Table 9 and Table 10, respectively.

Table 9: Boundary conditions in the chamber model transient simulation

Test conditions Simulated		APU	TRUCK
Surfaces of the Chamber Model (See Figure 8)	**1**	Constant pollutant concentration NO 230 ppm NO_2 30 ppm CO 150 ppm	Wall
	4	Wall	Time-dependent pollutant concentration input from measurements (underneath the truck engine)

Table 10: Boundary conditions in the cabin model transient simulation

Test conditions Simulated		APU	TRUCK
Surfaces of the Cabin Model (See Figure 9)	**1**	Wall	Time-dependent pollutant concentration input from the chamber simulation (above the engine hood and near the windshield in the chamber model)
	2		
	3		
	4		
	5		
	6		
	7	Time-dependent pollutant concentration input from the chamber simulation (APU intake surface in the chamber model)	Wall

Table 11: Time steps used in the transient simulation

Physical Time	Simulation Time Step
0 ~ 15 min	0.1 s
15 min ~ 30 min	0.2 s
30 min ~ 1 hour	0.5 s
1 hour ~ 2 hour	1 s

The CFD modeling and simulation for both the chamber and cabin models were conducted using ANSYS Fluent 12.1.4 (Ansys Inc., Canonsburg, PA, United States). Time steps used in the transient simulation were adjusted according to the elapsed physical time to avoid unnecessarily long iterations and are shown in Table 11. The simulation was stopped when the continuity residual decreased below 10^{-6} and regarded as the convergence. The CFD-derived results were compared to the experimental measurements afterward, and the root-mean-square normalized error (erms) was used to evaluate the deviation between the numerical and experimental results, as shown in the following equation:

$$e_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{\left(C_{\exp,i} - C_{CFD,i}\right)^2}{C_{\exp,i}^2}}$$

where n is the number of the experimental/simulation data pairs for pollutant concentration; $C_{exp,i}$ is the value of the experimentally measured concentration for the *i*th experimental condition (physical time); and, $C_{CFD,i}$ is CFD-based concentration for the *i*th condition.

Test Results

This section details test results of emissions, fuel consumption, noise, and performance of IRT devices and trucks. Each IRT device or truck was put through a hot and a cold test, if applicable to the device's capabilities. Otherwise the device would only be subjected to the either the hot or cold test. The conditions of the test, as described in the verification protocol, are shown below in Table 12.

Table 12: Test Conditions

Test Name	Chamber Temperature	Relative Humidity	Other Conditions	Target Cabin Temperature
Hot Test	100°F (37.8°C)	50%	Solar Load On	73°F (22.8°C)
Cold Test	0°F (−17.8°C)	Not applicable	20 MPH Wind Simulation	73°F (22.8°C)

Emissions and Fuel Consumption Results

Emissions and fuel consumption tests were run on the selected diesel APUs, DFHs, and class 8b trucks. With the exception of the DFH, each of these devices offered both a heating and a cooling option. The DFHs only offered a heating option, and therefore were not subjected to the hot test.

For comparison purposes, results from Truck #1, operating at idling rate of 600 RPM, with the AC or Heat activated and in Re-Cir mode, were used as the baseline. During the tests, at least three test runs for each IRT device or truck were conducted, and the average fuel consumption/emissions rates of the IRT device or truck were calculated. For MSAT only one sample was taken for each condition for each IRT device or truck, due to limitations of the project budget. Fuel consumption/emission rates of IRT devices and trucks were compared with the baseline. The comparison results are expressed as percentage of the baseline.

To determine if the comparison results are statistically meaningful, t-tests were performed. The null hypothesis was that the fuel consumption/emission rate of an IRT device/truck is statistically same to the baseline at a 95 percent confidence level (that is, $\alpha = 0.05$). The tests were performed for each IRT/truck for test conditions described below. In the case of results where the differences from the baseline are not statistically significant, the ratio (percentage of the baseline) values are underlined in the results tables later in this section. For example, comparing to NOx emission results of the baseline for hot test condition, the t-value of Truck #1 for Air-In mode was 0.28 (higher than the critical t-value of 0.025 at the confidence level, $\alpha = 0.05$) indicating that NOx emissions of Truck #1 for Air-In mode are statistically insignificant comparing to the baseline, but NOx emissions of Truck 3 for Air-In mode are statistically significant because the t-value was 0.0022.

Hot Test Results

Diesel Powered APU

Both diesel powered APUs were tested under the hot test conditions. The measured fuel consumption and emissions results of the diesel APUs and baseline are summarized in Table 13 and Figure 10. Table 14 and Figure 11 show the PM and MSAT results from the APUs.

Table 13: Fuel Consumption and Gaseous Emissions for APUs: Hot Test

	Rate					Percentage of Baseline (%)				
	Fuel (gal/hr)	CO_2 (kg/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	Fuel	CO_2	CO	NOx	THC
Baseline[†]	0.82	8.3	61	76	10.8	N/A[*]	N/A[*]	N/A[*]	N/A[*]	N/A[*]
Diesel APU #1	0.30	3.1	5.8	19	1.3	37	37	9	25	12
Diesel APU #2	0.35	3.6	7.3	24	0.8	43	43	12	31	8

[†] Tests at Re-Cir mode with Truck #1 (at low idle).

* Not Applicable.

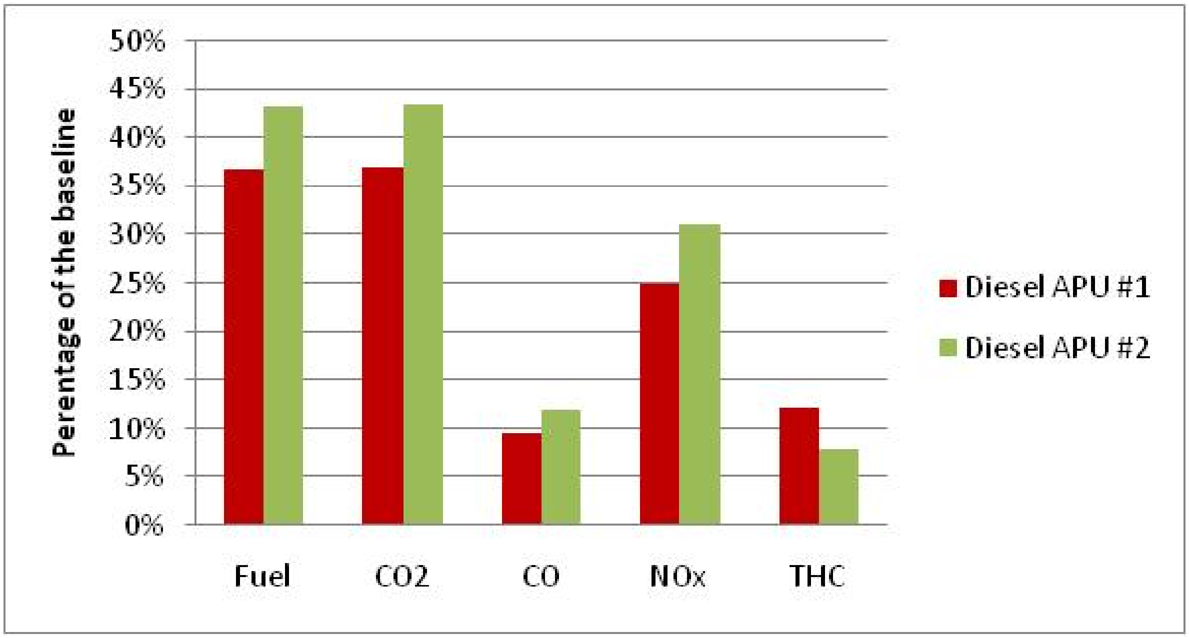


Figure 10: Fuel Consumption and Gaseous Emissions for APUs: Hot Test

Table 14: PM and MSAT Emissions for APUs: Hot Test

	Rate			Percentage of Baseline (%)		
	PM (g/hr)	CH_2O (g/hr)	CH_3CHO (g/hr)	PM	CH_2O	CH_3CHO
Baseline[†]	0.55	0.889[**]	0.313[**]	N/A[*]	N/A[*]	N/A[*]
Diesel APU #1	1.23	0.007	0.003	223	1[***]	1[***]
Diesel APU #2	0.58	0.076	0.063	104[****]	9[***]	20[***]

[†] Tests at Re-Cir mode with Truck #1 (at low idle).

* Not Applicable.

** Results were from Truck #1 Air-In mode (not Re-Cir mode) at low idle.

*** Comparisons with Truck #1 Air-In mode (not Re-Cir mode) at low idle.

**** Underlined percentage values – differences not significant at 95% confidence level.

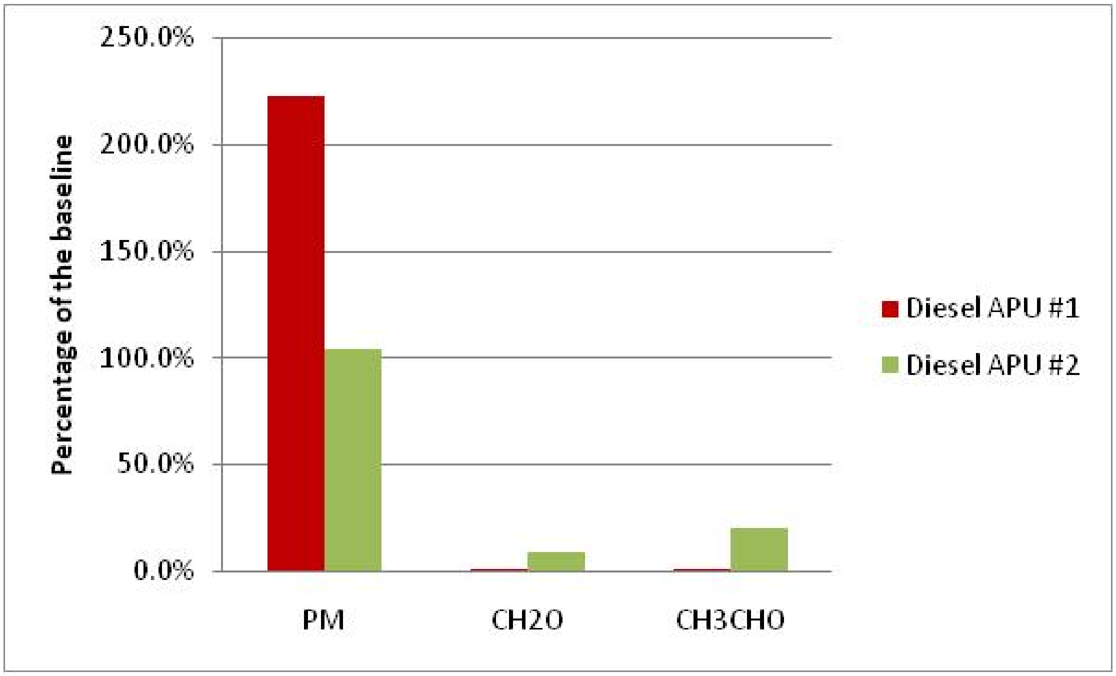


Figure 11: PM and MSAT Emissions for APUs: Hot Test

As shown in Table 13 and Figure 10, the fuel consumption and emissions rates of APUs, which have smaller engines (about 10 hp), are less than the rates of the baseline truck, which has a much larger engine (475 hp). The only exception was for PM emissions. The PM emissions rates of the diesel APU #1 (1.23 µg/hr) was over twice of the baseline (0.55 µg/hr). Similar PM emissions rates of an APU were reported in the literature. Storey et al. (*18*) showed that the PM emissions rates from a diesel APU were 1.00 µg/hr, which were higher than those of some diesel trucks tested during the hot testing under temperature of 32°C. In their study, during the hot testing, the APU consumed 0.239 gal/hr of diesel fuel, which is similar to the diesel APU #1's fuel consumption rate for this study of 0.30 and 0.35 gal/hr. The research team believes that the diesel APU #1 operated similarly to the diesel APU in the previous study of Storey et al. (*18*). The PM emissions of the diesel APU # 2 (0.58 µg/hr) was slightly higher than the baseline, but there are no statistically significant difference between them.

Compared to diesel APU #2, diesel APU #1 shows less fuel consumption and emission rates of all pollutants except PM, and THC. The research team believes that the difference was mainly ascribed from the different engines; a 2 cylinder engine for diesel APU #1 and a 3 cylinder engine for the diesel APU #2. However, the diesel APU #2 manufacturer did not provide detailed engine information, so that the research team could not perform any systematic comparisons based on engine specifications. Based on the engine specifications, the research team confirmed that the fuel consumption result shown in Table 13 is similar to that shown in the specification. For PM and THC, diesel APU #1 produced those pollutants more than diesel APU #2 for unknown reason(s). More investigations are necessary to determine the reason(s), which is beyond the scope of this work.

Trucks

As mentioned in the previous section, three trucks were also subjected to testing. In addition the different environmental conditions the trucks were also put through various different operating modes, as shown in Table 4. Due to the configuration of Truck #3, which did not allow for higher idling speeds, the research team was not able to test it under medium or high idling conditions. The measured fuel consumption and emissions results of the trucks are summarized in Table 8 as well as Figure 9, Figure 10, and Figure 11.

Table 15: Fuel Consumption and Gaseous Emissions Rates of Trucks: Hot Test

Truck	AC Mode	Idle Speed	Rate					Percentage of Baseline (%)				
			Fuel (gal/hr)	CO_2 (kg/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	Fuel	CO_2	CO	NOx	THC
Baseline[†]	Re-Cir	low	0.82	8.3	61	76	10.8	N/A[*]	N/A[*]	N/A[*]	N/A[*]	N/A[*]
Truck #2[**]	Re-Cir	low	1.21	12.4	30	8.3	4.0	148	149	49	11	37
Truck #3	Re-Cir	low	0.56	5.8	6.3	17	5.8	69	69	10	22	54
Truck #1	Air-In	low	0.68	6.2	38	71	10.5	83	74	63	94[***]	97[***]
Truck #2[**]	Air-In	low	1.19	12.3	20	10	3.1	146	147	33	14	29
Truck #3	Air-In	low	0.60	6.2	3.2	20	5.7	74	75	5	26	53
Truck #1	Re-Cir	med	1.61	16.3	93	66	31.3	196	196	153	87[***]	289
Truck #1	Re-Cir	high	2.24	22.6	125	111	27.6	273	272	205	147[***]	255
Truck #2[**]	Re-Cir	med	1.95	20.0	55.7	11	12.2	238	240	92[***]	14	113[***]
Truck #2[**]	Re-Cir	high	3.85	39.6	33.4	35	22.8	469	475	55	46	211[***]

[†] Tests at Re-Cir mode with Truck #1 (at low idle).

[*] Not Applicable.

[**] Low idle at 700 RPM, med idle at 1000 RPM, and high idle at 1300 RPM.

[***] Underlined percentage values – differences not significant at 95% confidence level.

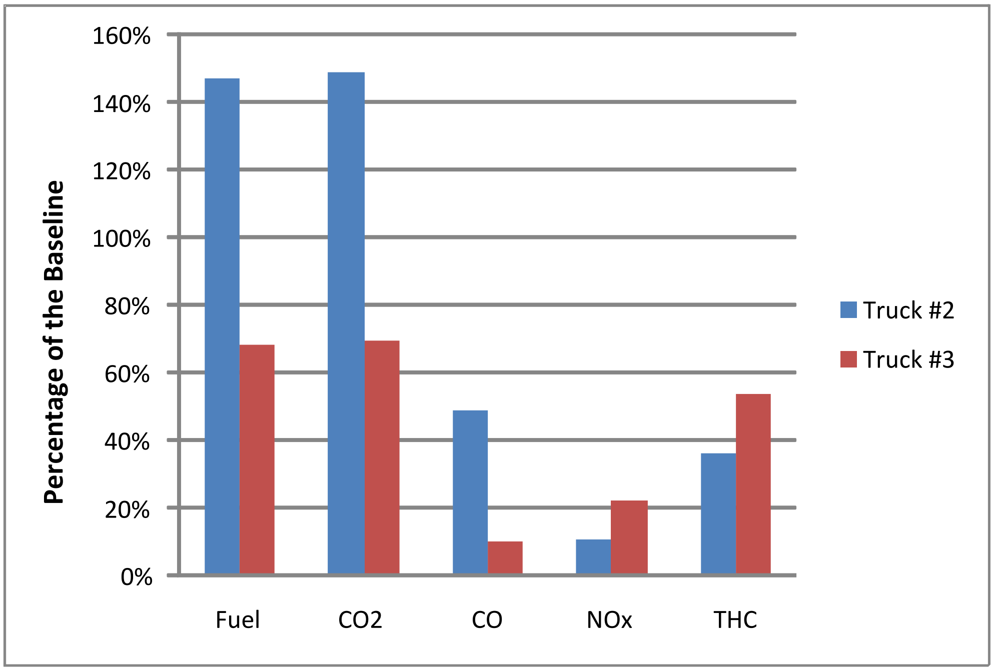


Figure 12: Fuel Consumption and Gaseous Emissions for Trucks in Re-Cir Mode at Low Idle: Hot Test

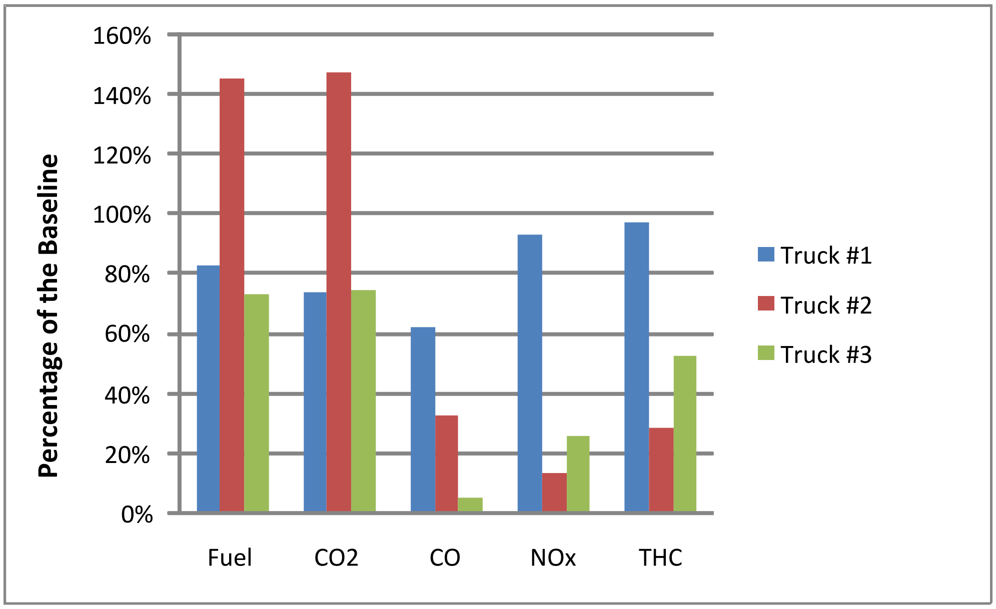


Figure 13: Fuel Consumption and Gaseous Emissions for Trucks in Air-In Mode at Low Idle: Hot Test

