Published in final edited form as:

J Build Perform Simul. 2016 ; 9: . doi:10.1080/19401493.2015.1066447.

Model Validation Study of Carbon Monoxide Transport due to Portable Electric Generator Operation in an Attached Garage

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Abstract

A series of tests was conducted to characterize the indoor CO concentrations resulting from portable electric generators operating in the attached garage of a test house under various use and environmental conditions. An extensive model validation effort using the multizone airflow and indoor air quality (IAQ) model CONTAM was carried out using the data from seven tests with a generator operating in the attached garage to compare predicted CO concentrations with measured values. The agreement between the measurements and predictions of the O₂ concentrations in the garage and the average CO concentration for the house zones was excellent for the dataset as a whole. The agreement was somewhat worse for the garage CO concentrations. Overall, the house zone average and garage CO concentration predictions and measurements were within about 20 % and 30 % respectively when averaged over all cases.

Keywords

Portable electric generator; carbon monoxide; CONTAM; indoor air quality; model validation; multizone airflow model

BACKGROUND

The U.S. Consumer Product Safety Commission (CPSC) is concerned about the hazard of acute residential carbon monoxide (CO) exposures from portable gasoline powered generators that can result in death or serious and/or lasting adverse health effects in exposed individuals. As of April 2012, CPSC databases contain records of at least 755 (695 from generator use alone, 60 from generator use in conjunction with another CO-producing consumer product) deaths from CO poisoning associated with consumer use of generators in the period of 1999 through 2011 (Hnatov 2012). In addition, the percentage of estimated

non-fire, consumer product-related CO poisoning deaths specifically associated with generators for CPSC's four most recent years of data are 51 % (2005), 49 % (2006), 38 % (2007), and 49 % (2008) (Hnatov 2011). Typically, these deaths occur when consumers use a generator in an enclosed or partially enclosed space or outdoors near an open door, window or vent, and they often occur after severe weather events such as hurricanes and ice or snow storms.

Since the possession of household generators in the U.S. has climbed continuously in recent years, from an estimated 9.2 million units in 2002 to 10.6 million units in 2005, CPSC is working to avoid future generator-related CO poisoning incidents, especially those associated with operating a generator indoors (CPSC 2006). Measures have been taken to educate people not to operate generators indoors and to require manufacturers of portable generators to warn consumers of CO hazards with a warning label (CFR 2007). In order to understand the CO exposures associated with such incidents and their potential reduction, the emission characteristics of these generators need to be better characterized. In an initial approach to characterizing these hazards, CPSC measured the CO emission rates from generators by testing them in a small, laboratory test chamber (Brown 2006). CPSC subsequently worked with the University of Alabama (UA) to develop a low CO-emission prototype generator by adapting off-the-shelf emission control technologies on a commercially-available portable generator.

In conjunction with these efforts, CPSC established an interagency agreement with the National Institute of Standards and Technology (NIST) to model indoor time course profiles of CO concentrations throughout a single-family residence resulting from CO emissions from a portable generator operating in the attached garage of a home under various use and environmental conditions to enable CPSC staff to understand the safety implications of operating a portable generator in these conditions. This paper describes an extensive model validation effort using the multizone airflow and IAQ model CONTAM carried out using the data from tests with a generator operating in the attached garage of a research house to compare predicted CO concentrations with measured values. A unique aspect of this effort is the validation of the multizone modeling when incorporating a complicated source which is dependent on the changing environmental conditions (i.e., the combustion is O₂ dependent).

EXPERIMENTAL

Test House

The test house used in this study was a manufactured house located on the NIST campus, which was erected in 2002 (Nabinger and Persily 2008). An aerial view and floorplan of the house (as displayed in the CONTAM sketchpad) are shown in Figures 1 and 2. The house includes three bedrooms (MBR, BR2, and BR3), a combination living room/ family room/ kitchen (LFK), and an attached garage. The house has a floor area of 140 m² and a volume of 340 m³. The attached garage has a floor area of 36.5 m², a volume of 90 m³ and was built as an addition to the house in 2007. The interior of the garage, including the ceiling, is finished with painted gypsum board. As part of the garage construction, the underlayment and siding of the exterior west wall of the house were removed and replaced with ¾ inch gypsum board on studs with fibrous glass batt insulation in the wall cavity.

Measurements of gas concentrations were made at various points throughout the house using sample lines suspended 1.5 m above the floor in the center of each of the three bedrooms, the living room, the kitchen, and the family room, as well as five sample lines located near the four corners and center of the garage. The six individual living space locations were measured for one minute each in a repeating six minute cycle. The garage sample locations were measured separately, as well as a single mixed sample, the latter of which is reported here. Indoor air temperature and humidity were measured with sensors in each room of the house and on two opposite walls of the garage. The outdoor temperature and wind speed were measured at a weather station located about 6 m behind the house for tests conducted in 2008. For tests in 2010, wind speed data were collected from a weather station located on the roof of Building 226 on the NIST campus (about 1.6 km from the test house), however, wind direction data were still collected at the local weather station.

