

Simulating Study of Carbon Monoxide Exposure from Portable Generator in U.S Residences

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Simulation Study of Carbon Monoxide Exposure from Portable Generators in U.S. Residences

SUMMARY

A simulation study was conducted to evaluate indoor CO exposures as a function of portable generator location and CO emission rate in order to support the potential generator emission limits. These simulations employed the multizone airflow and contaminant transport model CONTAM, which was applied to 87 dwellings that are representative of the U.S. housing stock. About one-hundred thousand 24-hour simulations were conducted over a range of generator locations, CO source strengths, and weather conditions. This report presents the results in terms of the maximum levels of percent carboxyhemoglobin for individuals located in the occupied portions of the dwellings as a function of CO emission rate. Considering cases in which the generator operates continuously for 18 hours, the maximum source strength for which 80 % of the simulated cases are below 30 % maxCOHb is 27 g/h.

Keywords: Carbon monoxide, multizone modelling, portable generators, residential buildings, simulation

INTRODUCTION

In recent years, concerns have increased about the hazard of residential carbon monoxide (CO) exposures from portable gasoline-powered generators that can result in death or serious adverse health effects. The U.S. Consumer Product Safety Commission (CPSC) databases contain records of 755 deaths from CO poisoning associated with consumer use of generators in the period of 1999 through 2011, with nearly three-quarters of those occurring between 2005 and 2011 (Hnatov 2012). Typically, these deaths occur when consumers use a generator in an enclosed or partially enclosed space or outdoors near a partially open door, window or vent. While avoiding the operation of such generators in or near homes is expected to significantly reduce indoor CO exposures, it may not be realistic to expect such usage to be eliminated completely. Another means of reducing these exposures would be to decrease the amount of CO emitted from these devices. The magnitude of such reductions needed to reduce CO exposures to some specific level depends on the complex relationship between CO emissions from these generators and occupant exposure. Technically achievable levels of CO emissions reduction have been studied by the National Institute of Standards and Technology (NIST) through an experimental investigation of CO emissions from generators in a small shed and a three-bedroom house. These investigations included measurements on prototype generators that were modified to reduce their CO emission rates (Emmerich et al. 2013). That study has provided a set of unique measurements of CO emission rates for both unmodified and modified generators.

To address the CO exposure associated with portable generators and to support potential control strategies such as reduced emissions, a better understanding of the relationship between CO emission rates and occupant exposure is needed. This relationship involves the interaction between generator operation, house characteristics, occupant activities, and weather conditions. In order to support life-safety based analyses of potential CO emission limits for generators, a computer simulation study was conducted to evaluate indoor CO exposures as a function of generator source location and CO emission rate. This paper presents the simulation results in terms of the maximum levels of percent carboxyhemoglobin (COHb) that would be experienced by individuals in the occupied portions of the dwellings as

a function of CO emission rate for different indoor source locations. More details on this work are available in Persily et al. (2013).

METHODOLOGIES

Simulations were performed using the multizone airflow and contaminant transport model CONTAM (Walton and Dols 2005), which was applied to 87 single-family, detached dwellings that are representative of the U.S. housing stock. Using these homes, indoor CO concentrations were calculated over a range of generator locations, CO emission rates, and weather conditions. These simulations yielded CO concentrations in the rooms of each house as a function of time during the 24-h analysis interval. In order to compare the results for different cases, the concentrations from each simulation were used to calculate COHb values in each occupied room. The maximum COHb value among the occupied rooms was used as a metric of CO exposure for each combination of house, source, and weather.

The homes used in the simulations are based on a collection of dwellings that were previously defined by Persily et al. (2006), which includes just over 200 dwellings that together represented 80 % of the U.S. housing stock at the time of their definition. Those dwellings are grouped into four categories: detached (83 homes), attached (53 homes), manufactured homes (4) and apartments (69). The definition of this set of dwellings was based on the following variables using the US Census Bureau's American Housing Survey (AHS) (HUD 1999) and the US Department of Energy's (DOE) Residential Energy Consumption Survey (RECS) (DOE 2005): housing type, number of stories, heated floor area, year built, foundation type, presence of a garage, type of heating equipment, number of bedrooms, number of bathrooms, and number of other rooms. In addition to defining the dwellings, multizone representations were created in the airflow and contaminant transport model CONTAM to support their use in analyzing a range of ventilation and indoor air quality issues.

Only the detached and manufactured home models were used in this analysis, for a total of 87 homes. The attached and apartment models were not employed based on the challenge in accounting for airflow between units and the lack of air leakage data for the partitions between units. Given the prevalence of single-family dwellings within the U.S. housing stock, these 87 homes represent on the order of 60 % of U.S. dwellings.