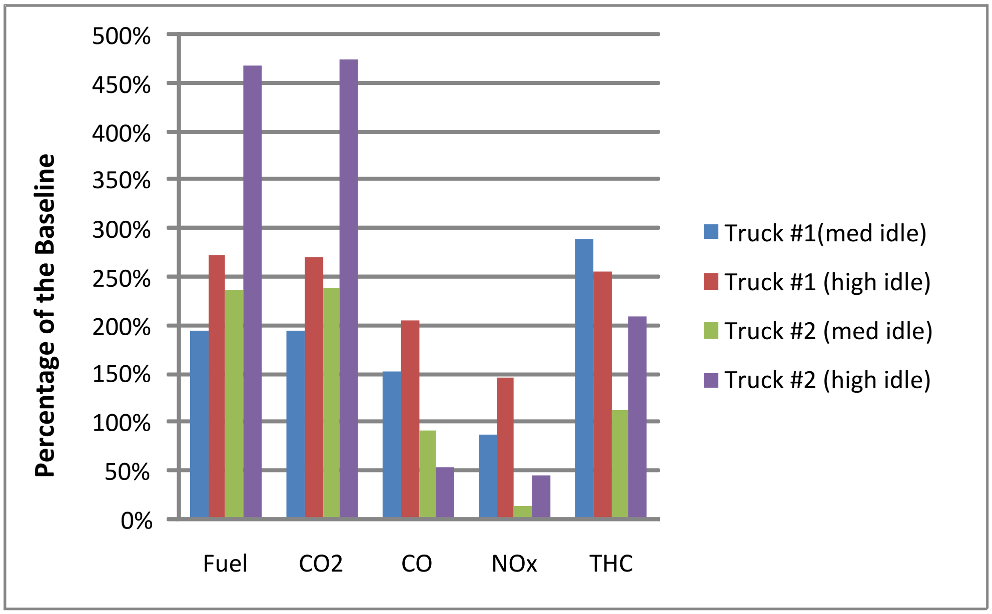


Figure 14: Fuel Consumption and Gaseous Emissions for Trucks in Re-Cir Mode at Medium and High Idle: Hot Test

Table 16: PM and MSAT Emissions from Trucks: Hot Test

Truck	AC Mode	Idle Speed	Rate		
			PM (g/hr)	CH_2O (g/hr)	CH_3CHO (g/hr)
Baseline[†]	Re-Cir	low	0.55	NA*	NA*
Truck #3	Re-Cir	low	0.01	0.154	0.054
Truck #1	Air-In	low	0.63	0.889	0.313
Truck #3	Air-In	low	0.01	0.069	0.040
Truck #1	Re-Cir	med	3.06	NA*	NA*
Truck #1	Re-Cir	high	7.18	1.263	0.551
Truck #2**	Re-Cir	high	-***	0.373	0.840

[†] Tests at Re-Cir mode with Truck #1 (at low idle).
* Not Available.
** High idle at 1300 RPM.
*** Data not available due to PM measuring instrument malfunctioning

At low idle, with the AC in Re-Cir mode, Truck #2 consumed more fuel and produced more CO_2 than the baseline truck. The research team speculates that this was probably resulted from the more powerful engine on Truck #2 (500 hp vs. 475 hp) and higher engine speed at low idle (700 RPM vs. 600 RPM). However, all other emissions from Truck #2 were less than half of the baseline as shown in Table 15 and Figure 12. This is expected due to the fact that Truck #2 complied with more stringent emissions standards than the baseline truck. For Truck #3, fuel consumption and all emissions rates were less than the baseline when idled at the same engine speed, as shown in Table 15 and Figure 12; Truck #3 has less power (430 hp) and a smaller engine (12.4 L vs. 15 L) when compared to the baseline truck idled at the same engine speed. Truck #3 also complied with more stringent emissions standards. PM emissions for this truck are significantly lower (only 3 percent of that from the baseline) mainly due to the DPF installed on the Truck #3. PM emissions results from Truck #2 could not be reported due to malfunctioning of the PM measurement instrument during the test. However, the research team speculates that the Truck #2's PM emissions will be similar to those of Truck #3 since Truck #2 was also equipped with a DPF.

For comparisons of trucks with the different AC operation modes, the fuel consumption and emissions rate results of three trucks under the Air-In mode were compared with the baseline as shown in Table 15 and Figure 13. Similar to the Re-Cir mode comparisons, fuel consumption and all emissions of the Trucks #2 and #3 were less than those of the baseline, except for fuel consumption and CO_2 of Truck #2. Compared to the baseline, fuel consumption and all emissions except for NOx, THC, and PM for the Air-In mode are less. NOx and THC emissions during the Air-In mode were similar to, or showed statistically insignificant differences from the baseline. The PM emissions rate from Truck #1 during the Air-In mode was 15 percent higher on average than the baseline, but the difference was statistically insignificant; that is, PM emissions rates during the Air-In mode were statistically not different from rates during the Re-Cir mode at the 95 percent confidence level.

When engine speed increases during the tested idling mode (Re-Cir mode), the corresponding fuel consumption and emissions of Truck #1 increase, except for NOx. This is shown in Table 15 and Figure 14. For NOx emissions, the differences between medium and low idle, and high and low idle were statistically insignificant. The research team believes that it might possibly be because during idling, higher engine speeds would not necessarily raise combustion temperature significantly. More systematic investigation with engine temperature measurements would be required to confirm or support this theory, but it is beyond the scope of this work.

During the medium and high idle modes, Truck #2 consumed more fuel and consequently emitted more CO_2 compared to Truck #1, which can also be explained as discussed above (due to engine power and speed). For all other emissions, the emissions rates from Truck #2 during the medium and high idle modes were lower or, at least, statistically not different from the baseline at the 95 percent confidence level, which can be again explained by the low emissions standards of Truck #2. For MSAT, at high idle, Truck #2 produced less CH_2O than Truck #1, which was an expected result. As shown in Table 16, MSAT emission rates of Truck #3 were less those of Truck #1 at low idle. However, Truck #2 produced more CH_3CHO than Truck #1 at high idle. Similar results (i.e., lower MSAT emissions from trucks during the high idle mode) were also reported in the study by Storey et al. (*18*). The research team examined this issue, but could not identify the reason based on the available information/data. Further investigation is necessary to elucidate the issue, which is beyond the scope of this work.

Cold Test Results

Both diesel APUs were tested for the cold testing condition. In addition to these two APUs, two DFHs were subjected to the cold test. The measured fuel consumption and emission results of the diesel APUs and DFHs are summarized in Table 17 and Figure 15. Table 18 and Figure 16 summarize the PM and MSAT emissions of the APUs and DFHs.

Table 17: Fuel Consumption and Gaseous Emissions Rates of Diesel APUs and DFHs: Cold Test

	Rate					Percentage of Baseline (%)				
	Fuel (gal/hr)	CO_2 (kg/hr)	CO (g/hr)	NOx (g/hr)	THC (g/hr)	Fuel	CO_2	CO	NOx	THC
Baseline[†]	0.85	8.6	88	110	19.9	N/A*	N/A*	N/A*	N/A*	N/A*
Diesel APU #1	0.39	4.0	3.9	22	1.2	45	46	4	20	6
Diesel APU #2	0.28	2.8	24	14	2.4	32	33	27	13	12
DFH #1	0.08	0.8	1.5	0.3	0.1	9	10	2	0.3	0.2
DFH #2	0.06	0.7	0.9	0.5	-**	7	8	1	0.4	-**

[†] Tests at Re-Cir mode with Truck #1 (at low idle).

* Not Applicable.

** Data not available due to THC measuring instrument malfunctioning.

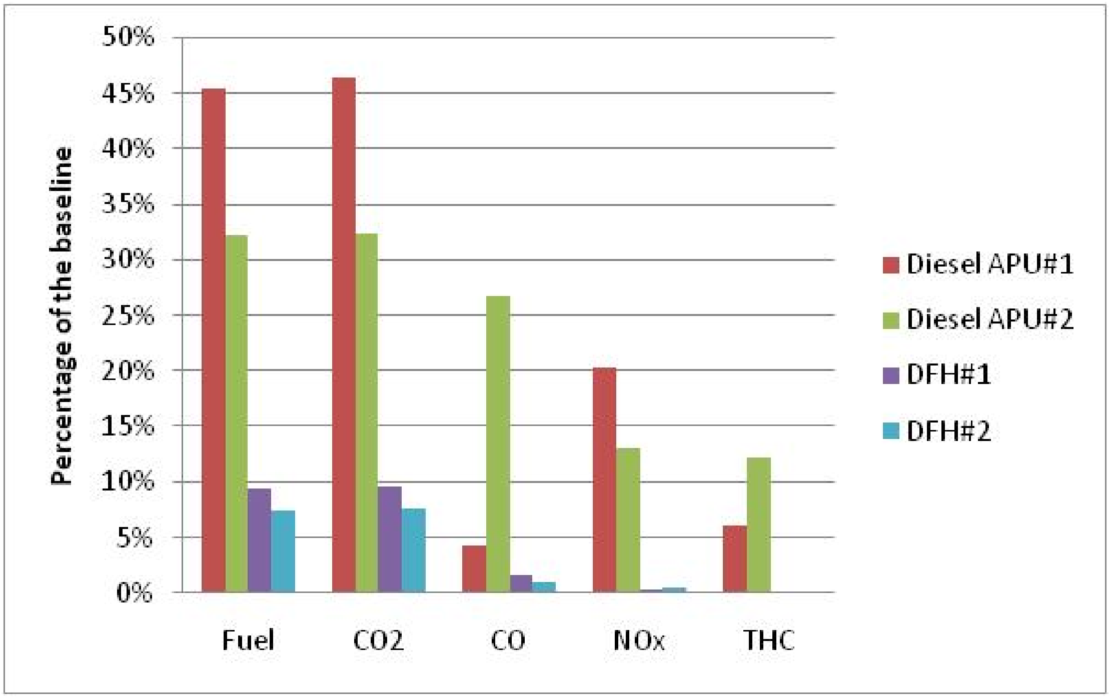


Figure 15: Fuel Consumption and Gaseous Emissions for APUs and DFHs: Cold Test

Table 18: PM and MSAT Emissions Rates of Diesel APUs and DFHs: Cold Test

Test Mode	**Rate**			**Percentage of Baseline (%)**		
	PM (g/hr)	**CH_2O (g/hr)**	**CH_3CHO (g/hr)**	**PM**	**CH_2O**	**CH_3CHO**
Baseline†	0.20	0.896*	0.356*	N/A**	N/A**	N/A**
Diesel APU #1	0.75	0.007	0.003	375	1***	1***
Diesel APU #2	0.98	0.116	0.051	486	13***	14***
DFH #1	0.01	0.003	0.004	6	0.3***	1***
DFH #2	0.07	0.001	0.001	37	0.1***	0.2***

†Tests at Re-Cir mode with Truck #1 (at low idle).

* Results were from Truck #1 Air-In mode (not Re-Cir mode) at low idle.

** Not Applicable.

*** Comparisons with TTI 06 truck at Air-In mode (not Re-Cir mode) at low idle.

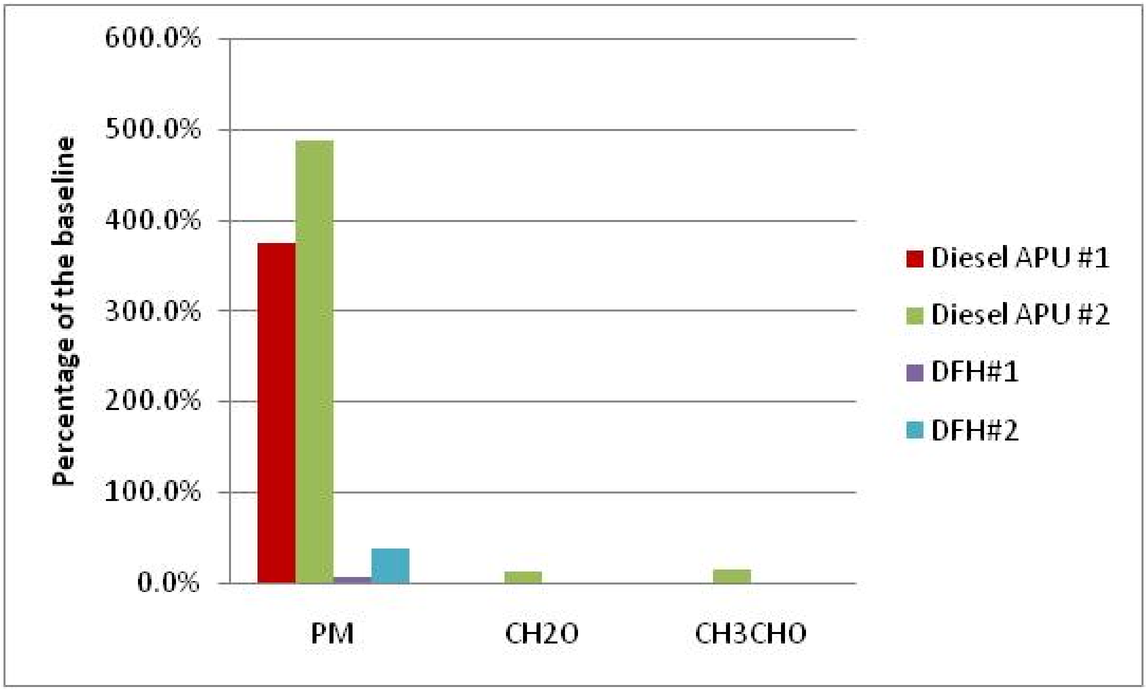


Figure 16: PM and MSAT Emissions for APUs and DFHs: Cold Test

One important note for diesel APU #1 and both DFHs is that these devices could not reach and/or maintain the target cabin temperature as outlined in the protocol, but only diesel APU #2 could. (Both diesel APUs were able to maintain the target temperature during the hot testing.) This implies that the cold testing involved more harsh conditions (raising the temperatures from 0 to 73°F) than the hot testing (lowering from 100 to 73°F). In addition, diesel APU #1 could possibly have reached and maintained the target cabin temperature by adjusting the setting on the device's controller to an even higher temperature. The original version of the protocol called for setting the IRT controller to 73°F. It was found, during the testing of APU #1, that some devices may be able to reach the target temperature, but only when their controller is set to an even more aggressive target (in this case, a higher temperature setting for the diesel APU #1). This modification to the protocol ensures that all devices are given the same chance to reach the target temperature, regardless of how their controller is designed.

As shown in Table 17 and Figure 15, fuel consumption and all gaseous and MSAT emissions rates from the APUs/DFHs are less than the baseline. Only PM emissions of both APUs were higher than the baseline as shown in Table 18 and Figure 16, which is similar to the hot test results.

Compared to rates from APU #1, APU #2 shows approximately two-third of the fuel consumption and CO_2 and NOx emissions rates. However CO, THC, and MSAT emissions rates from APU #2 were higher than those from APU #1. The research team examined the issue but could not identify the reason based on the available information only. Further investigation could clarify the issue. Fuel consumption and all emissions rates of both DFHs are significantly lower than the baseline rates as shown in Table 17, Table 18 Figure 15, and Figure 16. This is due to the fact that DFHs use very small amounts of diesel fuel for operation. Similar results were shown in the study by Storey et al. (*18*). For both PM and MSAT measurements, DFHs emitted lower amounts compared to the baseline.

Trucks

Table 19, Figure 17, Figure 18, and Figure 19 summarize the results of the cold testing for the trucks. Table 20 summarizes the PM and MSAT data for the cold testing of the trucks. Due to the configuration of Truck #3, which did not allow for higher idling speeds, the project team was not able to test it under medium or high idling conditions.

Table 19: Fuel Consumption and Gaseous Emissions Rates of Trucks: Cold Test

Test Mode	**Heat Mode**	**Idle Speed**	**Rate**					**Percentage of Baseline (%)**				
			Fuel (gal/hr)	**CO_2 (kg/hr)**	**CO (g/hr)**	**NOx (g/hr)**	**THC (g/hr)**	**Fuel**	**CO_2**	**CO**	**NOx**	**THC**
Baseline[†]	Re-Cir	low	0.85	8.6	88	110	19.9	N/A[*]	N/A[*]	N/A[*]	N/A[*]	N/A[*]
Truck #2	Re-Cir	low	1.13	11.6	48	16	2.4	133	135	54	15	12
Truck #3	Re-Cir	low	0.62	6.4	28	66	8.0	73	74	32	60	40
Truck #1	Air-In	low	0.90	9.1	100	112	19.8	106[**]	106[**]	113[**]	102[**]	99[**]
Truck #2	Air-In	low	1.07	11.0	39	20	1.7	126	128	44	18	9
Truck #3	Air-In	low	0.61	6.2	28	61	7.7	71	72	32	55	39
Truck #1	Re-Cir	med	1.54	15.6	114	172	19.2	181	181	129	157[**]	96[**]
Truck #1	Re-Cir	high	2.73	27.6	166	168	32.4	320	321	188	154	163
Truck #2	Re-Cir	med	1.86	19.1	63	26	6.1	218	222	72	23	31
Truck #2	Re-Cir	high	3.92	40.1	145	116	21.1	460	467	164[**]	106[**]	106[**]

[†] Tests at Re-Cir mode with Truck #1 (at low idle).

[*] Not Applicable.

[**] Underlined percentage values – differences not significant at 95% confidence level.

[****] Comparisons with TTI 06 truck at Air-In mode (not Re-Cir mode) at low idle.

[‡] Negligible.