Instrumentation

Gas concentrations were measured with two multi-gas engine exhaust analyzers, which are combinations of non-dispersive infrared (NDIR) and electrochemical sensor technologies. These analyzers measured CO on two channels covering different ranges of 0 % to 1 % and 0 % to 10 %, CO₂ from 0 % to 20 %, hydrocarbons (as hexane) from 0 % to 2 % and O₂ from 0 % to 25 % with a reported accuracy of 1 % of full scale for all five channels. An electrochemical sensor CO analyzer measured CO over a range of 0 ppm_v to 2000 ppm_v and with a reported accuracy of 1 % of full scale. Two additional NDIR CO analyzers were used, both with ranges of 0 ppm_v to 1000 ppm_v and reported accuracy of 1 % of full scale. Finally, a portable O₂ analyzer was also used. Not all instruments were used during every test. Repeated calibrations during the test periods found that typical measurement uncertainties were consistent with the manufacturers' reported accuracies. To protect the analyzers from condensed water and/or soot particles, desiccant and high efficiency particulate air (HEPA) filters were used in the sampling system.

A local weather station was used to measure ambient conditions. All gas concentration, air temperature, and humidity data were recorded by an automated data acquisition system. Nabinger and Persily (2008) provide more details on the SF₆, temperature, humidity, and ambient weather condition measurements including uncertainties.

Generators and Loading

Generators were selected with electrical power output ratings in the size range most commonly involved in fatal consumer incidents, which is 5.0 kW to 6.5 kW (Hnatov 2012). Tests were conducted with two different generators that were configured in multiple ways. One unmodified 'stock' (i.e., in their as-purchased condition) generator was tested. This generator (referred to here as Gen B) has a full-load electric power rating of 5.5 kW with a 10 horsepower (approximately 7.5 kW), carbureted, single cylinder gasoline engine and no specific CO emission control technology.

The second generator was powered by a carbureted 11 horsepower (approximately 8.2 kW) single-cylinder gasoline engine made by a different manufacturer than Gen B with an alternator with an electric output rating of 7 kW. This generator was tested as a modified

low-CO emission prototype (referred to as mod Gen SO1). The unmodified generator operates at air-fuel ratios (AFR, ratio of mass of air to mass of fuel) in the range of 10 to 13 AFR depending on the load, which is common for small air-cooled carbureted engines. The modifications were made by the University of Alabama (UA) and included adding an engine management system (EMS) with associated sensors and actuators for electronic fuel injection (replacing the carburetor) and a muffler with a small catalyst integrated into it. UA calibrated the EMS on the modified prototype to operate around a 14.6 AFR over the full range of loads.

The manufacturer of the EMS for Gen SO1 included programming to maintain rich AFR operation until the oil temperature rose above approximately 60 °C, resulting in an initial “spike” of CO when the engine was started cold. Gen SO1 was also tested in a configuration with a muffler that did not contain a catalytic converter (referred to as the noncat muffler). A full description of the prototype configuration of Gen SO1 is provided in greater detail in UA’s report to CPSC (CPSC 2012).

A portable AC resistive load bank connected to the generator’s 240-volt receptacle was used to draw electrical power. The load bank has manual switches in 250 W increments with a maximum setting of 10 kW. Some tests involved a constant load while others followed a cyclic load profile (see Table 1 for the loads in order of time sequence) similar to one used by UA during the durability and emission testing of their low CO emission prototype generator. Because the actual delivered power did not always match the load bank settings, particularly when oxygen depletion was occurring, the delivered power was measured and recorded during all tests. The instrumentation, equipment and measurements are described in more detail by Emmerich et al. 2013.

MODELING

Modeling Method

The simulations in this study used CONTAM (Walton and Dols 2010), a multizone IAQ and ventilation model developed in the Engineering Laboratory (EL) at NIST. The multizone approach is implemented by constructing a building model as a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones (primarily rooms) of a building. The network nodes represent the zones, which are modeled with a hydrostatically varying pressure, and uniform temperature and pollutant concentration within each zone. After calculating the airflow between zones and the outdoors, zone pollutant concentrations are calculated by applying mass balance equations to the zones. CONTAM has frequently been used to study a variety of residential IAQ issues in past simulation studies (Emmerich and Persily 1996, Emmerich et al. 2005).

The CONTAM airflow calculations are based on non-linear airflow-vs-pressure relationships as presented in (Walton and Dols 2010). These relationships are referred to as power-law airflow elements e.g., the orifice flow equation. Lorenzetti provides a detailed treatment of the computational aspects of the Newton-Raphson solution technique used to determine the nodal pressures that provide the mass balance of the multizone airflow problem (Lorenzetti 2002).