Source Locations and Emission Rates

The range of potential CO source or release scenarios for indoor operation of generators in actual homes is very large. Given the study goals of being reasonably conservative and avoiding excessive complexity, the simulated source scenarios included only a well-defined range of possibilities. The two types of sources that were considered are a constant CO generation rate lasting for several hours and a short "burst" of CO intended to represent a generator with some form of CO emission control technology (e.g. a shut off device) for which a constant generation rate is not a reasonable assumption. The constant CO generation rate for the first type of source and the mass of CO released by the second used in the simulations covered a range of values based on measurements and analyses conducted by CPSC and NIST. The source scenarios that were analyzed include the following:

Constant generation rate for 18 hours with the generator in the following locations:

- Closed garage (if applicable to the model house)
- Open garage (if applicable to the model house)
- Basement (if applicable to the model house)
- Interior room (on first floor)

Short term burst source with the generator in the following locations:

Closed garage (if applicable to the model house)

Basement (if applicable to the model house)

Interior room (on first floor)

The interior room for each house was selected from those rooms defined on the existing floor plans of the model homes employed, with the goal of selecting a room on the first floor where a generator could be expected to be located. The simulated CO emission rates for the constant (g/h) and the burst (total mg released) sources are contained in Tables 1 and 2 respectively, along with an explanation of each value. For all of the simulations the outdoor CO concentration was assumed to equal zero, since the indoor concentrations of interest are well above typical ambient levels.

All interior doors were assumed to be open during the simulations and all exterior doors and windows closed with the following exceptions. When the generator was located in an unfinished basement, the door between the basement and the upstairs was closed. Finished basements had an open stairway between the basement and the first floor, and all interior doors on both levels were open. For cases in which the generator was located in the attached garage, the door from the garage to the house was assumed be open roughly 5 cm to accommodate an electrical cord running from the generator. When the generator was in the garage with the garage door open, the model represented that open garage door as an opening that was 4.6 m wide and 0.6 m high.

Each house and generator source combination was analyzed for 28 individual days. Each of the 28 simulations employed a different day of weather conditions, including outdoor temperature, wind speed and wind direction, that varied each day on an hourly basis. These 28 days of weather include two weeks of cold weather, one week of warm and one week of mild. The hourly weather data for these three conditions were based on weather files for the following three cities: Detroit MI (cold), Miami FL (warm) and Columbus OH (mild). The weather files were obtained from the EnergyPlus Energy Simulation Software website: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm.

Each simulation corresponds to one house, one source location and source strength, and one day of weather. The output of each simulation is the CO concentration versus time in each zone of the house. Based on the simulation time step of 5 min, the output consists of 288 concentrations values in each zone for each 24-h simulation. In the case of the constant source, the CO generation stopped after 18 hours of generator operation, after which the indoor CO concentrations started decreasing back to ambient levels. COHb levels were calculated for an individual in each occupied zone of the house over the 24-h simulation period using the Coburn-Forster-Kane (CFK) equation (Petersen and Stewart 1975, Coburn et al. 1965), assuming an RMV (respiratory minute volume) of 15 L/min and an initial COHb level of 0.0024 ml/ml. The maximum COHb (maxCOHb) value among the occupied zones of each simulation case was used as the output metric for each simulation. The maxCOHb values were considered separately for each source location to generate a frequency distribution for each source/location combination. Fifty-six such distributions were generated from the simulation results, i.e., seven locations times eight source strengths per location. All of these distributions are presented in Persily et al. (2013).

Table 1 CO emission rates for the constant source

1000 g/h	Approximate maximum for an unmodified 5.5 kW generator running at close to ambient oxygen levels based on measurements (Wang et al. 2010).
750 g/h	Intermediate value of unmodified generator.
500 g/h	Typical value for an unmodified generator running at essentially ambient oxygen levels based on measurements (Wang et al. 2010).
400 g/h	Two times CPSC “reduced severity” estimate
200 g/h	CPSC estimate of emission rate needed to reduce severity of CO exposure in the home (Inkster 2006)
100 g/h	50 % of CPSC “reduced severity” estimate
50 g/h	25 % of CPSC “reduced severity” estimate
20 g/h	10 % of CPSC “reduced severity” estimate

Table 2 CO emission rates for the burst source

1000 g	Two times highest “constant source” generation rate running for 30 min
500 g	Highest “constant source” generation rate (1000 g/h) running for 30 min
200 g	Highest value from NIST tests of short term emissions (Persily et al. 2013)
100 g	One-half of highest value
50 g	Mid-range value from NIST tests
25 g	One-half of mid-range value
15 g	Lowest value from NIST tests
5 g	One third of lowest value from NIST tests

RESULTS AND DISCUSSION

This section presents the results of the COHb calculations for all of the houses considered in the simulations, which reflect the combined effects of source location, source strength and weather conditions. As noted earlier, the metric employed in analyzing the simulation results is the maximum COHb value (maxCOHb) among the occupied zones for each simulation. Each maxCOHb value corresponds to a 24-hour simulation of a specific house (among the 87 houses considered) for a specific source location, source strength and day of weather. For reference, COHb levels of 70 % or greater are associated with death in less than 3 min, levels of 50 % are associated with headache, dizziness and nausea in 5 min to 10 min and death within 30 min, levels of 30 % with dizziness, nausea and convulsions within 45 min and becoming insensible within 2 h, and levels of 20 % with a slight headache in 2 h to 3 h and a loss of judgment (Goldstein 2008).