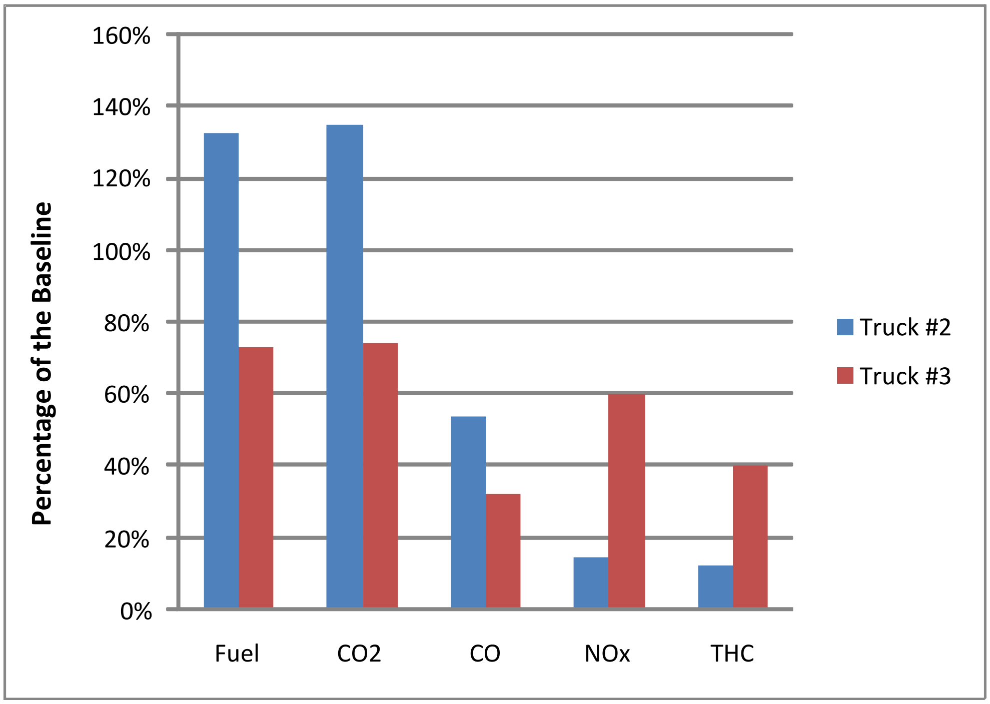


Figure 17: Fuel Consumption and Gaseous Emissions for Trucks in Re-Cir Mode at Low Idle: Cold Test

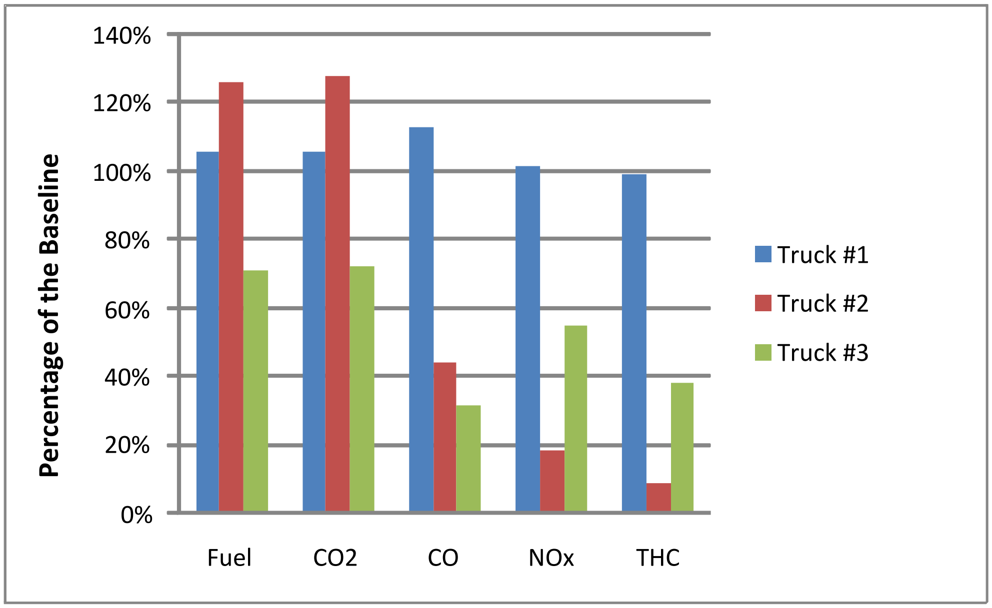


Figure 18: Fuel Consumption and Gaseous Emissions for Trucks in Air-In Mode at Low Idle: Cold Test

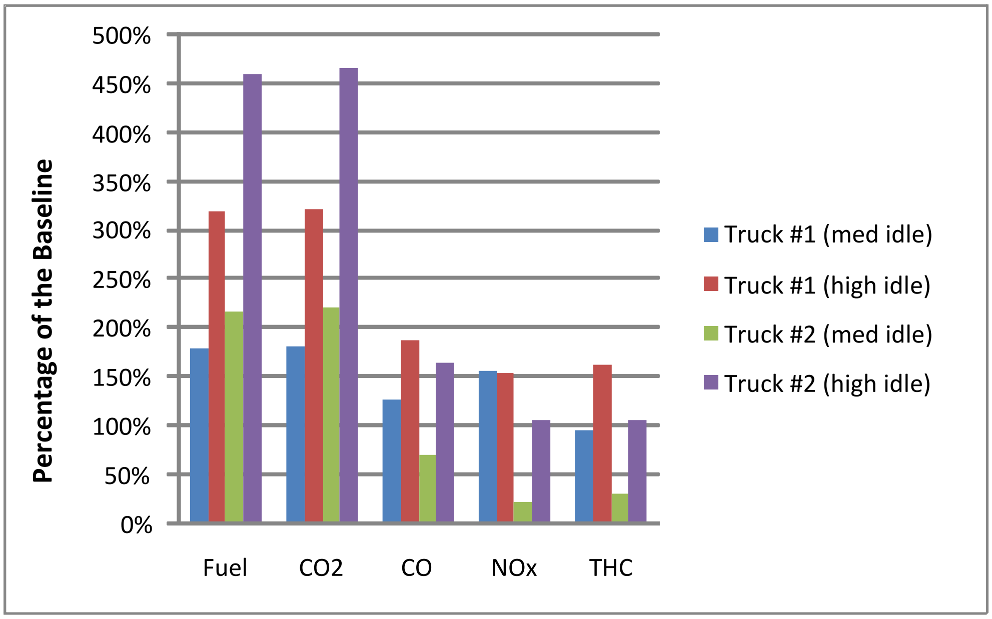


Figure 19: Fuel Consumption and Gaseous Emissions for Trucks in Re-Cir Mode at Medium and High Idle: Cold Test

Table 20: PM and MSAT Emissions from Trucks: Cold Test

Truck	**AC Mode**	**Idle Speed**	**Rate**		
			PM (g/hr)	**CH_2O (g/hr)**	**CH_3CHO (g/hr)**
Baseline[†]	Re-Cir	low	0.20	NA*	NA*
Truck #3	Re-Cir	low	0.02	NA*	NA*
Truck #1	Air-In	low	0.27	0.896	0.356
Truck #2	Air-In	low	-**	0.445	0.160
Truck #3	Air-In	low	0.02	0.209	0.124
Truck #1	Re-Cir	med	1.15	NA*	NA*
Truck #1	Re-Cir	high	4.14	NA*	NA*
Truck #2	Re-Cir	high	-**	1.613	1.466

[†] Tests at Re-Cir mode with Truck #1 (at low idle).
* Not Available.
** Data not available due to PM measuring instrument malfunctioning

Similar to the hot condition testing, Truck #2 consumed more fuel and produced more CO_2 than Truck #1 did for the baseline condition, shown in Table 19 and Figure 17. The research team ascribed it with the same explanation described in the previous hot condition truck testing section. Again, all other emissions from Truck #1 were about half of or less than the baseline. For Truck #3, similar to the hot condition testing, fuel consumption and all emissions were less than the baseline as shown in Table 19 and Figure 17. As same to the hot tests, these results were expected due to the smaller and less powerful engine with more stringent emissions standard compliance. Again, PM emissions results from Truck #2 could not be reported due to a malfunctioning PM measurement instrument.

As shown in Table 19 and Figure 18, fuel consumption and emissions of Truck #1 during the Air-In mode were not statistically different from those for the Re-Cir mode test. For the MY11 trucks, similar to the results found in the hot testing, all emissions except fuel consumption and CO_2 from Truck #2 were less than the baseline. Truck #2 also showed lower NOx emissions than that from Truck #3 as shown in Table 19 and Figure 18.

When engine speed increases during idling, the corresponding fuel consumption and emissions increase as shown in Table 19 and Figure 19. The exception was the CO, NOx, and THC during the medium idle NOx for Truck #2. For NOx emissions, the emissions rates during the medium idle fluctuated such that the difference between the emissions rates of low and medium idle were statistically not significant for Truck #1. However, the observed results of higher NOx emissions rates during the high idle represented a statistically significant difference from the baseline at the 95 percent confidence level.

During the medium and high idle modes, Truck #2 consumed more fuel and consequently emitted more CO_2 compared to baseline test, but all other emissions rates from Truck #2 were again lower or, at least, not statistically different from the baseline at the 95 percent confidence level. This is similar to the results shown in the hot condition testing. For MSAT, as expected, both Trucks #2 and #3 produced more CH_2O and CH_3CHO than Truck #1, and Truck #2 produced more at high idle than at low idle.

Performance Results of Battery Powered APUs and TSE Device

The two battery APUs and a TSE unit were tested for hot conditions. The TSE unit was also tested for cold conditions, while the battery APUs do not offer heating capabilities and were therefore not tested under cold conditions. Since battery APUs and the TSE unit do not consume fuel nor produce any direct emissions, fuel consumption and emissions tests were not applicable. The test results presented here for the battery APUs and the TSE units are the power consumption (peak during the initial start-up and non-peak) along with the average cabin temperature maintained while they operated. Although battery APUs showed higher peak power during their initial stage of the testing, TSE consumed same amount of power continuously during the entire testing periods as shown in Table 21. Note that none of the devices were able to maintain the cabin temperature within the desired range of 73°F ± 5°F.

Table 21: Performance of Battery-Powered APUs and TSE Unit

Test Mode	Peak Power (kW)	Non-Peak Power (kW)	Cabin Temperature (°F; average)
Battery APU #1 (Hot Test)	0.84	0.37	80
Battery APU #2 (Hot Test)	0.71	0.60	82
TSE (Hot Test)	1.7	1.7	84
TSE (Cold Test)	2.8	2.8	53

Noise Measurements

All tested devices, with the exception of the TSE device, were also subjected to noise measurements, as described in the verification protocol. Each device was tested using a Quest Technologies SoundPro DL device. The testing was conducted outside the EERF facility in a location described in the protocol. Table 22 shows test results. Because the TSE unit was installed inside the test chamber, it could not be tested outside, and therefore there are no noise test results for that device.

Table 22: Noise Test Results

Device	Noise Measurement
APU #1	68.8 dB (Hot Test)/ 65.1 dB (Cold Test)
APU #2	69.5 dB (Hot Test)/65.3 dB (Cold Test)
Battery APU #1	64.5 dB
Battery APU #2	64.1 dB
DFH #1	50 dB
DFH #2	48.9 dB

Infiltration Testing

Pollutant emissions infiltrate into the cabin through openings in the cabin floor in two ways—from the crankcase and from the surrounding ambient air, which is affected by the emissions from the truck's idling and other sources. Depending on the engine and the operating cycle, crankcase emissions are 10 to 25 percent of the total engine emissions. The EPA requires either closing the crankcase or measuring and adding them to exhaust emissions at the time of certification testing. Crankcase emission infiltration into the cab is not likely to happen for 2007 and later model trucks equipped with closed crankcase ventilation. However, some infiltration through the openings is still possible from the exhaust emissions while the truck is idling. In addition, while the air-conditioned air is provided, the ambient air can enter the cabin through the air conditioning system depending on the modes of operation.

The purpose of the infiltration testing was to investigate the infiltration of emissions into the cabin of the test truck during the truck idling and APU operation. Gaseous pollutants of NOx and CO inside the cab (in-cab) and ambient (adjacent to the test vehicle inside the environmental chamber) were measured using ambient monitoring instruments. The measurement results from the above step were analyzed using a CFD modeling tool. In this study, the TTI research team used CFD modeling tool to predict the pollutants distribution in the EERF and inside the cabin of TTI's MY06 truck used for the testing of IRT devices and the baseline. The flow field and transient pollutant dispersion results for the APU test conditions and the TRUCK test conditions are shown and discussed in the following sections.

APU Test Results

Pollutants in the Chamber

The steady state flow field simulation was first conducted, using the Reynolds Stress turbulent model. For the chamber model, APU exhaust (which was emitted inside the chamber) was the only source of flow and pollutants, and only the fans were used to drive the air circulation. Figure 20 shows the steady state flow field.

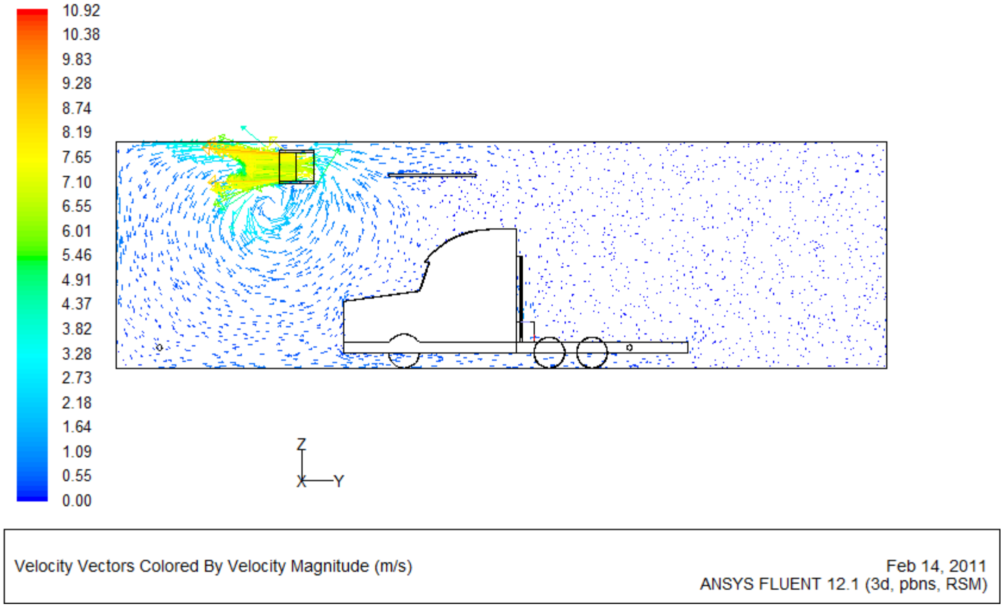


Figure 20: Steady State Flow Field of Chamber Model in the APU Test Conditions in Vectors View

After the steady state flow simulation, the pollutant dispersion simulation was conducted. The boundary condition for the APU exhaust surface was modified with the constant pollutant concentrations from the measured APU exhaust: 230 ppm for NO, 30 ppm for NO_2, and 150 ppm for CO. Based on the assumption of zero concentration at time zero, the concentration for both pollutants in the entire domain was set to be zero. Time-dependent pollutant concentration results in transient process are shown in Figure 21, Figure 22, and Figure 23. Since the pollutant concentrations in most locations in chamber are quite low comparing to that at APU exhaust during the transient process, especially in early period of time, a logarithmic scale was used in Figures 18–20. All of the results were shown on the same concentration color maps (with the concentration range from 10^{-30} to 2.3×10^{-4}) for easy comparison

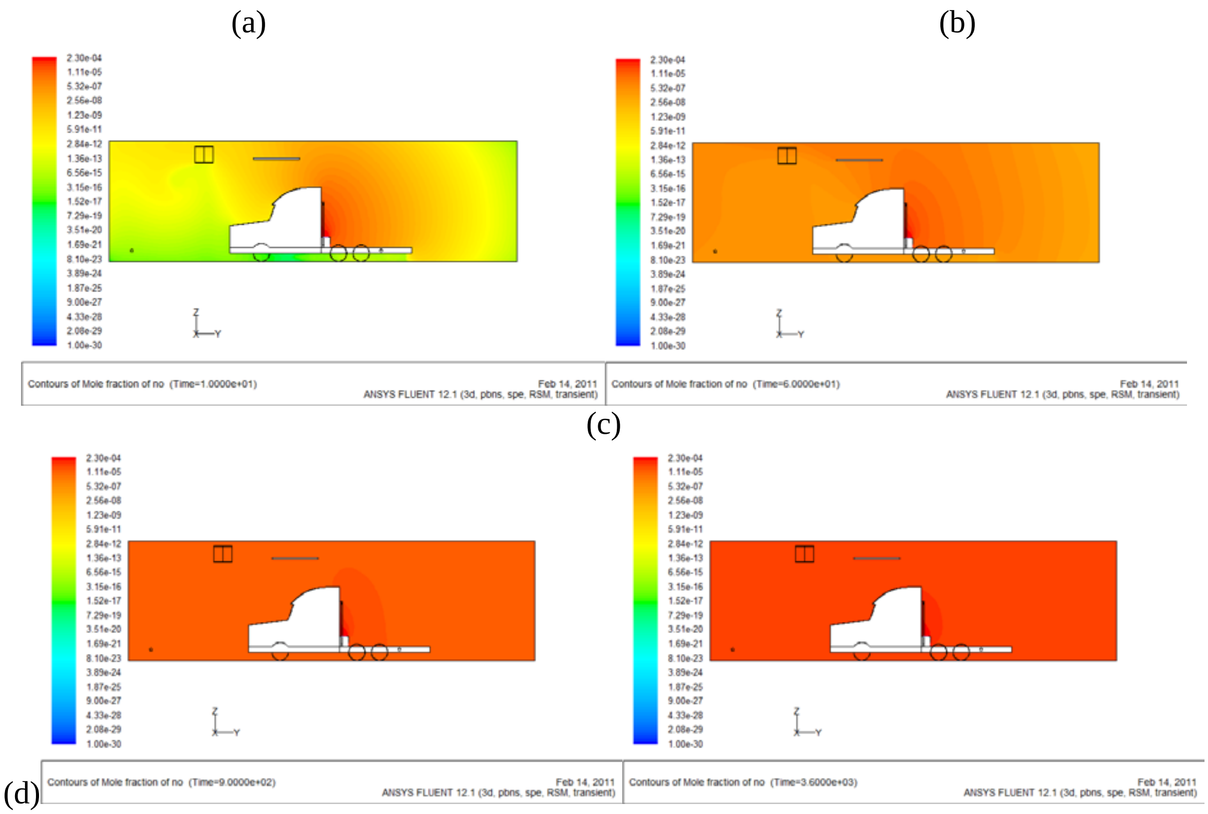


Figure 21: NO Concentration Distribution inside the Chamber in the APU Test Conditions at Physical Time of (a) 10 s, (b) 60 s, (c) 900 s, and (e) 3600 s

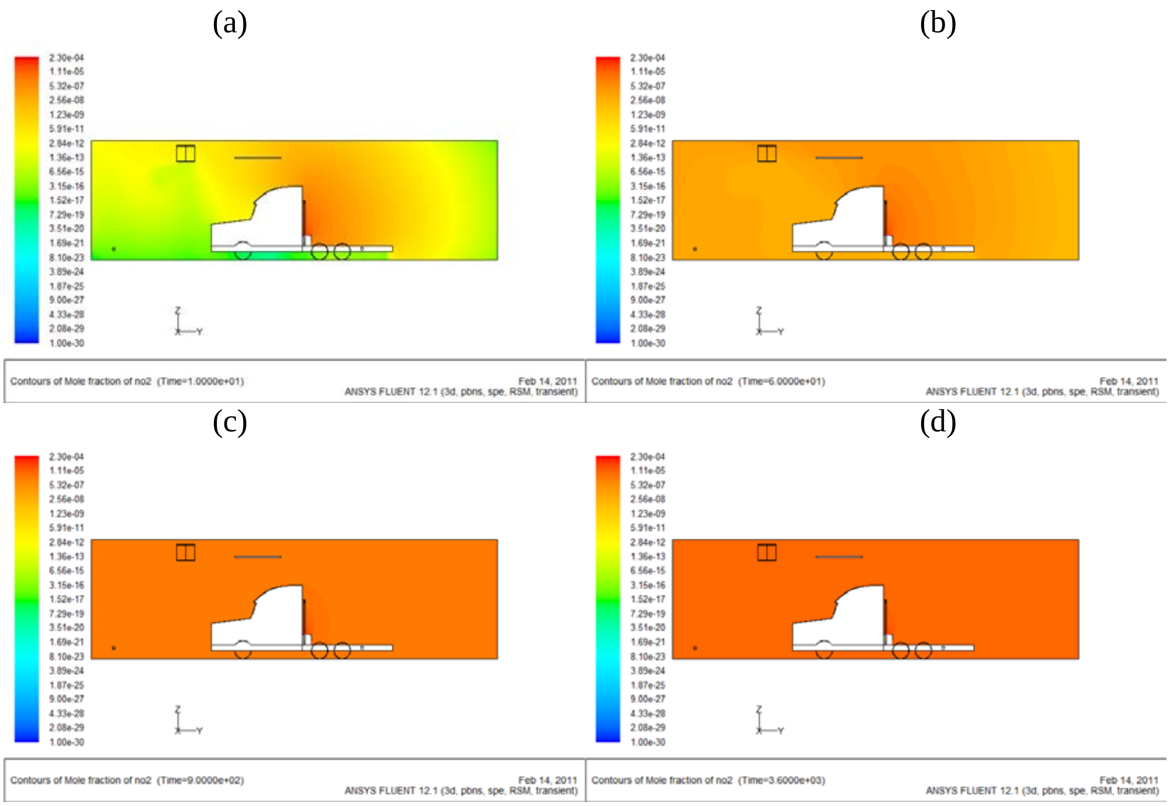


Figure 22: NO_2 Concentration Distribution inside the Chamber in the APU Test Conditions at the Physical Time of (a) 10 s, (b) 60 s, (c) 900 s and (d) 3600 s