CONTAM provides several methods of solving the contaminant mass balance equations. These methods are referred to as:

- default solver (implicit/semi-implicit Euler)
- short-time step (STS) solver (explicit Euler)
- CVODE solver (stiff, general ODE solver)

The default solver implements an implicit Euler method (backward difference) by which the contaminant mass balance equations are reformulated as a set of DAEs that can be solved using a number of available linear solution techniques (Walton and Dols 2010). This default solver has also been coupled with the computational fluid dynamics, zero-equation turbulence model solver (CFD0) to capture the within-zone variations of airflow and contaminant concentrations (Wang et al. 2010). The STS solver employs an explicit Euler method (forward difference) to directly solve the DAEs as well as allowing for the treatment of one-dimensional convection-diffusion within designated zones, e.g., long hallways, and ducts. Lorenzetti, et al. present the general-purpose solution technique for ODEs as implemented by the CVODE solver that has recently been implemented within CONTAM to better handle mass transport process the can lead to stiff contaminant mass balance equations, e.g., chemical sorption and reactions (Lorenzetti et al. 2013).

The graphical representation of the main floor of the test house as it appears in CONTAM is shown in Figure 2. The test house crawlspace and attic were included in the model but are not shown. The layout of the test house within CONTAM and the division of the zones were defined to represent the actual floorplan of the test house, therefore each zone typically represents one room although the kitchen, living, dining and family room spaces are combined into a single CONTAM zone, referred to as zone LFK, due to the lack of any partitions separating them.

Nabinger and Persily (2008) and Nabinger et al. (2010) describe a study of ventilation rates and energy consumption in the test house before and after a retrofit effort to improve the tightness of both the building envelope and air distribution systems. That study included fan pressurization tests of both the envelope and air distribution systems, measurements of HVAC system air flows and tracer gas decay tests of air change rates. A CONTAM airflow model of the building was created and the predicted infiltration rates agreed well with the measured values over a range of weather and system operation conditions. The air leakage values (in terms of the effective leakage area (ELA) at a reference pressure difference of 4 Pa) and HVAC system airflows from Nabinger et al. (2010) were used.

The CONTAM airflow model described by Nabinger et al. 2010 was modified to add the attached garage, including leakage paths from the garage to ambient and to the house. The modeled garage leakage was based on fan pressurizations tests conducted in April, July and August 2008 with analysis following the methods described by Emmerich et al. 2003.

Garage Pressurization Tests—Additional pressurization tests were conducted on the house to measure the leakage of the house, garage, and the house-garage (HG) interface in order to include the garage and HG interface leakage in the CONTAM model. The

pressurization tests were generally conducted according to ASTM Standard E 779–10 (ASTM 2010) and are described by Emmerich et al. (2013). The total leakage from the house to the garage ($ELA_{4,HG}$) of 157 cm^2 was equal to the average total leakage from the house to the garage for the five houses tested by Emmerich et al. (2003). The effective leakage areas for the garage and HG interface were distributed vertically along the walls of the garage and on the ceiling in the CONTAM model.

Temperatures were measured in most of the individual rooms, garage, crawlspace and attic of the test house during the tests and used as input to the model. Temperatures in the LFK zone were based on an average of the living room, family room, and kitchen measurements. Both BR2 and BR3 temperatures were based on measured BR3 temperatures as there was no measurement available for BR2. Temperatures in the Utility zone were based on the adjacent family room temperature except when the door to the garage was open in which case they were based on an average of the temperature in the LFK zone and the garage. Temperatures in other zones without measurements such as bathrooms were based on an average of all room (i.e., not including garage, crawlspace or attic) measurements.

Model Validation—This section describes the model validation efforts that were carried out to establish the ability of the CONTAM model to predict CO levels in the garage and the house and to develop an estimate of its uncertainty of these predictions relative to the measured values. A number of past studies (e.g., Emmerich and Nabinger (2001) and Emmerich et al. (2004)) have also examined the issue of multizone IAQ model validation as reviewed in Emmerich (2001).

Statistical Evaluation of Model Predictions

As part of this validation effort, predicted CO concentrations were compared with measured values from a series of experiments in the test house. The predictions and measurements were compared using ASTM D5157 Standard Guide for Statistical Evaluation of Indoor Air Quality Models, which provides quantitative and qualitative tools for evaluation of IAQ models (ASTM 2008). It provides guidance in choosing data sets for model evaluation and focuses on evaluating the accuracy of indoor concentrations predicted by a model. As part of the comparison of CONTAM predictions to measurements of CO and O₂ concentrations, the ASTM D5157 suggested criteria were applied. The data sets collected during this study meet the ASTM D5157 criteria for model evaluation, as they are entirely independent of the data used to develop the model and to estimate model inputs. Also, the data are of sufficient detail to evaluate the CONTAM predictions of individual zonal CO concentrations.