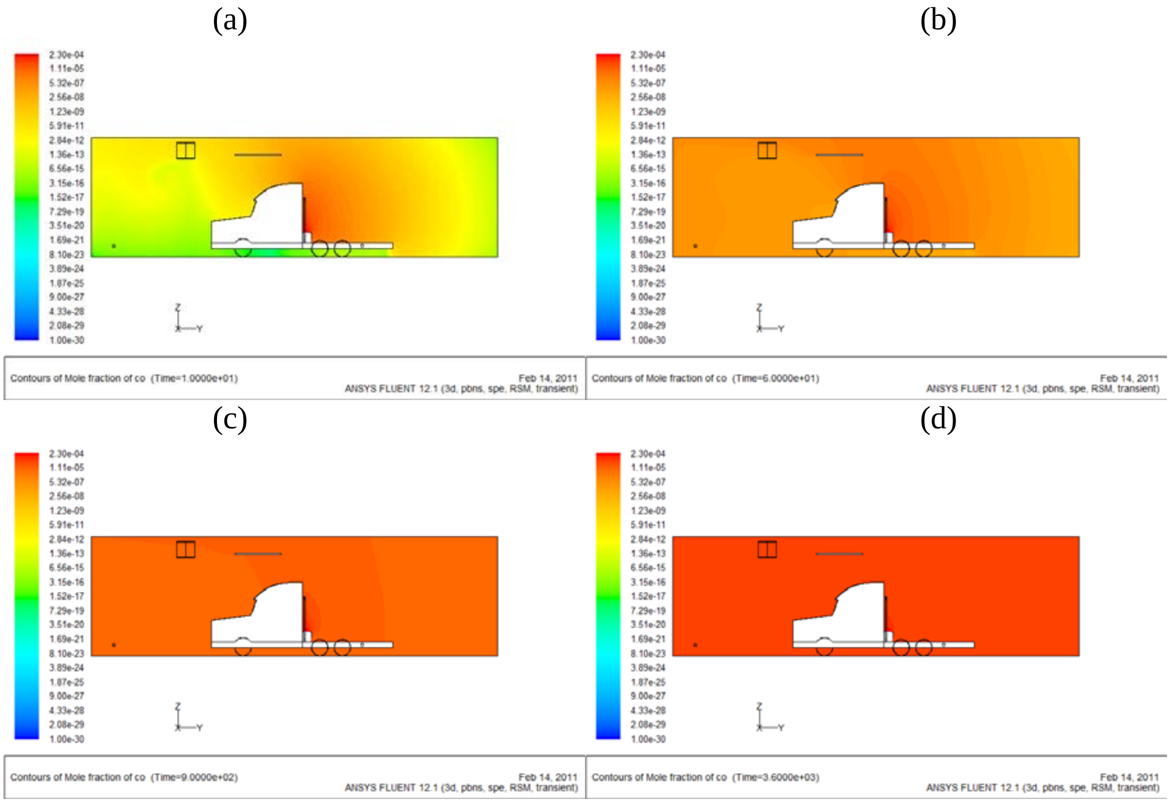


Figure 23: CO Concentration Distribution inside the Chamber in the APU Test Conditions at the Physical Time of (a) 10 s, (b) 60 s, (c) 900 s and (d) 3600 s

The results show that, after being released from the APU exhaust surface, the pollutants were convected upward and then toward the front region of the truck (east side of the chamber) due to the air flow driven by the fans. Due to their higher diffusion coefficients (*39*), dispersion of NO and CO in the chamber was more rapid than that of NO_2. At early times, there was a significant concentration gradient near the rear end of the truck under the flat bed. One possible explanation for this phenomenon was that in this region, the air flow (from east to west) was in opposite direction to pollutant diffusion (from west to east because the concentration difference), which would delay pollutant infiltration into this region

Pollutants in the Cabin

Again, the steady state flow field simulation of the cabin was first conducted. Velocity vectors in the cabin model are shown in Figure 24. The air entered through the inlets on the lateral walls of the cabin (2 on each side) at a speed of 1.1 m/s, and exited through the outlet on the rear wall.

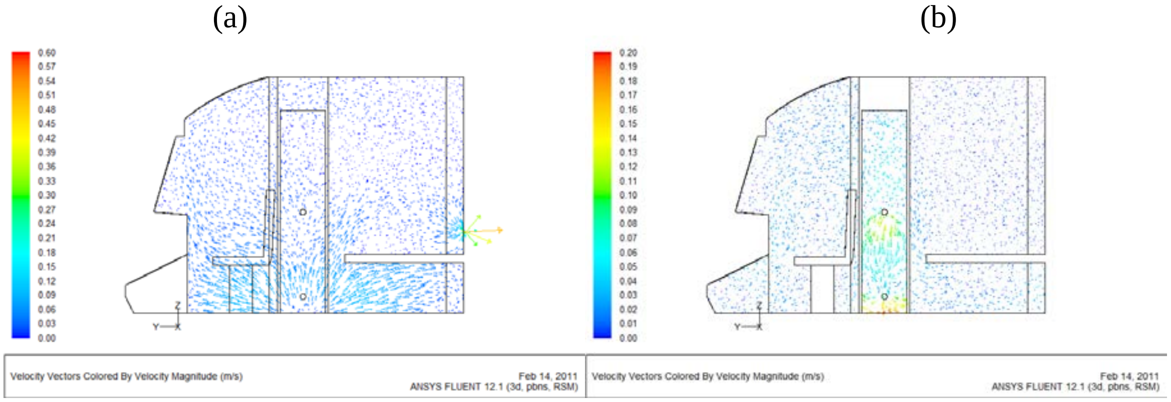
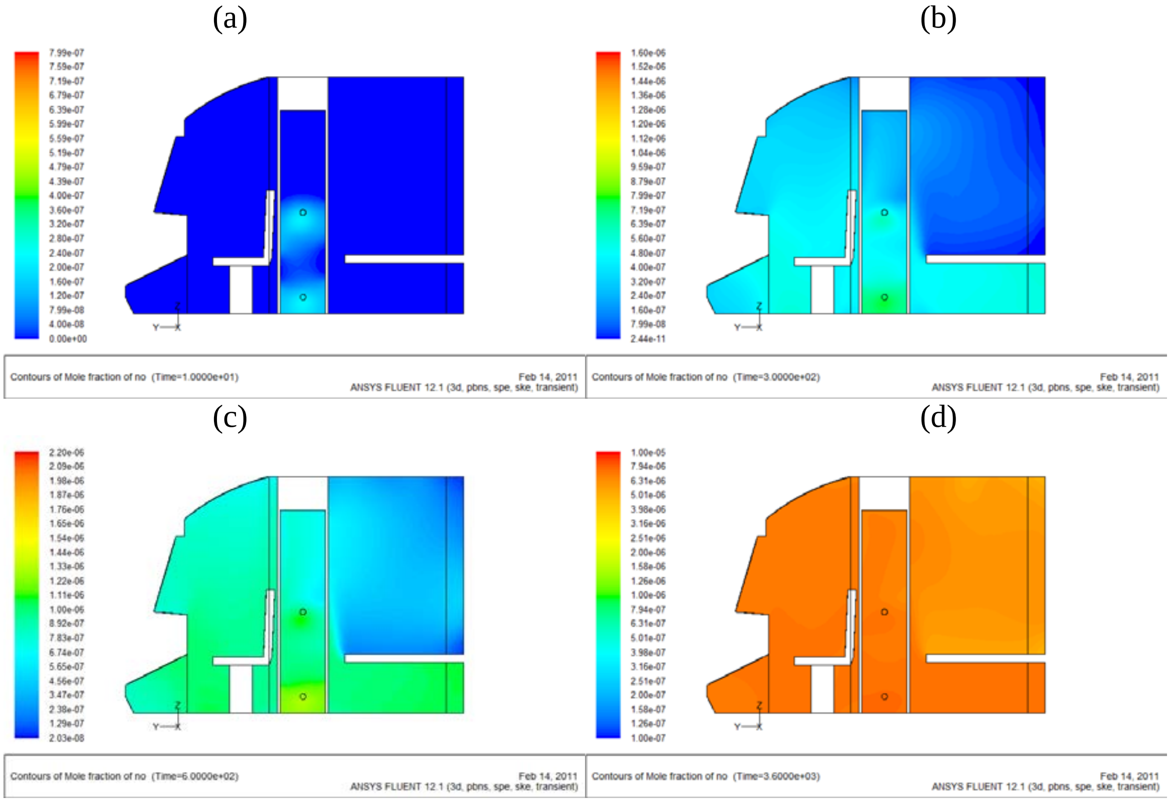


Figure 24: Steady State Flow Field in the Cabin Model in the APU Test Conditions at (a) the Middle Section Plane and (b) the Section Plane through the Driver Seat

After the steady state flow field results in the cabin was obtained, the pollutant species were introduced and the transient simulation was conducted. The pollutant concentrations at the cabin inlets were obtained from the time-dependent concentration data at the APU intake surface from the chamber simulation. Unlike the chamber model, the pollutant source concentration in the cabin model was not constant. The time-dependent NO concentration results in the cabin are shown in Figure 25.


(a)

(b)

(c)

(d)

Figure 25: NO Concentration Distribution in the Section Plane through the Driver's Seat in the APU Test Conditions at Physical Time of (a) 10 s, (b) 300 s, (c) 600 s and (d) 3600 s

TRUCK Test Results

Pollutants in the Chamber

For the truck test as well, the steady state flow field was first simulated with the Reynolds Stress model. Both of the fans and truck's AC fans were the sources for air flow. The flow field simulation results are shown in Figure 26. Truck's exhaust was vented out, so that source of emissions from the truck was attributed only to crankcase emissions of the truck.

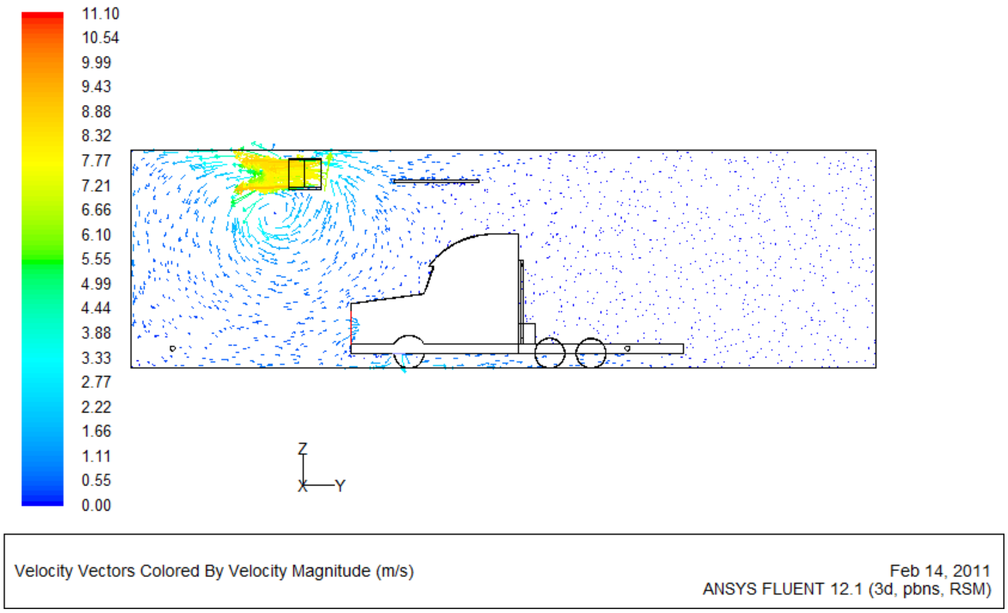


Figure 26: Steady State Flow Field of Chamber Model in the TRUCK Test Conditions

High velocity occurred near the outlet region of the fans where the average air speed was 6.4 m/s and the maximum velocity was up to 8 m/s. An obvious flow circulation could be noticed below the fans, and the air flow would turn downward after being driven out of the fans and, then, toward the truck engine front. Part of the downward flow would enter the engine cooling air intake, of which average air velocity was approximately 3 m/s. Consequently, underneath the truck, the engine exhaust surface would result in a region with relatively high air velocity.

After the steady state flow field simulation was conducted, the transient pollutant dispersion simulation was conducted. The truck engine's crankcase emissions were the only pollutant source in this model; the exhaust emissions were transported outside the EERF through a duct, so that there were no residual exhaust emissions inside the EERF). The pollutant concentration at the engine exhaust surface was not constant. These time-dependent concentration data were experimentally obtained and used as boundary conditions in the transient simulation. The transient simulation results are shown in Figure 27, Figure 28, and Figure 29.

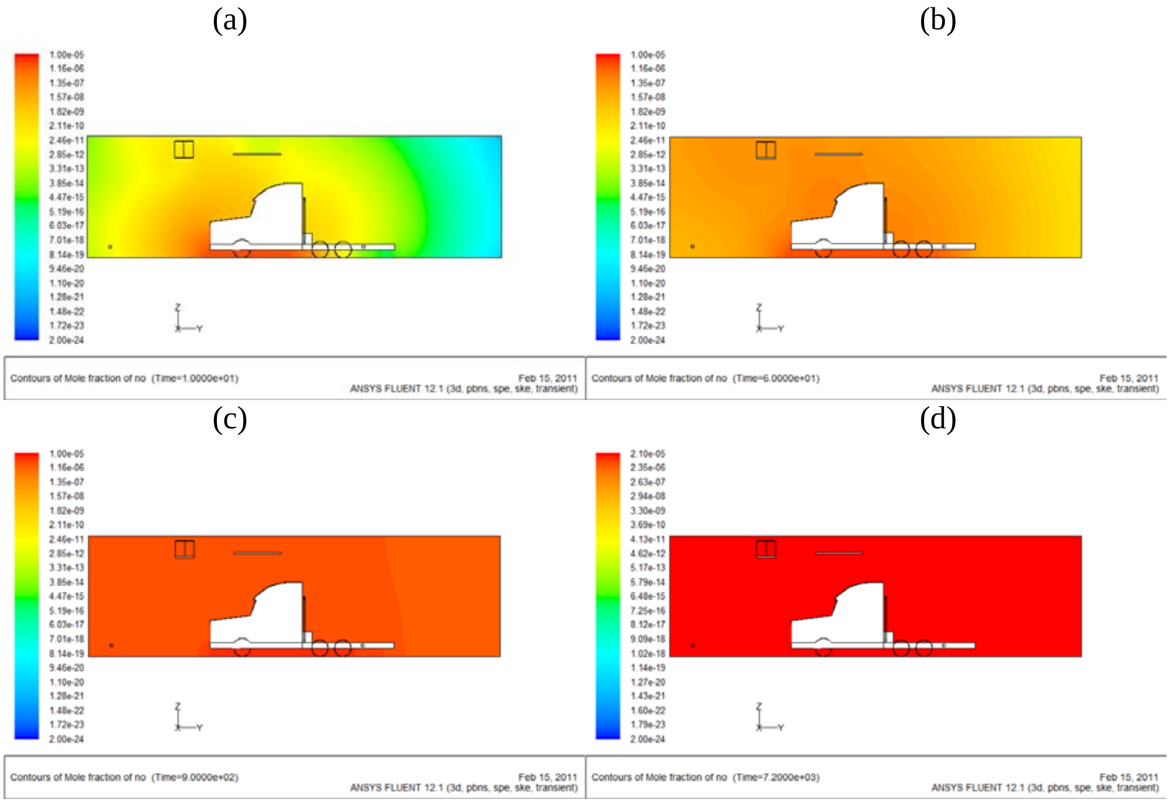


Figure 27: NO Concentration Distribution inside the Chamber in the TRUCK Test Conditions at Physical Time of (a) 10 s, (b) 60 s, (c) 900 s, and (d) 7200 s

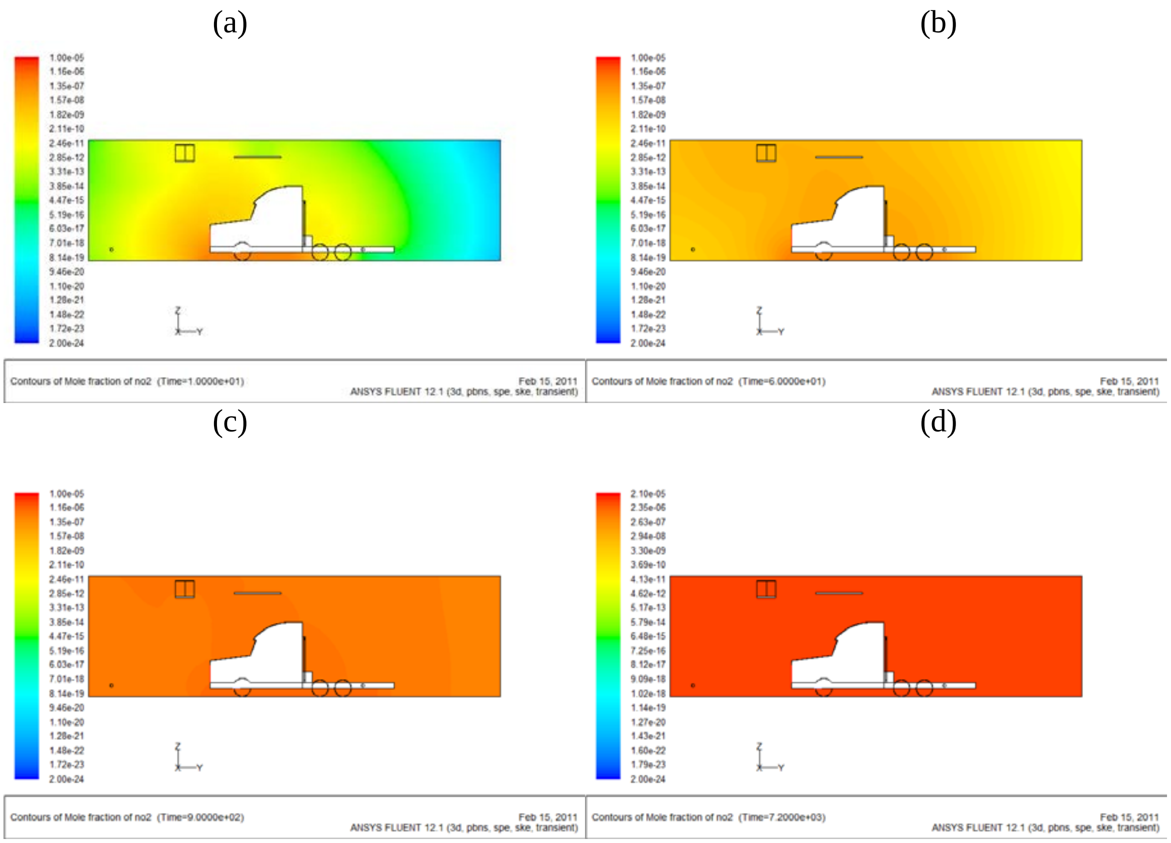


Figure 28: NO_2 Concentration Distribution inside the Chamber in the TRUCK Test Conditions at Physical Time of (a) 10 s, (b) 60 s, (c) 900 s, and (d) 7200 s

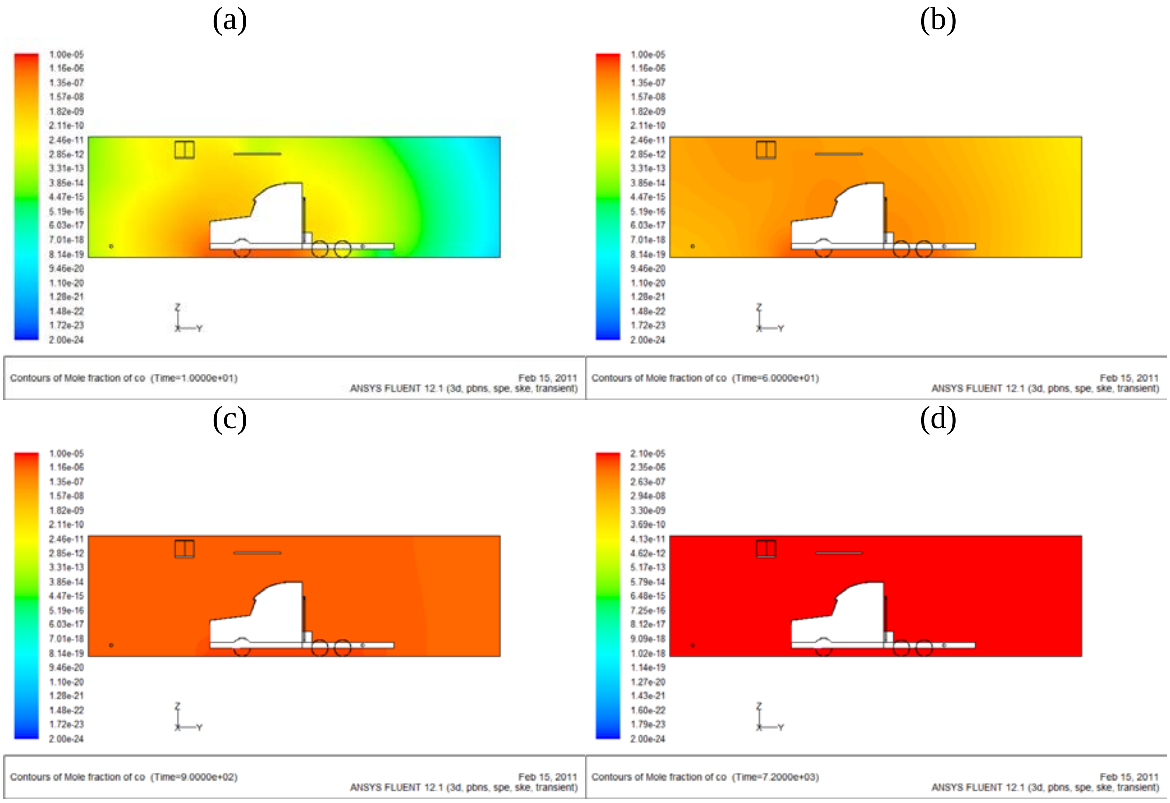


Figure 29: CO Concentration Distribution inside the Chamber in the TRUCK Test Conditions at Physical Time of (a) 10 s, (b) 60 s, (c) 900 s, and (d) 7200 s

The results show that in the beginning, pollutants were predominantly concentrated underneath the truck engine. Over time, the pollutant concentration in the chamber increased and became spatially uniform.

Pollutants in the cabin for the truck test, after the simulation in the chamber model, the steady state flow simulation of the cabin model was conducted first. The results were quite different from those for the APU test because the flow field and the pollutant sources were different. Figure 30 shows the simulation results.

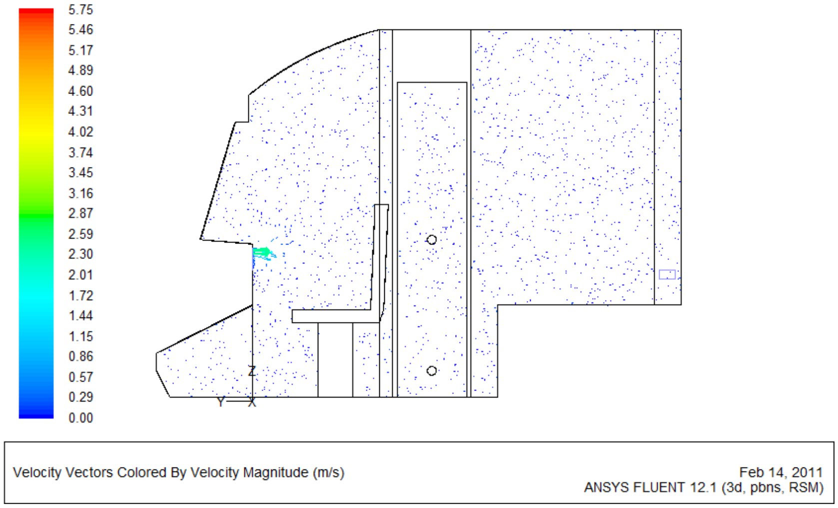


Figure 30: Steady State Flow Field in the TRUCK Test Conditions at the Section Plane through the Driver Seat

After the flow simulation, the transient pollutant dispersion simulation in the cabin model was conducted. The time-dependent pollutant concentration at the location of the truck cabin air intake (above the engine hood and near the windshield in the chamber model) was used for the boundary condition of the cabin model. Figure 31 shows the distribution results. Since the truck AC flow rate was about 7 to 9 times higher than that of cabin inlet flow in the APU test, the pollutant concentrations inside the cabin became uniform more rapidly.

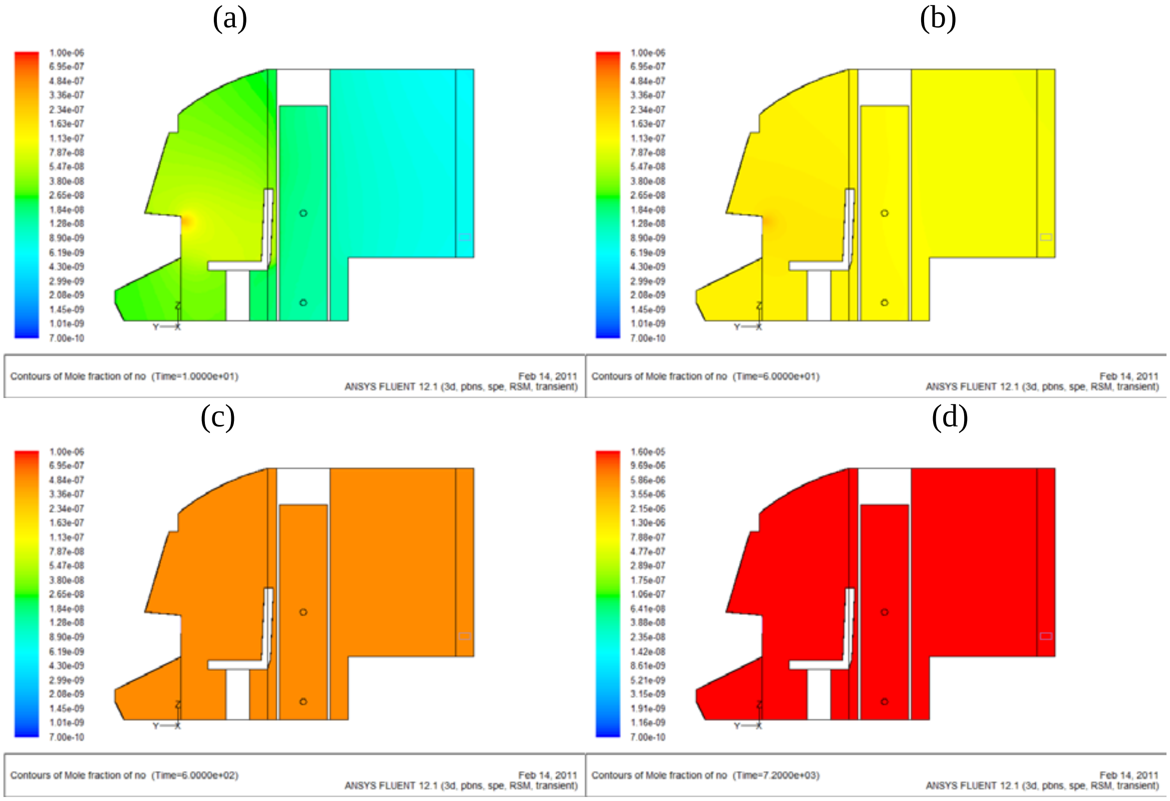


Figure 31: NO Concentration Distribution inside the Cabin in the TRUCK Test Conditions at Physical Time of (a) 10 s, (b) 60 s, (c) 600 s, and (d) 7200 s

Comparisons of Pollutant Concentrations

As shown in the simulation results in above sections, pollutant concentrations inside the EERF became uniform in a similar time frame because the flow is mainly driven by the fans; approximately 22.5 min for APU Truck idling as shown in Figure 32 and approximately 21 min for as shown in Figure 33. However, for concentrations inside the cabin, the test results showed that the faster and more truck AC flows caused faster infiltration than the slower and less APU AC flows; approximately 45 min for APU as shown in Figure 34 and approximately 22.5 min for truck idling as shown in Figure 35.

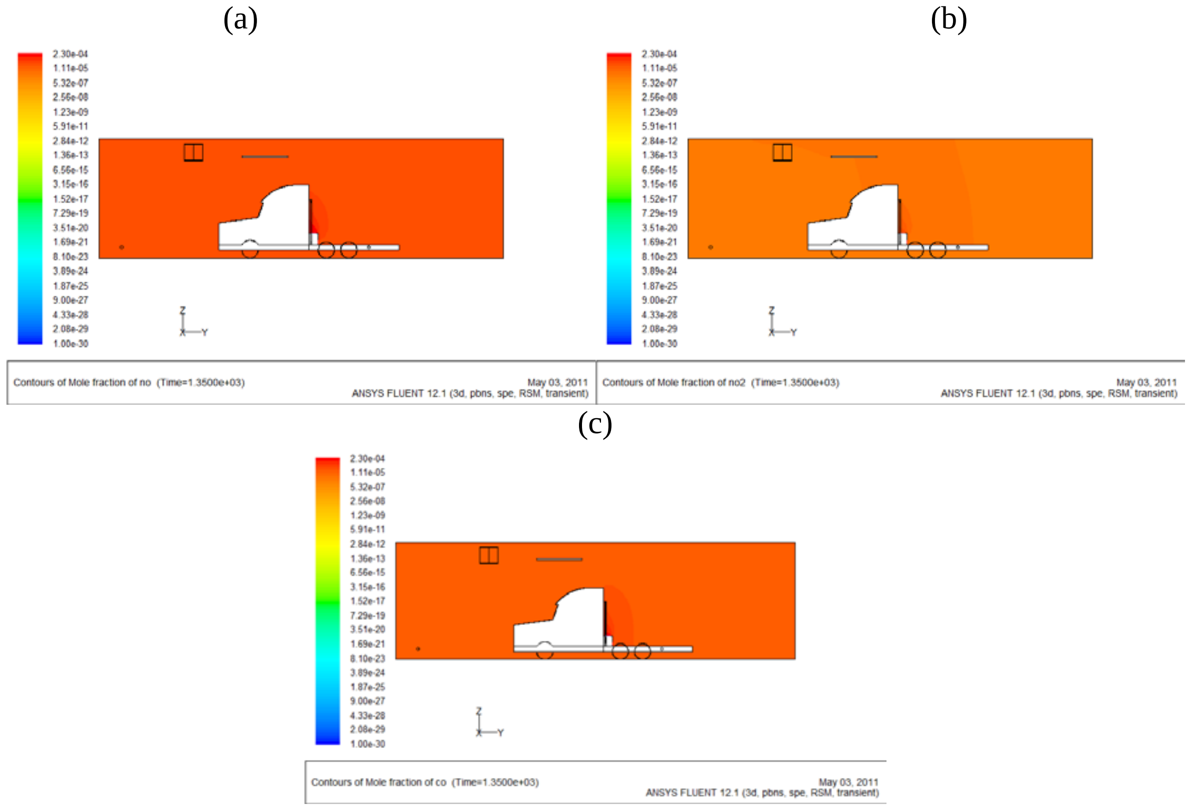


Figure 32: Pollutant Concentration Distribution inside the EERF in the APU Test Conditions at Physical Time of 22.5 min: (a) NO, (b) NO_2, (c) CO

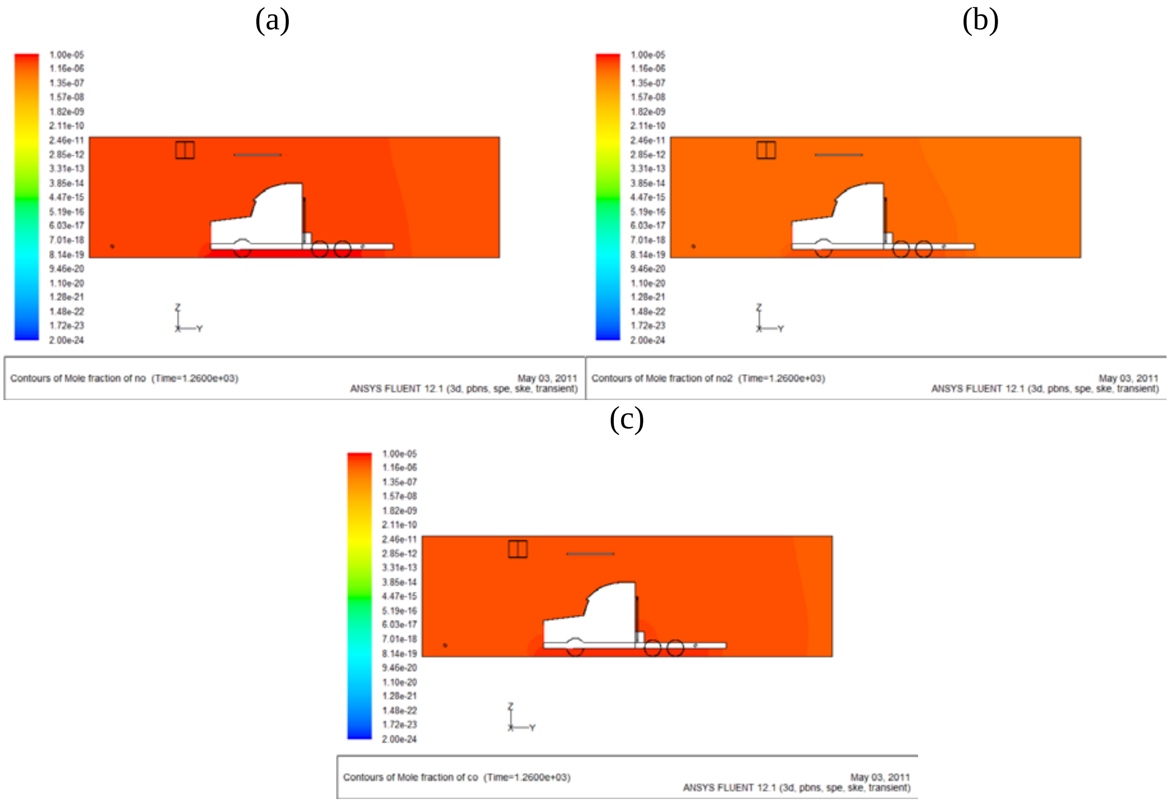

(a) (b) (c)

Figure 33: Pollutant Concentration Distribution inside the EERF in the Truck Idling Test Conditions at Physical Time of 21 min: (a) NO, (b) NO$_2$, (c) CO

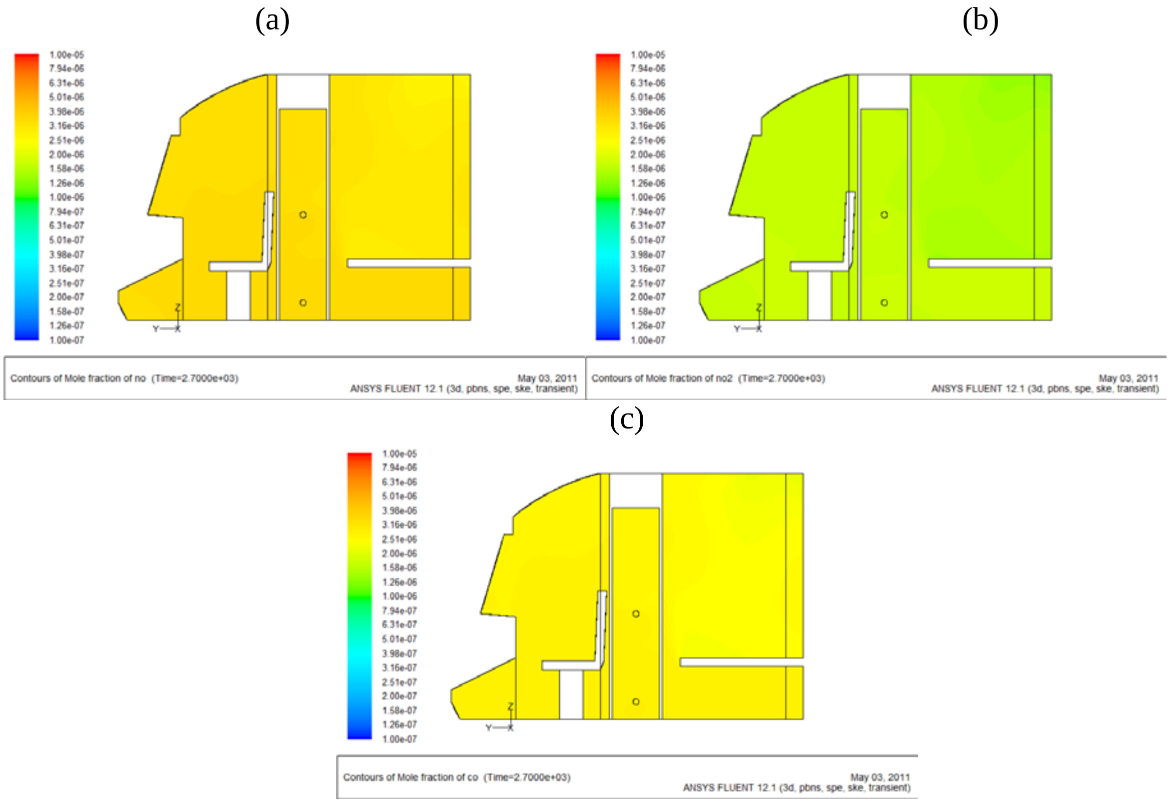


Figure 34: Pollutant Concentration Distribution inside the Cabin in the APU Test Conditions at Physical Time of 45 min: (a) NO, (b) NO_2, (c) CO