ASTM D5157 provides three statistical tools for evaluating the accuracy of IAQ model predictions and two additional statistical tools for assessing bias. Values for these statistical criteria are provided to indicate whether the model performance is adequate. The tools for assessing agreement between predictions and measurements, and the criteria for model evaluation, include:

1. The correlation coefficient of predictions and measurements should be 0.9 or greater.

2. The line of regression between the predictions and measurements should have a slope between 0.75 and 1.25 and an intercept less than 25 % of the average measured concentration.
3. The normalized mean square error (NMSE) should be less than 0.25. The NMSE is calculated as:

$$NMSE = \sum_{i=1}^N (C_{pi} - C_{oi})^2 / 2\bar{C}_o\bar{C}_p \quad (1)$$

where C_p is the predicted concentration and C_o is the observed concentration, and the over-bar represents an average over the N data points during the test period for each case.

ASTM D5157 also provides two statistical measures of bias with values for judging adequate model performance. These measures of bias include:

1. Normalized fractional bias (FB) of the mean concentrations. The absolute value of the fractional bias should be 0.25 or lower and is calculated as:

$$FB = 2(\bar{C}_p - \bar{C}_o) / (\bar{C}_p + \bar{C}_o) \quad (2)$$

2. The absolute value of the fractional bias based on the variance (FS) which should be 0.5 or lower. FS is calculated as:

$$FS = 2(\sigma_p^2 - \sigma_o^2) / (\sigma_p^2 + \sigma_o^2) \quad (3)$$

where σ_p is the standard deviation of the predicted concentrations and σ_o is the standard deviation of the observed concentrations.

Testing Configurations

Testing was conducted under seven different test house configurations to evaluate their impacts on the ability to predict the build-up of CO in the garage and its transport into the different rooms in the house. These configurations included two different garage bay door positions (fully closed or open nominally 0.6 m), two connecting door positions between the garage and the house (fully closed or open nominally 5 cm), and two house central heating, ventilating, and air conditioning (HVAC) fan settings (on or off). When the garage bay door was open, there was also a vertical opening of approximately 0.15 m at the top of the bay door. All internal house doors were kept open throughout all validation tests and model analyses.

Table 2 includes a summary of the validation tests conducted including information on the generator tested, the test house configuration (door positions and fan status), the date the test

was conducted, the average ambient temperature and wind speed, and the test load on the generator.

RESULTS

As shown in Table 2, seven validation cases were conducted under a variety of conditions between October 2008 and May 2010. Typically the temperature varied several degrees during the course of a test and wind speed varied from below 1 m/s up to 10 m/s. Local measured weather data was input to the simulation in one minute time steps. The tests consisted of operating one of the generators in the attached garage and measuring the concentrations in the house and garage for two to six hours.

Case #1

In the first validation case, Gen B was operated with a nominal load of 2.5 kW for 2 h in the garage with the garage bay door closed, house entry door open and the HVAC system off. Based on the shed test results and the fact that the O_2 in the garage did not drop below about 19 % during this test, a constant CO emission rate of 760 g/h and a constant O_2 consumption rate of 4140 g/h were applied in the simulations of this case. These values are based on the average shed test results plotted on Figures 8a and 8b of Emmerich et al. 2013 for O_2 at 19 % or above.

The observed and predicted CO and O_2 concentrations for the garage zone and the LFK zone in the house are shown in Figure 3. Table 3 shows average observed and predicted zone CO concentrations and percent differences, along with the ASTM D5157 statistical parameters (described previously) calculated for the zone average concentrations. The suggested ASTM D5157 statistical criteria were evaluated for overall zone average concentrations for the entire testing period for all cases. The columns of Table 3 (and subsequent tables) include the zone average observed concentration (C_o), average predicted concentration (C_p), standard deviation of observed concentrations (σ_o), standard deviation of predicted concentrations (σ_p), correlation coefficient (R), regression slope (m), regression intercept divided by the average observed concentration (b/C_o), normalized mean square error (NMSE), fractional bias of the mean concentrations (FB), and fractional bias based on the variance (FS). The average concentration in the bottom row of the tables is a linear average of the five zone concentrations.

The bold values in Table 3 are those that meet the ASTM suggested criteria. Based on the statistical parameters, this case exhibits excellent agreement between measurements and predictions. Specifically, the values for R, m, b/C_o , NMSE, FS and FB calculated for the average zone concentrations all meet the ASTM D5157 suggested limits. Additionally, the average of the absolute percent differences between the zone values of C_o and C_p was 15 %.