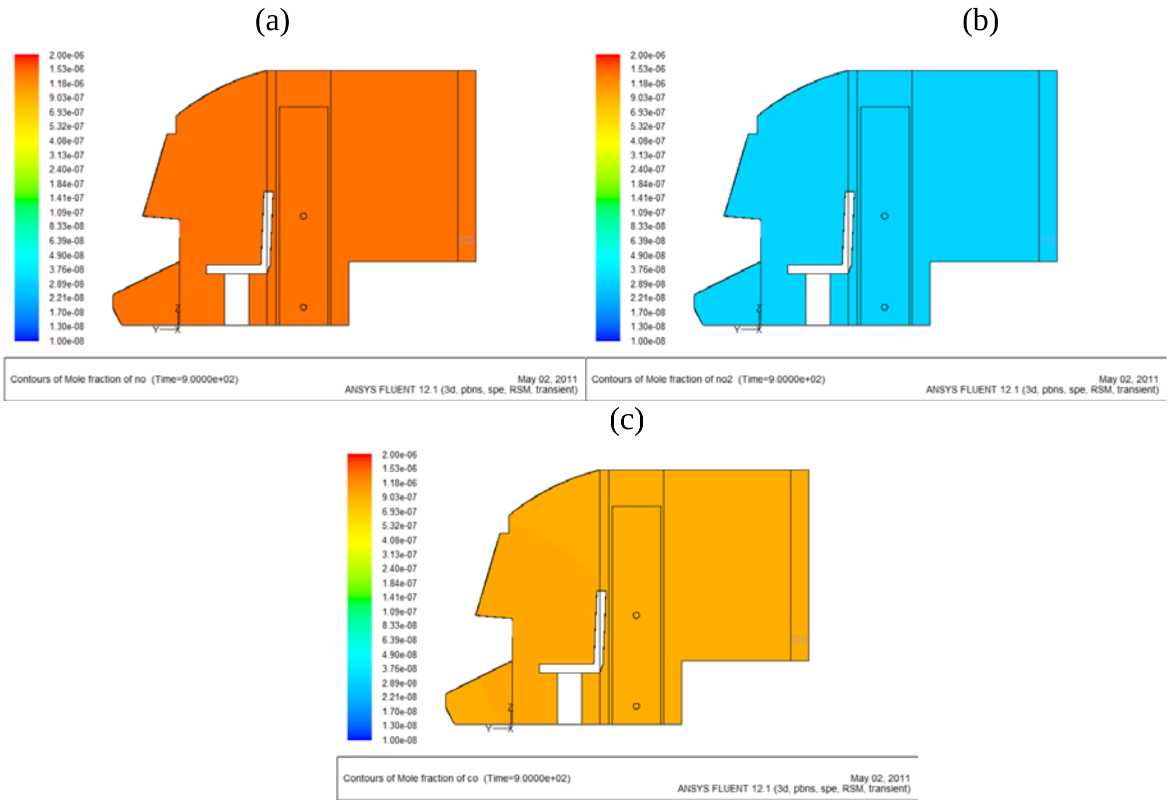


Figure 35: Pollutant Concentration Distribution inside the Cabin in the Truck Idling Test Conditions at Physical Time of 15 min: (a) NO, (b) NO_2, (c) CO

Table 23 shows simulated pollutant concentrations. The results simulated at 4 hours after the testing started showed that the in-cab concentrations during the truck testing (20.4 ppm of NOx and 19.9 ppm of CO) were more than twice of those during the APU testing (9.8 ppm of NOx and 8.6 ppm of CO) while chamber concentrations during the truck testing were about 1.5 times higher than those during the APU testing.

Table 23: Simulated Pollutant Concentrations after 4 Hours of Testing

		Concentration (ppm) at	
		Lateral wall	Driver seat
APU testing	NOx	15.5 ppm	9.8 ppm
	CO	13.5 ppm	8.6 ppm
Truck testing	NOx	23.2 ppm	20.4 ppm
	CO	21.3 ppm	19.9 ppm

The infiltration emissions source concentrations would be much higher for truck idling in the field than for APU operation. The chamber simulation results for the TRUCK test were obtained only with crankcase emissions not exhaust emissions, which are greater than the crankcase emissions, but were transported out during the test. In the field where truck emissions rather than crankcase emissions would be the main infiltration sources, truck idling would provide more infiltration into the truck's cabin than APU operation.

Development of a Web-Based Information System

The purpose of this task is to create a web-based information system that is accessible to all stakeholders, including EPA, the trucking industry, IRT manufacturers, and others in a user-friendly format. The system shall include information such as emissions, fuel consumption, and AC and/or Heat performance of both class 8b long-haul trucks as well as the different categories of IRT devices.

The web-based system will be developed and hosted on TTI's web server. This server allows TTI access to continually update the data as more testing occurs in the future. The address of the website will be http://ttiairquality.tamu.edu/eerftesting. The website will allow users to search the database of past testing results, for both IRT devices as well as trucks that are tested under the protocol.

The website will also have a copy of the current version of the protocol available. This will allow users that are viewing the testing results to see the procedures that were used to obtain the results. Any future changes to the protocol will be updated on the website in an effort to keep all interested parties informed of the current status of the protocol.

Concluding Remarks

TTI research team developed a NOx verification protocol for testing IRT devices and performed testing of selected IRT devices following the developed test protocol. Testing of truck idling under various modes and conditions, for different truck types, was also performed to compare the testing results of IRTs with the truck idling results. In addition, noise tests and infiltration tests were performed. A summary of the major contributions and findings of this research are described below:

- A verification protocol for IRT devices was developed as part of this research. While the primary focus was for NOx emissions verification, the protocol also covered other emissions, fuel consumption and energy performance, noise levels, and overall temperature performance of IRT devices. The development of the verification protocol was based on an investigation of relevant literature and resources including national testing standards and recommended practices, consultation with EPA staff and discussions with IRT device manufacturers. Based on lessons learned during the course of this project, the draft protocol was revised, and the revised protocol is attached in Appendix A.
- The testing of the selected IRT devices was performed based on the developed protocol, and the collected test results were compared with the results from the baseline testing of idling trucks. IRT devices were selected in consultation with EPA staff, and the selected IRT devices were tested per the test protocol under different test conditions (cold and hot) inside TTI's EERF. Testing was performed in a controlled environment (temperature and/or relative humidity). The test results from the IRT devices were compared with truck idling test results (baseline data) also conducted inside TTI's EERF.
- For all of the measured IRT devices, the NOx emission rates were lower than the baseline truck emissions. The IRTs' CO_2 and other pollutant emissions and fuel consumption rates were overall lower than or close to the baseline values. The only exception was the PM emissions rates of the diesel APUs, which showed higher emissions than the baseline truck.
- While the test trucks were able to reach and maintain the desired cabin temperature for both hot and cold test conditions, the diesel APUs could do so for only hot conditions, and the TSE unit could not reach the desired cabin temperature for both hot and cold conditions. Battery APUs (tested only for hot conditions) and DFHs (tested for only cold conditions) could not reach the desired cabin temperatures, either.
- Comparison of Truck #1 tests under different ventilation modes indicated that fuel consumption and emissions rates with ventilation (Air-In mode) were either lower than or not statistically different (at the 95 percent confidence level) from the baseline (Re-Cir mode, i.e., with cabin air recirculation).
- The comparison of truck emissions/fuel consumption at different engine idle speeds (i.e., low, medium, and high idle modes) for Truck #1 showed that as the engine speed increased, fuel consumption and CO_2 and other pollutants' emissions rates were higher, with the exception of NOx and THC.
- For the comparisons of different trucks under both of hot and cold test conditions, the fuel consumption and CO_2 emission rates of one of the MY11 trucks were higher than the baseline, which can be attributed to the truck having more power and operating at a

higher engine speed (700 RPM). However, all other emissions for this truck were lower than the baseline. For the other MY11 truck, the fuel consumption and all emissions rates were less than the baseline.

- All the IRT devices except the TSE unit were tested for noise outside of EERF as described in the protocol, and the observed noise levels were below 70 db. Using CFD, the pollutants distributions in the EERF and inside cabin of TTI 06 truck were simulated to study cabin infiltration during truck idling and during operation of one of the APUs. The simulation showed that concentrations became uniform throughout the EERF test chamber over similar time periods for the truck test and the APU test, which is expected because the flow is mainly driven by the EERF's air conditioning fans. However, for concentrations inside the cabin, the cabin infiltration occurred faster when the truck engine was running than when the APU was operational.

This research project developed a verification protocol for the comprehensive evaluation of the performance of IRT devices from both a user perspective and in terms of the environmental benefits such as emissions reduction and fuel consumption reduction. No such protocol currently exists, and this allows for testing of IRT device performance on a common basis, under controlled conditions. The results from the testing of IRT devices, and comparison with data collected from idling trucks, provide an overview of the relative emissions and fuel benefits, and the performance of these devices in terms of various parameters including noise, cabin infiltration, and ability to reach and maintain desired temperatures. The results of this research will be very useful as the use of IRT devices continues to increase among long-haul truck fleets.

References

1. *Current U.S. Idling Situation*. http://www.makealeap.org/current_idle_situation, accessed February 2011.

2. *Guidance for Quantifying and Using Long Duration Truck Idling Emissions Reductions in State Implementation Plans and Transportation Conformity.* Publication EPA420-B-04-001. U.S. Environmental Protection Agency, Washington, D.C., January 2004.

3. Zietsman, J., Bubbosh, P., Li, L., Bochner, B. S., and Villa, J.C. *National Deployment Strategy for Truck Stop Electrification.* Preprint of the 86th Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C. 2006.

4. Stodolsky, F., Gaines, L., and Vyas, A. *Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks.* Center for Transportation Research, Argonne National Library for U.S. Department of Energy, June 2000.

5. Irick, D. K. and Wilson, B. NOx Emissions and Fuel Consumption of HDDVs during Extended Idle. 12th Annual On-Road Vehicle Emissions Workshop, San Diego, CA, April 2002.

6. Wilson, B. *A Research Agenda for Extended Idling.* IdleAire Technologies Corporation, Knoxville, TN, July 2002.

7. *Study of Exhaust Emissions from Idling Heavy-Duty Diesel Trucks and Commercially Available Idle-Reducing Devices*. Publication EPA410-R-02-025. U.S. Environmental Protection Agency, Office of Air and Radiation, October 2002.

8. Lutsey, N., Brodrick, C., Sperling, D., and Lipman, T. *Market Potential of Fuel Cell Auxiliary Power Units in Long-Haul Trucks.* Preprint of the 83rd Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C., 2004.

9. Zietsman, J., Schneider, W., and Borowiec, J. *Increasing Fleet Content of Clean and Energy Efficient Vehicles.* Texas Department of Transportation, August 2004.

10. Zietsman, J., Bochner, B. S., and Perkinson, D. G. *Determination of Extended Idling Portion of Mobile Source Emissions Inventories.* Texas Department of Transportation, Austin, TX, November 2005.

11. Zietsman, J. and Perkinson, D. G. “Estimating Extended Idling Emissions of Heavy Duty Diesel Trucks in Texas.” In *Transportation Research Record* 1941, Transportation Research Board, National Research Council, Washington, D.C. 2005, pp. 34–42.

12. *Solid Oxide Fuel Cells.* http://www.csa.com/discoveryguides/fuecel/overview.php, accessed April 2011.

13. 'Clean-Idling' Technology Could Stop Trucks from Wasting a Billion Gallons of Fuel Annually in the U.S. http://earthandindustry.com/2010/08/how-to-stop-idling-trucks-from-wasting-1-2-billion-gallons-of-fuel-annually-in-the-u-s/, accessed March 2011.

14. *Guidance for Quantifying and Using Long Duration Truck Idling Emissions Reductions in State Implementation Plans and Transportation Conformity*. EPA 420-B-04-001, U.S. Environmental Protection Agency, Washington, D.C., January 2004.

15. Motor Vehicle Emission Simulator Highway Vehicle Implementation (MOVES-HVI) Demonstration Version. http://www.epa.gov/otaq/models/ngm/movesdemo/420p07001.pdf, accessed, November 2007.

16. American Transportation Research Institute (ATRI). *Compendium of Idling Regulations*, http://www.atri-online.org/research/idling/ATRI_Idling_Compendium.pdf. Accessed on April 2011.

17. Lutsey, N., Brodrick, C-J., Sperling, D., and Oglesby, C. "Heavy-Duty Truck Idling Characteristics: Results from a Nationwide Truck Survey," *Transportation Research Record: Journal of the Transportation Research Board* 1880, 2004. 29–38.

18. Storey, J. M., Thomas, J. F., Lewis, Sr., S. A., Dam, T. Q., and Edwards, K. D. "Particulate Matter and Aldehyde Emissions from Idling Heavy-Duty Diesel Trucks." *Society of Automotive (SAE) Technical Paper*. No. 2003-01-0289, 2003.

19. Zietsman, J., Villa, J. C., Forrest, T. L., and Storey, J. M. *Mexican Truck Idling Emissions at the El Paso - Ciudad Juarez Border Location*. Texas Transportation Institute, 2005.

20. Lambert, D. C., Vojtisek-Lom, M., and Wilson, P. J. *Extended Idling Emissions Study*. IdleAire Technologies Corporation, 2002.

21. Gaines, L. and Hartman, C. J. B. Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks. Submitted for 88th Annual Meeting of the *Transportation Research Board*, 2009.

22. Lim, H. *Study of Exhaust Emissions from Idling Heavy-Duty Diesel Trucks and Commercially Available Idle-Reducing Devices*. U.S. Environmental Protection Agency, 2002.

23. Zietsman, J., Farzaneh, M., Storey, J. M., Villa, J. C., Ojah, M., Lee, D.-W., and Bella, P. *Emissions of Mexican-Domiciled Heavy-Duty Diesel Trucks Using Alternative Fuels*. Texas Transportation Institute, 2007.

24. Khan, A. S., Clark, N. N., Thompson, G. J., Wayne, W. S., Gautam, M., and Lyons, D. W. “Idling Emissions from Heavy-Duty Diesel Vehicles: Review and Recent Data.” *Journal of the Air & Waste Management Association*, 56 (2006): 1404–1419.

25. Lee, D.-W., Zietsman, J., Farzaneh, M., Li, W.-W., Olvera, H. A., Storey, J. M. E., and Kranendonk, L. “In-Cab Air Quality of Trucks Air Conditioned and Kept in Electrified Truck Stop,” *Transportation Research Record: Journal of the Transportation Research Board* 2123, 2009: 17–25.

26. Wagner, F. *Heavy-Duty Truck Idle Reduction Technology Demonstrations*, U.S. Department of Energy (DOE), 2005.

27. Chen, Q. Y. “Ventilation performance prediction for buildings: A method overview and recent applications.” *Building and Environment,* 44: 848–858, 2009.

28. Hu, Z. H. and Sun, D. W. “Effect of fluctuation in inlet airflow temperature on CFD simulation of air-blast chilling process.” *Journal of Food Engineering*, 48: 311–316, 2001.

29. Hoang, M. L., Verboven, P., De Baerdemaeker, J., and Nicolai, B. M. “Analysis of the air flow in a cold store by means of computational fluid dynamics.” *International Journal of Refrigeration*, 23: 127–140, 2000.

30. Lien, S. T. J. and Ahmed, N. A. “Numerical simulation of rooftop ventilator flow.” *Building and Environment*, 45: 1808–1815, 2010.

31. Moureh, J. and Derens, E. “Numerical modeling of the temperature increase in frozen food packaged in pallets in the distribution chain.” *International Journal of Refrigeration*, 23: 540–552, 2000.

32. Yau, Y. H., Ghazali, N. N. N., Badarudin, A., and Goh, F. C. “The CFD Simulation on Thermal Comfort in a library Building in the Tropics.” *AIP Conference Proceedings*, 1233: 1529–1534, 2010.

33. Amin, M., Dabiri, D., and Navaz, H. K. “Tracer gas technique: A new approach for steady state infiltration rate measurement of open refrigerated display cases.” *Journal of Food Engineering*, 92: 172–181, 2009.

34. Lawrence, T. M. and Braun, J. E. “Evaluation of simplified models for predicting CO2 concentrations in small commercial buildings.” *Building and Environment*, 41: 184–194, 2006.

35. Foster, A. M., Swain, M. J., Barrett, R., and James, S. T. “Experimental verification of analytical and CFD predictions of infiltration through cold store entrances.” *International Journal of Refrigeration*, 26: 918–925, 2003.

36. Yang, J. R., Li, X. T. and Zhao, B. “Prediction of transient contaminant dispersion and ventilation performance using the concept of accessibility.” *Energy and Buildings*, 36: 293–299, 2004.

37. Huang, H., Ooka, R., Chen, H., Kato, S., Takahashi, T., and Watanabe, T. “CFD analysis on traffic-induced air pollutant dispersion under non-isothermal condition in a complex urban area in winter.” *Journal of Wind Engineering and Industrial Aerodynamics*, 96: 1774–1788, 2008.

38. Deng, T., Yang, Z, Zou, L., Zhang, Q, Li, J., and Zhang, G. “Visual Simulation and Evaluation on Transmission Path of Contaminants in a Ventilated Room.” Fifth International Workshop on Energy and Environment of Residential Buildings and Third International Conference on Built Environment and Public Health, Vols I and II, Proceedings, 481–489, 2009.

39. Massman, W. J. “A review of the molecular diffusivities of H2O, CO2, CH4, CO, O-3, SO2, NH3, N2O, NO, AND NO2 in air, O-2 AND N-2 near STP.” *Atmospheric Environment* 32**:** 1111–1127, 1998.

Appendix A – Verification Protocol

Draft Framework for Idle Reduction Evaluation Program – Rev. 2.3.K 03/09/2011

1. Scope and General Provisions

1.1. Scope and Applicability

a. The recommended procedures of this document apply to portable idle reduction technologies (PIRTs) for evaluating their fuel consumption, emissions, noise, and energy performance in a controlled environment and under standardized testing procedures.

b. This document is applicable to four major categories of commercially available PIRTs: internal combustion auxiliary power units (IC-APUs, including generator sets), battery-powered heating and air conditioning (BP-HVAC) systems, direct-fired heaters (DFH), and thermal storage cooling (TSC) systems.

c. This evaluation process will address four elements of PIRT operational characteristics: emissions of key pollutants (oxides of nitrogen [NOx - NO and NO_2], carbon monoxide [CO], carbon dioxide [CO_2], total hydrocarbon [THC], and particulate matter [PM]), fuel consumption, noise, and energy performance.

d. The evaluation procedures of this document address only the performance of a PIRT unit in de-greened state. Durability evaluation or aged performances are not covered by the procedures.

e. Only commercially available products can be considered for formal evaluation under the evaluation procedures of this document. Non-commercial products and those in the status of research and development (R&D) may apply the testing procedures of this document for informal evaluation.