Case # 2

Case # 2 involved operation of Gen B in the garage with the bay door open, the house entry door open and the HVAC system fan off. A constant nominal load of 5 kW was applied for this case. Based on the shed test results and the fact that the O_2 in the garage did not drop below 20.8 % during this test, a constant CO emission rate of 1090 g/h (corresponding to the

highest O₂ point during the shed testing [see Fig 6a of Emmerich et al. 2013]) and a constant O₂ consumption rate of 5640 g/h (see Fig 6b of Emmerich et al. 2013) were applied to the simulations.

The observed and predicted concentrations for garage zone and the LFK zone in the house are shown in Figure 4, and the calculated D5157 statistical parameters are shown in Table 4. Based on the statistical parameters, the agreement between measurements and predictions was not as good as for Case #1. Specifically, only the values for R and FB calculated for the average zone concentrations meet the ASTM D5157 suggested limits while m, b/Co, NMSE, and FS fall outside the limits. Also, the average of the absolute percent differences between the zone values of C_o and C_p, i.e., 24 %, was worse than Case 1. This larger average value was driven primarily by a large difference in the garage zone, though smaller differences are seen in the house zones. One possible reason for poorer agreement is the lack of shed test data for an O₂ level above 20.5 % (see Figure 8a of Emmerich et al. 2013).

Case # 3

Case # 3 involved operation of Gen B in the garage with the bay door closed, the house entry door closed and the HVAC system fan on. A constant nominal load of 5 kW was applied for this case. Based on average values from the shed test results in Figure 8 of Emmerich et al. 2013, a constant O₂ consumption rate of 5940 g/h was applied and the CO emission rate was dependent on the predicted O₂ level per the relationship in Table 5.

The observed and predicted transient concentrations for the garage zone and the LFK zone in the house are shown in Figure 5, and the D5157 statistical parameters shown in Table 6. Based on the statistical parameters, this case resulted in agreement between measurements and predictions similar to that seen in Case 2. Specifically, the values for R and b/Co calculated for the comparison of average zone concentrations meet the ASTM D5157 suggested limits while those for m, NMSE, FB, and FS fall outside the limits. However, the average of the absolute percent differences between C_o and C_p, i.e., 16 %, was better than Case 2. Again, there are large differences in the garage zone concentrations, but differences in the house zones are smaller.

Case # 4

Case # 4 involved operation of Gen SO1 with the CAT muffler in the garage with the bay door closed, the house entry door open, the HVAC system fan off and a cyclic electrical load. During the test, a load bank fuse failed and the load dropped in half for a few minutes before the fuse was replaced and the test continued. Also, this test includes a natural decay period of about 40 min (included in plots and analysis below) following generator shut-off.

Based on average values from the shed test results shown in Figure 11 of Emmerich et al. 2013, load-dependent O₂ consumption and CO emission rates were used for this case (see Table 7 which shows the loads and rates in time sequence order), with both rates dependent on the electrical load. In addition, past measurement of Gen SO1 operation in both the shed and garage showed that an initial spike of CO is consistently observed immediately following a cold start (note the ECU algorithm is programmed to operate rich upon start-up). Based on analysis of cold start-up data following the method described previously for shed

testing, a 430 g/h source of CO was included in the model at start-up in place of the Table 7 value until the measured AFR exceeded 13.5 (the first five minutes of operation for this case).

The observed and predicted transient concentrations for the garage zone and LFK zone in the house are shown in Figure 6, and the D5157 statistical parameters calculated for the zone average concentrations are shown in Table 8. Based on the statistical parameters, this case resulted in agreement between average concentration measurements and predictions similar to Case #2. Specifically, only the value for R and FB calculated for the comparison of average zone concentrations met the ASTM D5157 suggested limits while m, b/Co, NMSE, and FS fall outside the limits. Additionally, the average of the absolute percent differences between zone values of C_o and C_p was 26 %, which was driven by a large difference in the garage zone but much smaller differences in the LFK zone.

Case # 5

Case # 5 involved operation of Gen SO1 with CAT muffler in the garage with the bay door open, the house entry door open and the HVAC system fan on. A cyclic load was applied for this case. Also, this test includes a natural decay period of about 25 min following generator shut-off. Based on average values from the shed test results shown in Figure 11 of Emmerich et al. 2013, load-dependent O_2 consumption and CO emission rates were used for this case (see Table 7) along with a 430 g/h source of CO at start-up in place of the Table 7 emission until the measured AFR exceeded 13.5 (ten minutes for this case).

The observed and predicted transient concentrations for the garage zone and the LFK zone in the house are shown in Figure 7, and the D5157 statistical parameters calculated for the zone average concentrations are shown in Table 9. Based on the statistical parameters, this case resulted in good agreement between measurements and predictions. The average absolute value of the percent differences between the zone measurements and predictions was 20 %, and the absolute difference was less than 10 $\mu\text{L/L}$ for all zones. Additionally, the values for R, NMSE, and FB calculated for the comparison of average zone concentrations meet the ASTM D5157 suggested limits, while m, b/Co, and FS fall somewhat outside the limits.