1.2. Record Keeping

a. Forms: The following forms should be filled out by applicants and testing organizations prior to, during, and after conducting all tests.

   i. F1 - Application Form: The application form will be filled out by the applicant. The form will include all necessary information about the applicant and the PIRT unit that is being submitted for testing.

ii. F2 - Truck Form: The truck form is to be filled out by the testing organization. It contains all details about the truck that will be used for the test. Applicants can obtain a copy of this form prior to testing.
iii. F3 - Test Form: The test form is to be filled out by the testing organization during testing. It will contain all relevant facts about the test procedure, special notes that are made during the test, and all other information that is collected to be used in the evaluation statement.
iv. F4 - Evaluation Statement: The evaluation statement (ES) is the form that is filled out by the testing organization after the test data have been collected and analyzed. The ES will include all test results from all relevant tests for the PIRT.

1.3. References

a. RTI-EPA CR826152-01-03 p. 21.
b. 40CFR Part 1065.25.
c. CARB CCR Title 13 Division 3 Chapter 14 p. 1.
d. 40 CFR Part 1065.1001.

1.4. Definitions

a. Applicant: The applicant is the person/organization that is requesting that their PIRT be tested.
b. Portable Idle Reduction Technology (PIRT): A device that is installed on a long-haul truck to offer drivers amenities like air conditioning and electricity to the sleeping cabin during driving breaks while the engine is turned off.
c. Internal Combustion Auxiliary Power Unit (IC-APU): A PIRT unit that is powered by an internal combustion engine. IC-APUs usually provide conditioned air as well as electricity to the cabin.
d. Battery-Powered Heating, Ventilation, and Air Conditioning (BP-HVAC) System: A PIRT unit that is powered by a battery-powered electrical system to offer ventilation and air conditioning to the sleeping cabin.
e. Thermal Storage Cooling (TSC) System: A PIRT unit that provides cooling to the sleeping cabin through a thermal storage system. A thermal storage system stores energy in cold storage as the truck is driven and then provides air conditioning when the truck is turned off.
f. Direct-Fired Heaters (DFHs): A PIRT system that provides only heat by combusting fuel that is drawn from the truck's main or other fuel tanks.
g. Integrated PIRT System: A PIRT system that is integrated to a truck's system in a way that moving it to other trucks is not possible or has significant adverse impact on the performance of the PIRT system.

h. Add-On PIRT System: A PIRT system that is not designed for a specific truck so that it can be moved from one truck to another with a few modifications, if any.
i. Test Vehicle: A long-haul truck with a sleeping cabin (night cabin) that is used by the testing organization for the purpose of testing the performance of a PIRT system.
j. Test Unit: A PIRT unit that is submitted to the testing organization to be tested.
k. Test Run: A test run is a single test event for an evaluation element of a test sequence. Multiple test runs can be included in a single test sequence; e.g., multiple fuel consumption measurements.
l. Test Sequence (also test): A series of testing runs conducted on a PIRT unit to evaluate its performance. Multiple evaluation elements such as exhaust emissions, fuel consumption, and energy performance, can be run during a single test. A single test sequence could include multiple test runs for different evaluation elements. The noise evaluation test must be run as a separate test.
m. De-Greening Period: A brief period of use needed to achieve a stable PIRT performance that allows representative testing.
n. Aging: Entails subjecting the PIRT unit to operating conditions that cause normal wear equivalent to at least 33% of the expected durability period declared by the manufacturer.

2. Measurement Instruments and Equipment

2.1. Emissions

a. Emission Measurement Instruments

  i. This test procedure adopts the requirements for laboratory exhaust gas sampling and analysis systems and PM sampling and dilution systems established in the federal emissions certification program described in 40 CFR Part 1065. For equipment and specifications not covered by that citation, 40 CFR Part 86, Subpart N will apply.
  ii. Measurements can be also performed using a portable emissions measurement system (PEMS) that contains instruments using the same measurement technologies and meeting the same audit criteria as the instrument described in 40 CFR Part 1065 Subpart D.

2.2. Fuel Consumption

a. The fuel flow meter method requires a fuel flow meter must be capable of temperature density compensation and must be calibrated to a minimum accuracy of ±1% at a flow rate consistent with the PIRT unit being tested.
b. The gravimetric measurement method requires a good quality scale, accurately calibrated in increments of 0.1 lb (45 g) or 1 oz (28.4 g). Scales should have a resolution of 0.1% of the expected fuel mass consumed (approximately 1/10 oz for

1 gallon diesel fuel). When reading a scale with graduation marked at each ounce, it is a simple matter to interpolate to 1/4 oz.

c. The carbon balance method must be conducted to comply with EPA's regulations as outlined in 40 CFR Part 600, and 40 CFR part 86 subpart N. Carbon balance fuel efficiency must be calculated using the method outlined in SAE Standard J1094a.16.

2.3. For determination of fuel consumption by carbon balance, it is acceptable to use either of the options listed in section 2.1.a. Sound Level Measurement

a. Sound level meter: A sound level meter must comply with the requirements of the Type I or S1A of American National Standard Institute (ANSI), specifications for Sound Level Meters, S1.4-1983. Measurements can be made directly by using a microphone or a sound level meter with a data recorder and/or a graphic level recorder or other indicating instrument that meet the requirements of SAE J184.
b. Sound level calibrator: A sound level calibrator must be capable of calibrating a sound level meter within ±0.5 dB.

2.4. Other Measurements

a. Anemometer: An anemometer must be accurate within ±10% at 20 km/h (12 mph).

2.5. References

a. 40 CFR Part 1065 Subpart B.
b. EPA (2007) SmartWay Fuel Efficiency Test Protocol for Medium and Heavy Duty Vehicles.
c. 40CFR Part 1065 Subpart D.
d. 40CFR Part 600.
e. 40CFR Part 86 Subpart N.
f. SAE J1094a.16.

3. Test Application

3.1. General

a. Sufficient information must be recorded to identify the test vehicle, the PIRT system under test, and the test procedures. Minimum information required is shown on forms F1, F2, and F3.
b. PIRT units submitted for this evaluation program must be commercially ready. This requirement is also applied to any engine or other components' control systems associated with the PIRT system.

3.2. Application Process

a. The submitted units must be labeled properly. At a minimum, the label must include the following information: applicant and manufacturer’s information (name, address, phone, and email address), model number, serial number, and date of manufacture.
b. For a given product (brand and model) a single application must be filed. An application can include request for evaluation of more than one unit of a specific product. The applicant may file a new application for the same unit (brand and model) at any time.
c. For a given product (brand and model) only a single evaluation statement (ES) will be issued.
d. Applicants must specify the fueling or charging requirements and recommended procedures and should provide the necessary equipment (e.g., chargers) to testing organization.
e. Applicants must specify the fuel and lubricating oil requirements necessary for proper function of the system. The applicant must also specify any consequences that will be caused by failure to comply with these requirements as well as methods for reversing any negative consequences.
f. Applicants must identify all normal maintenance requirements for their systems including cleaning or replacing components during the testing period. The testing period refers to the period that the PIRT unit stays at the testing facility including storage time and testing period.
g. Applicants must clearly identify what types of services are provided by the submitted PIRT to the sleeper cabin: i.e., electricity, cooling, heating.
h. Applicants must provide recommended sleeper cabin blower settings. These settings will be applied to all measurements for the test unit.
i. When applicable (i.e., IC-APU and DFHs), applicants must clearly define the fully warmed up state for the submitted units either by specific temperature readings of the products or recommended warming up time to reach this state.

3.3. References

a. RTI-EPA CR826152-01-03 p. 28.
b. CARB CCR Title 13 Division 3 Chapter 14 p. 39.

4. Test Preparations

4.1. General Considerations

a. De-greening.

   i. The submitted unit must be in a de-greened condition for the testing. It is the applicant’s responsibility to perform and document de-greening efforts.
   ii. De-greening is defined as a brief period of use needed to achieve a stable operational condition that allows representative testing.
   iii. At a minimum, the de-greening period must include a 25-hour operation for fuel-operated PIRTs or 4 charging-discharge (100% to 20%) cycles for other PIRT systems.
   iv. Alternatively, the de-greening time requirement can be specified and proposed by the technology applicant as indicated by either previous testing or technical requirements. If this time requirement is less than the minimum period stated in the previous paragraph, a technical justification must accompany the proposed alternative de-greening time requirements.

4.2. Warming Up

a. When applicable (i.e., IC-APU and DFHs), measurements must be made when the PIRT system is in a warmed up working condition. In the absence of manufacturers recommendations, use good engineering judgment to determine the warmed up state. A period of 15 minutes of operation is generally considered appropriate for this purpose.

4.3. PIRT Fueling and Charging

a. Fueling – If the submitted PIRT requires fuel from a fuel tank for operation, it must have enough fuel for the duration of the test prior to the test.

b. Charging – The submitted PIRT must be fully charged prior to the test. Charging is not required for each run of a single test (with the exception of the extended duration energy performance test, Section 9.2.b). Charging shall be accomplished using the procedure(s) recommended by the applicants for each PIRT.

4.4. References

a. RTI-EPA CR826152-01-03 p. 20.

5. General Testing Configurations

5.1. Testing Organization

a. The testing organization must have all facilities and instruments required to prepare and perform all testing procedures.

5.2. Testing Facility

a. Fuel consumption, emissions, and energy performance measurements must be performed inside an environmental chamber that can provide consistent ambient conditions (temperature and relative humidity) for the entire duration of testing.
b. Noise measurements must be performed in a location that meets the criteria of paragraph 8.2.h.

5.3. Test Fuels and Engine Fluids

a. Fuels

   i. Standard highway diesel meeting 40 CFR part 1065 subpart H. A fuel analysis must be attached to the evaluation statement (form F4).
   ii. A winterized diesel (85% standard highway diesel and 15% kerosene with maximum 15 ppm sulfur content) shall be used for heating tests.
   iii. Applicants should specify the special fuel requirement for the device if the required fuel is different from the standard test fuel described above.
   iv. The unit must be fueled from the same fuel source during the entire test to ensure consistent fuel quality.

b. Lubricants

   i. Applicants must specify and provide all necessary lubricants that are required to operate the submitted PIRT.

c. Coolants

   i. Applicants must specify and provide all necessary coolants that are required to operate the submitted PIRT.

5.4. Installation of PIRT

a. Applicants are responsible for proper installation of their unit on the test truck.
b. Due to the fact that the test unit will be removed after the test, the applicant and the testing organization may agree to a modified installation of the unit. However, modifications should not affect the performance of the unit. Modifications can be made

only to protect the test vehicle from damage due to installing and uninstalling the unit and must be reported on the ES.

5.5. Standard Truck Cabin Features/Description

a. The testing organization must supply the applicants with the following information about the test vehicle. These features should also be included in the truck form (form F2) as well as noted on the ES (form F4).
    i. Dimensions.
    ii. Make and Model.
    iii. Model Year.
    iv. Insulation: including location and R-value for cabin insulation and curtain.
    v. Color: exterior color is important for the solar load.

b. Standard cabin insulation features such as door seals and sleeper curtain must be in good shape and free of any obvious leak or damage.

5.6. Service Loading

a. If the unit provides electricity to the cabin (APUs and BP-HVAC), a constant standard load 120 Watt must be applied to the unit for all measurements. This load is equivalent to a typical laptop computer and a small television.

b. Two ambient conditions (test chamber settings) are considered for fuel consumption, emissions, and energy performance measurements. Each condition represents different services to be provided to sleeper cabin, i.e., cooling or heating.
    i. Ambient condition for cooling testing: Measurements must be made at an ambient temperature of 100±4°F (38±2°C), a relative humidity (RH) of 50±5%, and a 600±10 W/m^2 vertical solar load measured at the roof's surface on the vehicle.
    ii. Ambient condition for heating testing: Measurements must be made at an ambient temperature of 0±4°F (−18±2°C), and a wind load blowing directly into the face of the truck at an average speed of 20±2 mph (32±3.2 km/h). The average wind speed measurements are made at the points shown by "X" signs in FIGURE Figure 1.

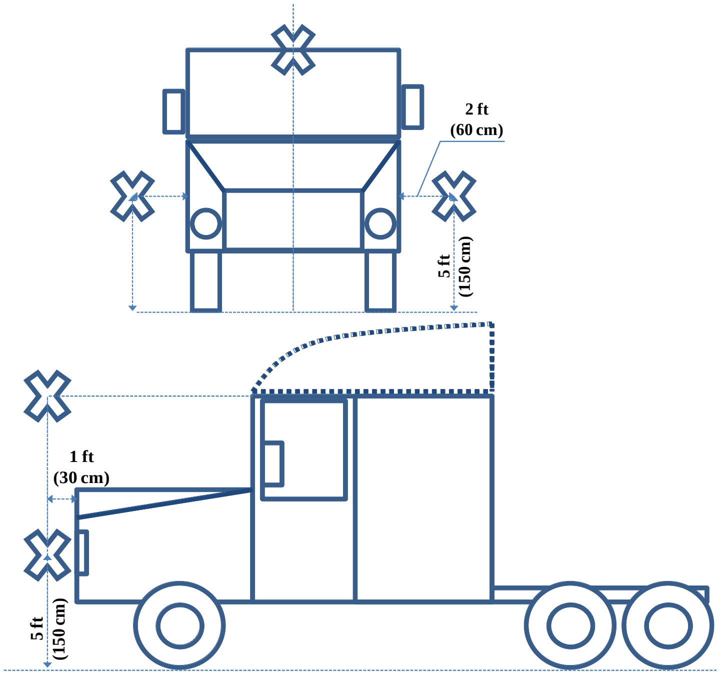


Figure 1: Locations of Wind Speed Measurements

c. All the measurements must be performed under steady-state ambient conditions. This requires that the key ambient parameters (i.e., temperatures, relative humidity, solar load, and/or wind speed) must remain within their desired range for at least a 5-minute period before the testing starts.

d. A sleeper cabin soak time of no shorter than 30 minutes at 73±2°F (23±1°C) is required before the first test run can begin. The truck's main engine or other means, such as a space heater, can be utilized to reach and maintain this target temperature prior to the testing.

e. All the measurements must be started when steady-state temperature of the cabin is at 73±2°F (23±1°C). This requires that the cabin temperature must remain within 73±2°F (23±1°C) range for at least a 5-minute period prior to the test.

f. A test run may begin once the sleeper cab has maintained a steady-state temperature in the cabin of 73±2°F (23±1°C) for a minimum of 5 minutes. The truck's main engine or space heater, or other means, may be used to achieve this steady state condition. If used the other means must be turned off prior to beginning the test run. The test run is said to have started when both the test unit has been turned on and all other devices used to achieve the target temperature have been turned off. With the exception of an extended duration energy performance test (Section 9.2.b) the test unit may be used, alone or together with other devices, to assist in reaching the steady-state temperature.

5.7. Measurement of Cabin Temperature

a. It is required to collect and record cabin temperature at a minimum frequency of 0.1 Hz for the entire duration of fuel, overall energy performance, and emissions measurement. Other measurements should have a minimum frequency of 1 Hz.

b. There must be six thermal probes in the sleeper compartment's area as shown in FIGUREFigure 2.[1]

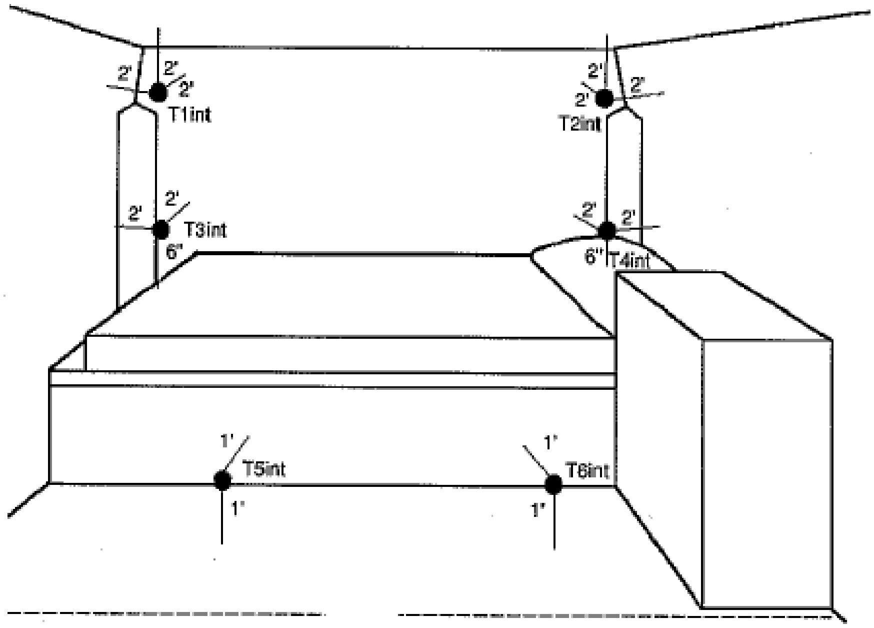


Figure 2. Location of Temperature Probes.

c. The sleeper cabin temperature is presented as the average of the six probes.

d. An optional single thermal probe may be installed at the front of PIRT's outlet vent to measure the initial temperature of the heated/cooled air. This temperature may be included on the ES for the tested unit, but should not be included in the calculation of the sleeper cab temperature.

5.8. Minimum Number and Duration of Tests

a. The recommended number and duration of test runs for each measurement are selected to provide statistical significance at 5% significance level (i.e., with 95% confidence). The number of runs is discussed in later sections based upon the measurement being taken.

---

[1] ATA Technology and Maintenance (TMC) 432

5.9. Other Considerations

a. The sleeper curtain will be always closed during the measurement for all the tests covered in this document, unless the blower of the test unit is located in front of the curtains. In this case the curtains may remain open, but the configuration must be noted in the ES.
b. For all the measurements, the PIRT's thermostat must be set so the steady state temperature in the cabin can reach the target value of 73±2°F (23±1°C). The reading on the thermostat that is required to meet the temperature must be reported in the ES. If the PIRT does not have a thermostat the blower controls should be adjusted so that the steady state temperature in the cabin reaches 73±2°F (23±1°C).
c. If the PIRT is unable to meet the required steady state temperatures inside the cabin then the ES shall include the temperatures PIRT was capable of reaching at max setting.

5.10. References

a. 40 CFR Part 1065 Subpart H.
b. ATA Technology and Maintenance (TMC) 432.