Case # 6

Case # 6 involved operation of Gen SO1 with CAT muffler in the garage with the bay door closed, the house entry door closed and the HVAC system fan on. A cyclic load was applied for this case. Based on the average values from the shed test results shown in Figure 11 of Emmerich et al. 2013, load-dependent O_2 consumption and CO emission rates were used for this case (see Table 7) along with a 430 g/h source of CO at start-up in place of the Table 7 emission until the measured AFR reached 13.5 (ten minutes for this case). There was a problem with the Family room temperature measurement for this case so the utility room temperature was set equal to the kitchen temperature.

The observed and predicted transient concentrations for the garage zone and the LFK zone in the house are shown in Figure 8, and the D5157 statistical parameters calculated for the zone average concentrations are shown in Table 10. The average absolute value of the

percent differences between the zone measurements and predictions was 16 %. Based on the statistical parameters, this case resulted in excellent agreement between measurements and predictions. Specifically, the values for R, m, b/Co, NMSE, FB and FS calculated for the comparison of average zone concentrations all meet the ASTM D5157 suggested limits.

Case # 7

Case # 7 involved operation of Gen SO1 with nonCAT muffler in the garage with the bay door closed, the house entry door closed and the HVAC system fan off. A cyclic load was applied for this case. This case included a natural decay for about 45 min after generator shut-off (included in plots and analysis below). Based on average values of the shed test results shown in Figure 12 of Emmerich et al. 2013, load-dependent O₂ consumption and CO emission rates were used for this case (see Table 11 for the loads and rates in time sequence order) along with an 840 g/h source of CO at start-up in place of the Table 11 emission until the AFR reached 13.5 (the first ten minutes of operation for this case).

The observed and predicted transient concentrations for the garage zone and the LFK zone in the house are shown in Figure 9, and the D5157 statistical parameters calculated for the zone average concentrations are shown in Table 12. The average absolute value of the percent differences between the zone measurements and predictions was 17 %. Based on the statistical parameters, this case resulted in excellent agreement between measurements and predictions. Specifically, the values for R, m, b/Co, NMSE, FB and FS calculated for the comparison of average zone concentrations all meet the ASTM D5157 suggested limits.

Summary of Validation Cases

Table 13 summarizes the statistical parameters calculated for all the cases based on the average zone concentrations. The bold values in Table 13 are those that meet the ASTM suggested criteria. As seen in the table, statistical agreement varies for the individual cases. The agreement was generally better for the cases with both the bay and house entry doors closed (3, 6, and 7). This improved agreement is not a surprise, as the cases with better agreement rely primarily on CONTAM's ability to model airflow through smaller leaks. While CONTAM includes elements to model flow through larger openings (used for the open bay and entry doors of Cases 1, 2, 4 and 5), those flow predictions are thought to be less reliable given the physical theory on which CONTAM is based. Table 13 shows that the statistical agreement was generally somewhat worse for those cases.

While the statistical evaluation of the individual cases is useful to understand strengths and weaknesses of the model, a more important statistical evaluation is the comparison of the entire set of cases. This overall evaluation indicates the model's ability to predict the relative outcome when individual parameters are changed (e.g., door open vs. closed, or one type of generator vs. another). The last three rows of Table 13 include summary statistics for the average CO and O₂ concentrations in the garage and for the average CO calculated for the house zones. The agreement between the measurements and predictions for this entire set of cases was excellent for both the garage O₂ concentrations and the house CO concentrations. All of these statistical values met the D5157 criteria. The agreement, however, was somewhat worse for the garage CO concentrations, with some parameters falling slightly

outside the ASTM criteria limits. The average concentrations for individual house zones (i.e., LFK, MBR, BR2 and BR3) from all cases are plotted in Figure 10 to show the comparison of predictions and measurements. To summarize, average individual house zone and garage CO concentration predictions and measurements were within about 20 % and 30 % respectively when averaged over all cases.

As discussed previously (Emmerich 2001), absolute validation of a complex model, such as CONTAM, is impossible as there are infinite possible building models that can be created by a user. However, the primary objective of this experimental validation is to evaluate the accuracy of the CONTAM model predictions for this specific application, to identify large sources of error, and to determine the level of confidence that we may have in the predictions for the other cases simulated. For the cases modeled in this effort, no significant errors in the CONTAM model were identified. Additionally, some of the discrepancies between model predictions and experimental measurements may be due to measurement limitations instead of model deficiencies. For example, this effort involved a fairly rich data set in terms of number of variables monitored and spatial and temporal detail. Still, there are additional measurements that would have been helpful for the simulations. Specifically, the utility room provided the primary pathway for contaminant transport from the garage into the house; however, temperatures and concentrations were not measured in this zone. Also, uncertainties in experimental measurements include more than simply the instrument accuracy. Many of the reported measurements are a single point that was used to represent an average room concentration. The ability of this single point measurement to represent the room may be questionable at times.

CONCLUSION

NIST conducted a series of tests to characterize the indoor time course profiles of CO concentrations resulting from portable generators through both measurements and simulations of both unmodified and low CO emission prototype generators. An extensive model validation effort was carried out using measurements from seven tests where portable generators were operated in the attached garage of a test house to establish the ability of the NIST CONTAM model to predict CO levels in the garage and the house and to develop an estimate of the uncertainty of its predictions. An absolute validation of a complex model, such as CONTAM, is impossible as there are infinite possible building models that can be created by a user. However, for the cases modeled in this effort, no significant errors in the CONTAM model were identified. The agreement between the measurements and predictions of the O₂ concentrations in the garage and of the average CO calculated for the house zones for the collective set of data was excellent. All of the calculated statistical values met the ASTM D5157 criteria. The agreement, however, was somewhat worse for the garage CO concentrations, with some parameters falling slightly outside the ASTM criteria limits. Overall, the average individual house zone and garage CO concentration predictions and measurements were within about 20 % and 30 % respectively when averaged over all cases.

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Figure 1.
Aerial view of NIST manufactured test house

Figure 2.
CONTAM Sketchpad Representation of Test House (Notes: BR2 = bedroom 2; BR3 = bedroom 3; GAR = garage; LFK = living room/family room/kitchen; MBR = master bedroom; The top of the figure is approximately due north.).

Figure 3.

Predicted and observed CO and O₂ concentrations for Case #1 (Note: Plotted house concentration is from the LFK zone for Figures 3 through 9.)

Figure 4.
Predicted and observed CO and O₂ concentrations for Case # 2

Figure 5.
Predicted and observed CO and O₂ concentrations for Case # 3

Figure 6.
Predicted and observed CO and O₂ concentrations for Case # 4

Figure 7.
Predicted and observed CO and O₂ concentrations for Case # 5

Figure 8.
Predicted and observed CO and O₂ concentrations for Case # 6

Figure 9.
Predicted and observed CO and O₂ concentrations for Case # 7

Figure 10.
Comparison of predicted and observed individual house zone average CO concentrations for all cases

Table 1

Hourly cyclic load profile

Load bank setting (W)	Duration (min)
no load	3
500	4
1500	18
3000	17.5
4500	12
5500	5.5

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Table 2

Model Validation Tests Conducted

Generator	Garage bay door	Garage to house entry door	HVAC fan	Date	Average Outdoor Temp (°C)	Average wind speed (m/s)	Load
B	Closed	Open	OFF	10/8/08	18.4	4.5	2.5 kW
B	Open	Open	OFF	10/23/08 a.m.	8.8	2.2	5 kW
B	Closed	Closed	ON	10/23/08 p.m.	13.1	3.8	5 kW
SO1 cat	Closed	Open	OFF	04/01/10	19.9	6.3	Cyclic
SO1 cat	Open	Open	ON	04/22/10	20.4	7.8	Cyclic
SO1 cat	Closed	Closed	ON	04/29/10	17.8	9.5	Cyclic
SO1 with noncat muffler	Closed	Closed	OFF	05/13/10	15.6	6.5	Cyclic

Table 3

Statistical parameters for Case #1 (concentrations in units of $\mu\text{L/L}$) (Note: (Note for all tables: BR2 = bedroom 2; BR3 = bedroom 3; GAR = garage; LFK = living room/family room/kitchen; MBR = master bedroom)

Zone	C_o	C_p	$C_o - C_p$	% diff										
GAR	2802	3066	-265	9										
LFK	435	414	21	-5										
MBR	307	337	-30	10										
BR2	308	383	-75	24										
BR3	289	369	-81	28										
Average % difference				15										
	C_o	C_p		σ_o	σ_p	R	m	b/ C_o (%)	NMSE	FB	FS			
Room Average Concentrations	828	914		1100	1200	1.00	1.09	1.5	0.02	0.10	0.27			

Table 4Statistical parameters for Case # 2 (concentrations in units of $\mu\text{L/L}$)

Zone	C_o	C_p	$C_o - C_p$	% diff								
GAR	329	470	-142	43								
LFK	96	61	34	-36								
MBR	55	49	6	-11								
BR2	73	52	21	-28								
BR3	50	51	-1	2								
Average [% difference]				24								
				σ_o	σ_p	R	m	b/ C_o (%)	NMSE	FB	FS	
Room Average Concentrations	120	137		118	186	0.99	1.57	-43	0.26	0.19	1.0	

Table 5O₂ dependent CO emission rate for Gen B

O ₂ level (%)	CO emission (g/h)
O ₂ >20	1370
19<O ₂ <20	2070
18<O ₂ <19	3000
17<O ₂ <18	3150
O ₂ <17	2140