6. Fuel Consumption Measurement

6.1. General

a. Fuel consumption measurement is required for PIRTs, which consume fuel to deliver service. IC-APUs and DFHs are examples of this group.
b. Fuel consumption measurement can be performed using any of the following methods: Fuel Flow Meter, Gravimetric Measurement, and Carbon Balance Method as described in part 2.2.
c. This test procedure is structured for fuel consumption measurement of PIRT systems at their fully warmed up state as described in definitions provided by the manufacturer or applicant. The cold start fuel consumption can be measured and recorded for the first test run only.
d. No more than 1 person can be present inside the cabin during measurements.
e. When a fuel flow meter is used it must be capable of temperature density compensation, must measure and record fuel flow rates at a minimum frequency of 1 Hz, and must be calibrated as described in section 2.2.[2]
f. When the gravimetric measurement method (Portable Weigh Tank Method) is used, fuel consumption is measured by weighing the fuel consumed using a portable fuel tank. In this method, a portable fuel tank is weighed empty, filled with fuel, weighed

---

[2] Directly taken from SAE J1321

again, and then mounted on the test vehicle. The test unit's fuel line is connected to the portable tank the moment the test begins, and disconnected at the conclusion of each test run, after which the portable tank is removed and reweighed. The fuel consumed during the test is calculated using the density of the fuel and the difference in the weight of the portable fuel tank before and after the test, to yield the volume (gallons) of fuel used.

g. Gravimetric measurement requires a portable tank of at least 1 gallon but no larger than 3 gallons capacity. The portable tank must have provisions for both supply and return lines of fuel. The fuel lines connections to the portable tank must be fitted with quick disconnect fittings to allow for removal without spillage. The portable tank weigh method requires a good quality scale that meets the specifications in section 2.2.
h. When using a portable tank, it must be weighed on the same portable scale. The outside of the portable tank should be wiped clean of dirt and fuel each time prior to being weighed. The scale should be placed inside a building to protect it from winds. Scales must be checked with a known deadweight before each series of readings. The deadweight shall be similar to that of a tank filled with fuel. The portable scale must not be moved between the initial and final weighting of a given test run.[3]
i. The fuel temperature in the portable weighing tank must be kept below 160°F (71°C). Fuel coolers can be used to maintain the temperature below this value.
j. When gravimetric measurement method is used, the density of the test fuel must be determined following ASTM Test Method D-1298, Standard Test Method for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer.
k. When the carbon balance method is used, an emission measurement system that meets the criteria of part 2.1 and is capable of performing simultaneous measurement of CO_2, CO, and THC at a minimum frequency of 1 Hz must be used.
l. Test fuel shall be consistent for all the runs of a single test.
m. RPM measurements shall be recorded for all IC-APU systems. A RPM sensor should be used to measure IRT unit's engine speed. At a minimum, the RPM sensor must have a measurement range of 100–10,000 RPM, an accuracy of 1 RPM, and reports/records readings at a minimum rate of 1 Hz.

6.2. Test Procedure

a. Maintain the desired steady-state ambient condition as described in paragraph 5.6.c.
b. Execute the recommended warm up and cabin soaking procedures as described in sections 4.2.a and 5.6.d. Skip this step if the PIRT unit has already warmed up, or does not require warm up, and the cabin has been soaked.

---

[3] Directly taken from SAE J1321

c. Record ambient temperature, relative humidity, wind speed, and solar load. Although these data are not used in calculations, they are useful in evaluation of test results.
d. The PIRT and truck's main engine are turned off. Vehicle windows and vents must be in the closed position for the entire duration of test runs.
e. When using the gravimetric measurement method portable fuel tanks should be full, weighed, and the weight recorded.
f. When the fuel flow meter or carbon balance method is used, the fuel flow meter or emissions measurement instrument is reset and the data recording is started.
g. The unit's thermostat and blower settings are set to the required target values as described in paragraphs 5.9.b., 5.9.c., and 5.9.d.
h. Start the unit and apply the required loading, as described in part 5.6, immediately. The starting time is recorded on the test form. If fuel flow meter or carbon balance method is used, the measurements must be started just prior to starting the unit.
i. Each test run consists of measurements for a continuous operation of the unit for at minimum duration of 60 minutes. A longer period may be needed for gravimetric method. Time to complete a test run must be repeated within ±0.5% (±18 seconds for 60 minutes testing). Fuel consumption data should not be used from runs that failed to repeat time within ±0.5%.
j. At the end of each test run, the unit can be stopped or continue running, depending on the method being used to measure fuel consumption. If the gravimetric method is being used the unit must be stopped immediately to ensure the correct amount of fuel usage is recorded.
k. At the conclusion of each test run, all data are recorded and the measurement instruments are calibrated. The temperature of the sleeper cabin must be brought to the required initial range as described in paragraph 5.6.d prior to the next test run.
l. A test consists of a minimum of three valid test runs. The final fuel consumption is reported as the average of these valid runs.

6.3. References

a. SAE J1321.

7. Emissions Measurement

7.1. General

a. Measurement of pollutant emissions is required for PIRT systems, such as IC-APU and DFHs, which use fuel to deliver service.
b. The following tailpipe emissions are required to be measured and reported: NOx (NO and NO_2), CO, CO_2, THC, and PM.
c. Measurements and reporting of air toxics are optional.

d. Emissions measurements instruments must comply with the criteria stated in section 2.1.
e. This test procedure is structured for emissions measurement of PIRT systems at their fully warmed up state as described in section 4.2.
f. No more than 1 person can be present inside the cabin during emissions measurements.
g. Emissions measurements can run in parallel with fuel consumption and energy performance measurements.
h. Test fuel shall be consistent for all runs of a single test.

7.2. Test Procedure

a. Maintain the desired steady-state ambient condition as described in paragraph 5.6.c.
b. Execute the recommended warm up and cabin soaking procedures as described in sections 4.2.a and 5.6.d. Skip this step if the PIRT unit has already warmed up, or does not require warm up, and the cabin has been soaked.
c. Record ambient temperature, relative humidity, wind speed, and solar load. Although these data are not used in calculations, they are useful in evaluation of test results.
d. The PIRT and truck's main engine are turned off. Vehicle windows and vents must be in the closed position for the entire duration of test runs.
e. Fuel tank must have sufficient fuel for the entire duration of testing.
f. Emissions measurement instruments are reset and data recording should begin. Any filters/cartridges should be prepared and in place for testing.
g. Emission measurement instruments must capture or record the emissions data for the entire duration of the test run.
h. The unit's thermostat and blower settings are set to the required target values as described in paragraphs 5.9.b., 5.9.c., and 5.9.d.
i. The unit is started and the required loading as described in part 5.6 is applied immediately and the starting time is recorded on the test form (form F3). The measurements must be started prior to starting the unit.
j. Each test run consists of a measurement for a continuous operation of the unit for a minimum of 60 minutes. A longer testing period may be needed for filter sample collection. Time to complete a test run must be repeated within ±0.5% (±18 seconds for 60 minutes testing). Emissions data should not be used from runs that failed to repeat time within ±0.5%. A shorter period (e.g., 30 minutes) can be used for filter and cartridge sample collection.
k. At the end of each test run, the unit can be stopped or continue running. Immediately after stopping the test, time is read and recorded, filter samples are removed and stored properly, and other emission data are marked and recorded.
l. At the conclusion of each test run, all data are recorded and the measurement instruments are calibrated. The temperature of the cabin must be brought to the required initial range as described in paragraph 5.6.d. prior to starting the next test.

m. A test consists of minimum of three valid test runs; i.e., within ±0.5% duration time.
n. The final emission rates are reported as the average rates of the valid runs.

8. Noise Measurement

8.1. General

a. This part describes the procedures for determining truck’s sleeper-cab interior sound level due to the operation of PIRT systems. This part applies to all PIRT systems.
b. The sound level measurement must be reported for the reference cab temperature of 25±1°C (77 ± 2°F). If the relationship between the measured sound level and the cabin temperature is known, the test results at other temperatures can be corrected to the nominal reference temperature of 25°C and reported as a “corrected sound level” measurement.
c. Microphones must be held in place in a manner that ensures the mechanical vibration will not affect the sound level measurement.
d. All the measurements must be made with the microphone oriented vertically upward.
e. To minimize the impact of bystanders on the measurements, only 1 person can be present inside the cabin during measurements.
f. When applicable, a test fuel that meets the specifications of part 5.3 must be used for noise measurement. Test fuel shall be consistent for all the runs of a test.
g. When PIRT has multiple blower fan settings, noise measurement shall be performed for all of them.

8.2. Test Procedure

a. Measurements must be made at the expected locations of the operator’s head while using the sleeper cabin. At a minimum, measurements must be made at two points representing operator’s head at sleeping and sitting positions. Use good engineering judgment to interpret the terms ‘‘sleeping’’ and “sitting” in this part to select the measurement points.
b. Vehicle windows and vents must be in closed position.
c. The truck engine and all the accessories must be turned off.
d. The PIRT must be running within the manufacturer’s recommended operating conditions.
e. Use the truck engine to reach the reference temperature of 25°C, turn the engine off, and start the PIRT. Alternatively, the PIRT can be used to reach the reference temperature.
f. When applicable (i.e., for IC-APU and DFHs), measurements must be made when the PIRT system is warmed up as described in part 4.2.

g. Measurements must be made for both heating and cooling modes. The field calibration must be made immediately before and after each test run.
h. No large sound-reflecting surface should be within 15 m (50 ft) of the test vehicle. Figure 3 graphically demonstrates this requirement.

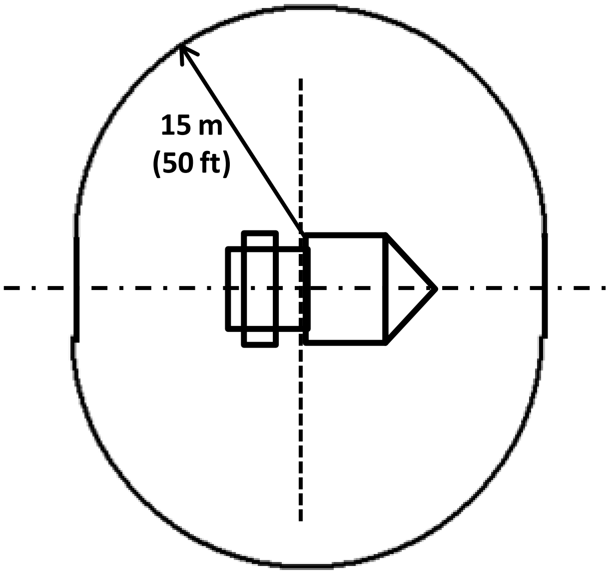


Figure 3. Location Requirement for Noise Measurement.

i. Measurements must be taken on a smooth, dry concrete, or asphalt surface.
j. Wind speed should not exceed 20 km/h (12 mph).
k. A minimum of 3 test runs must be performed. Each test run shall be made within 5 minutes from the previous test. Each test run consists of a minimum of 4 measurement readings that are 30 to 60 seconds apart. The test runs must be repeated until 4 consecutive readings of that run are within a 2dB range. The average of these 4 readings is recorded as representative value for that run.
l. All readings must be the A-weighted sound level measurements.
m. The reported sound level will be the highest average test run sound level value.
n. The observer is cautioned to rerun a test if unrelated peaks should occur. Peaks are due to sounds coming from other sources not caused by the operation of the PIRT.
o. If a data recording system is used, make a recording during each test run. Record a calibration signal of known acoustic level immediately prior to and following each test run. For analysis of the test run recordings, use the calibration signal to establish a playback gain and thus calibrate the analysis system. Set the level indicating instruments for “fast-exponential-averaging” or equivalent for analysis of the recorded data.

Table 1: Calculation Table for Noise Measurements.

			A-weighted Sound Level (dB)								
	Temperature ^{0}C (^{0}F)	Relative Humidity %	Measurement 1	Measurement 2	Measurement 3	Measurement 4	Measurement 5	Measurement 6	Measurement 7	Measurement 8	Average of consecutive 4 measurements within 2dB
Run 1											
Run 2											
Run 3											
Run 4											
Run 5											
Run 6											
										Final Sound Level (db)	

8.3. References

a. SAE (2001) SAE J336: Sound Level For Truck Cab Interior, SAE Recommended Practice.
b. SAE (2000) SAE J1096: Measurement of Exterior Sound Levels for Heavy Trucks Under Stationary Conditions, SAE Recommended Practice.
c. SAE (1998) SAE J184: Qualifying A Sound Data Acquisition System, SAE Recommended Practice.

9. Energy Performance Measurement

9.1. General

a. Two sets of energy performance (EP) testing shall be performed depending on types of PIRT systems: overall energy performance (OEP) and extended duration energy performance (EDEP) testing.
b. Overall energy performance testing is required for all PIRT systems. Extended energy performance testing is required only for PIRT systems that are charged while a truck's main engine is operating. BP-HVACs and TSC systems are examples of this type.
c. OEP testing includes measurements representing the average EP of the PIRT system while it maintains the target sleeper cabin temperatures. The purpose of this testing

procedure is to determine the duration that the PIRT system can continuously provide service to the sleeper cabin.

d. EDEP testing consists of measurements demonstrating the ability of the PIRT system to provide service to the sleeper cabin for an extended period of time.
e. No more than 1 person can be present inside the cabin at any time during the testing.
f. Energy performance measurements can run in parallel with fuel consumption and emissions measurements.

9.2. Test Procedure

a. Overall Energy Performance (OPE) Testing.
    i. Truck's main battery and the PIRT system must be fully charged before the first measurement.
    ii. Maintain the desired steady-state ambient condition as described in paragraph 5.6.c.
    iii. Execute the recommended cabin soaking procedures as described in paragraph 5.6.d. No warm up is needed for this test.
    iv. Record ambient temperature, relative humidity, wind speed, and solar load. Although these data are not used in calculations, they are useful in evaluation of test results.
    v. The unit and truck's main engine are turned off. Vehicle windows and vents must be in closed position for the entire duration of test runs.
    vi. Electricity and temperature measurement instruments are reset and data recording should begin.
    vii. Electricity and temperature instruments must capture and record data for the entire duration of a test run.
    viii. The unit's thermostat and blower setting are set to the required target values as described in paragraphs 5.9.b., 5.9.c., and 5.9.d.
    ix. The unit is started and the required loading per paragraph 6.5.a is applied immediately, the starting time is recorded, and data recording is started. The measurements must be started prior to starting the unit.
    x. Each test run consists of a measurement for a continuous operation of the unit for at least 60 minutes. A longer testing period may be needed when no solar load is applied for cooling testing. Time to complete a test run must be repeated within ±0.5% (±18 seconds for 60 minutes testing). Data should not be used from runs that failed to repeat time within ±0.5%. The operational events of these runs must be identical.
    xi. The following parameters are required to be measured and recorded at a minimum frequency of 1 Hz:
        - BP-HVAC systems: voltage and current at PIRT's output, voltage and current at truck's main battery pack output, sleeper cabin temperature.

  - TSC systems: voltage and current at truck’s main battery pack output, sleeper cabin temperature.
  - IC-APU or DFHs: If these systems connect to the truck battery for any reason the voltage and current must be measured at the truck’s main battery.

xii. At the end of each test run, the unit must be stopped. Immediately after stopping the test, the end time is read and recorded.

xiii. At the conclusion of each test run, all data are recorded and the measurement instruments are checked. The temperature of the cabin must be brought back to the required initial range as described in section 5.6c. prior to starting the next test.

xiv. A test consists of minimum of three valid test runs; i.e., within ±0.5% duration time.

b. Extended Duration Energy Performance (EDEP) Testing.

i. Maintain the desired steady-state ambient condition as described in paragraph 6.5.e.

ii. The PIRT system and truck’s main battery must be fully charged.

iii. Execute the recommended cabin soaking procedures as described in paragraph 6.5.f. No warm up is needed.

iv. Record ambient temperature, relative humidity, wind velocity, and solar load. Although these data are not used in calculations, they are useful in evaluation of test results.

v. The unit and truck’s main engine are turned off. Vehicle windows and vents must be in the closed position for the entire duration of test runs.

vi. Electricity and temperature measurement instruments are reset, and data recording should begin.

vii. Electricity and temperature instruments must record data for the entire duration of a test run.

viii. The unit’s thermostat and blower setting are set to the required target values as described in paragraph 5.9.

ix. Start the unit and apply the required loading, as described in part 5.6, immediately. The starting time is recorded on the test form and data recording is started. The measurements must be started prior to starting the unit. The electrical loading of paragraph 5.6.a will be applied only for the first two hours. After this initial period only the HVAC system must remain operational.

x. The following parameters are required to be measured and recorded at a minimum frequency of 1 Hz:
  - BP-HVAC systems: voltage and current at PIRT’s output, voltage at truck’s main battery pack output, sleeper cabin temperature.
  - TSC systems: voltage at truck’s main battery pack output, sleeper cabin temperature.

xi. Each test run consists of a single measurement for a continuous operation of the unit for 10 hours or until it can no longer provide the necessary services to the sleeper cabin; i.e., reaching the point of no service (PNS). The PNS is reached when the temperature in the sleeper cabin has been continuously out of 73±5°F (23±3°C) range for 10 minutes or the unit turns off. If the unit cannot meet the requirements of 73±5°F (23±3°C), the temperature must remain within ±5°F (±3°C) of the PIRT's optimal temperature. If the unit is still running after 10 hours the applicant and testing organization may agree to keep the test running until the unit turns off. The total duration time that the unit runs is then reported on the ES.

xii. At the end of the test run, the unit must be stopped. Immediately after the test is stopped, the end time is read and recorded.

xiii. At the end of the test run, the test crew must attempt to start the truck's main engine. The result is reported as either "failed" (engine could not be started) or "passed" (engine started) (form). If the truck will not start due to circumstances other than the voltage of the battery, it must be noted on the ES.

xiv. At the conclusion of the test run, all data are recorded and the measurement instruments are checked.

xv. A test consists of minimum of one valid test run.

9.3. Reporting of Results

a. The final energy performance should be reported as follows: electricity usage, the time the target cabin temperature was maintained (for EDEP testing), the time to point of no service (EDEP testing), and whether the engine could be started at the end of the service period (EDEP testing).

9.4. References

a. Department of Defense (1989) Military Standard: Generator Sets, Engine Driven Methods of Tests and Instructions, MIL-STD-705C.

Appendix B – Testing Forms

Form F1- Application Form

Name	
Company	
Address	
Phone Number	
Email	
Model Name	
Power Type	Diesel Battery Other:
Provides	Heating Cooling
Provides Auxiliary Power Outlets	Yes / No
Diesel Engine Specifications	

Form F2 – Truck Form

VIN #				
License Plate				
Model Year				
Make / Model				
Exterior Color				
Reflective Exterior Surface	Yes / No	Type/Color:		
Engine Make / Model				
Engine MY				
Cabin Type	Sleeper Cab	Day Cab	Other	-
Mileage				

Form F3 – Test Form

Test Description				
Date				
Cabin Air Conditioning	AC (cooling)	Heater	None	
Blower/Fan Setting				
Target Engine RPM				
Test Components	Emissions	Fuel	In-Cab Air Quality	Cab Temperature
	CO2 , CO	Fuel Flowmeter	NO , NO2	Number of Probes
	NOx , THC	Gravimetric	CO , THC	
	PM , MSAT	Carbon Balance	Other:	
	Other:			
Start Time				
Starting Ambient Temperature	°F	°C		
Soaking Period Duration @ 73°F				
Starting Cabin Temperature	73°F	23°C		
Starting Ambient RH	50%			
End Time				
End Ambient Temperature	°F	°C		
End Cabin Temperature	°F	°C		
End Ambient RH	%			
Duration				
Notes:				

Form F4 – Evaluation Statement

Test						
Model						
Emissions	CO	CO_2	NOx	THC	PM	MSAT
Exhaust						
In Cab						
Temperature	Cold Test	Chamber		In Cab		
	Hot Test	Chamber		In Cab		
Sound Level	Heat					
	Cool					
Battery Voltage	Start					
	Finish					
Power Consumption						
Fuel Consumption						