Table 6Statistical parameters for Case # 3 (concentrations in units of $\mu\text{L/L}$)

Zone	C_o	C_p	$C_o - C_p$	% diff									
GAR	9542	12978	-3436	36									
LFK	434	322	111	-26									
MBR	275	254	20	-7									
BR2	289	289	0	0									
BR3	262	289	-27	10									
Average [% difference]				16									
Room Average Concentration	2160	2827		4130	5580	1.00	1.37	-6.6	0.39	0.27	0.85		

Table 7

Hourly cyclic load profile for Gen SO1 cat

Load bank setting (W)	Duration (min)	CO emission (g/h)	O ₂ consumption (g/h)
no load	3	20	2620
500	4	15	3880
1500	18	17	3080
3000	17.5	47	4820
4500	12	96	4370
5500	5.5	102	3710

Table 8Statistical parameters for Case # 4 (concentrations in units of $\mu\text{L/L}$)

Zone	C_o	C_p	$C_o - C_p$	% diff									
GAR	175	326	-151	86									
LFK	85	73	12	-14									
MBR	83	69	14	-17									
BR2	77	69	7	-10									
BR3	69	70	0	1									
Average [% difference]				26									
				σ_o	σ_p	R	m	b/ C_o (%)	NMSE	FB	FS		
Room Average Concentrations	98	121		43	114	0.99	2.6	-135	0.39	0.21	1.6		

Table 9Statistical parameters for Case # 5 (concentrations in units of $\mu\text{L/L}$)

Zone	C_o	C_p	$C_o - C_p$	% diff								
GAR	41	41.9	-0.5	1								
LFK	26	29.2	-2.8	11								
MBR	23	28.4	-5.8	25								
BR2	21	28.5	-7.5	36								
BR3	23	28.7	-5.9	26								
Average [% difference]				20								
	C_o	C_p		σ_o	σ_p	R	m	b/ C_o (%)	NMSE	FB	FS	
Room Average Concentrations	27	31		8.4	5.9	0.98	0.69	48	0.03	0.15	-0.54	

Table 10Statistical parameters for Case # 6 (concentrations in units of $\mu\text{L/L}$)

Zone	C_o	C_p	$C_o - C_p$	% diff									
GAR	631	686	-55	9									
LFK	87	88	0	0									
MBR	72	84	-12	17									
BR2	63	84	-22	34									
BR3	72	86	-13	19									
Average [% difference]				16									
	C_o	C_p		σ_o	σ_p	R	m	b/C_o (%)	NMSE	FB	FS		
Room Average Concentrations	185	206		250	269	1.00	1.07	3.5	0.02	0.10	0.25		

Table 11

Hourly cyclic load profile for Gen SO1 noncat

Load bank setting (W)	Duration (min)	CO emission (g/h)	O ₂ consumption (g/h)
no load	3	150	2580
500	4	88	2780
1500	18	97	3450
3000	17.5	236	4110
4500	12	271	4190
5500	5.5	236	4440

Table 12Statistical parameters for Case # 7 (concentrations in units of $\mu\text{L/L}$)

Zone	C_o	C_p	$C_o - C_p$	% diff								
GAR	1712	1944	-232	14								
LFK	266	223	42	-16								
MBR	264	212	52	-20								
BR2	263	216	47	-18								
BR3	261	216	46	-18								
Average [% difference]				17								
				σ_o	σ_p	R	m	b/ C_o (%)	NMSE	FB	FS	
Room Average Concentrations	553	562		648	772	1.00	1.19	-18	0.04	0.02	0.36	

Table 13

Summary of statistical parameters from comparison of average observed and predicted zone CO concentrations for all cases

Case	C _o	C _p	Avg %diff	σ_o	σ_p	R	m	b/C _o (%)	NMSE	FB	FS
1	828	914	15	1100	1200	1.00	1.09	1.5	0.02	0.10	0.27
2	120	137	24	118	186	0.99	1.57	-43	0.26	0.19	1.0
3	2160	2827	16	4130	5580	1.00	1.37	-6.6	0.39	0.27	0.85
4	98	121	26	43	114	0.99	2.6	-135	0.39	0.21	1.6
5	27	31	20	8.4	5.9	0.98	0.69	48	0.03	0.15	-0.54
6	185	206	16	250	269	1.00	1.07	3.5	0.02	0.10	0.25
7	553	562	17	648	772	1.00	1.19	-18	0.04	0.02	0.36
<i>Overall summary statistics for all tests</i>											
Garage CO	2180	2790	28	3400	4620	1.00	1.36	-7.6	0.28	0.25	0.81
Garage O ₂	19.5	19.1	2.5	1.1	1.3	0.94	1.18	-20	0.001	-0.02	0.41
House zones CO	165	160	17	130	128	0.96	0.94	3.0	0.05	-0.03	-0.08