An example of the simulation results are presented in Figure 1 in the form of a cumulative frequency distribution of the fraction of simulation cases with maxCOHb values below the reference values on the x-axis for the generator located in the garage with the garage bay door open. Each solid line in the graph corresponds to a different CO emission rate and always reaches 100 % of the values for the highest bin. No maxCOHb bins are presented above 80 % because distinctions between such high levels are not of interest based on health effects at such high levels. This plot shows that as the CO emission rates are reduced, more of the cases correspond to lower values of maxCOHb. This trend is exhibited by the cumulative frequency distribution curves shifting towards the upper left hand corner of the plot, which corresponds to more of the cases having low values of maxCOHb.

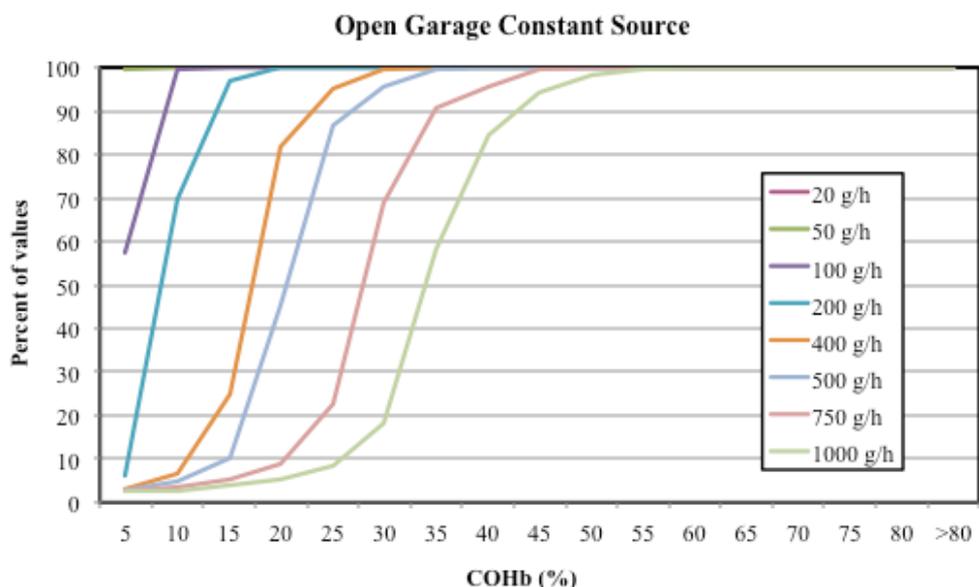


Figure 1. Frequency Distribution of % COHb for Constant Source in Open Garage

The results of the simulations constitute a large amount of data. A helpful way to interpret these data is to consider the percentage of cases that meet a specific criterion for the target value of maxCOHb. Determination of such criteria was beyond the scope of this project but for comparison purposes Table 3 presents the maximum source strength for which 80 % of the cases simulated are below 30 % maxCOHb for each of the seven source locations and types considered. The values of 80 % below 30 % maxCOHb are used only for illustrative purposes and are not presented as life-safety based limits to support any policy or regulatory decisions. Note also that the maximum source strengths in the table are estimated by interpolating between the values used in the simulations. Based on this interpolation, the individual values are estimated to have an uncertainty of approximately 10 %. As noted in the table, none of the simulated source strengths in two of the source locations (Basement/constant and Interior room/constant) resulted in 80 % of the cases being below 30 % maxCOHb. In those cases, the maximum source strength is noted as “< 20 g/h,” given that 20 g/h was lowest value simulated. The full report, which describes the study in detail (Persily et al. 2013), presents these COHb limits for different house sizes, weather conditions and airtightness levels.

Figure 2 is the frequency distribution of the maxCOHb values for all of the constant source cases. Considering all the constant source results in combination (not shown), the maximum source strength corresponding to 80 % of the cases having a value of maxCOHb below 30 % is 27 g/h. This value is on the low end of those simulated, which indicates that operating a generator for 18 hours as simulated in this study is likely to result in high CO exposures whether the generator is in the house or the garage. Note that the CO emission rates measured in unmodified generators in a separate NIST study tended to be well above this value, but that the modified generators tested were in this range (Emmerich et al. 2013).

Table 3 Maximum source strength corresponding to 80 % of the simulated cases with maxCOHb < 30 % (source strengths based on interpolation between simulated values)

Source location/type	Maximum source strength
Closed garage/constant	139 g/h
Open garage/constant	646 g/h
Closed garage/burst	443 g
Basement/constant	< 20 g/h*
Basement/burst	123 g
Interior room/constant	< 20 g/h*
Interior room/burst	83 g

* No simulated source strengths result in 80 % of cases having maxCOHb < 30 %.

Figure 3 is the frequency distribution of the maxCOHb values for all of the burst source cases. Considering all of the burst results in combination (not shown), the maximum source strength corresponding to 80 % of the cases having a value of maxCOHb below 30 % is 139 g. This value is on the higher end of the burst source strengths measured by NIST (as indicated in Table 2), i.e., there were many measurements below this value in the modified generators. Therefore, generators that incorporate an effective shut off technology have the potential to significantly reduce indoor CO exposures relative to continuously operating generators with no controls to reduce emissions.

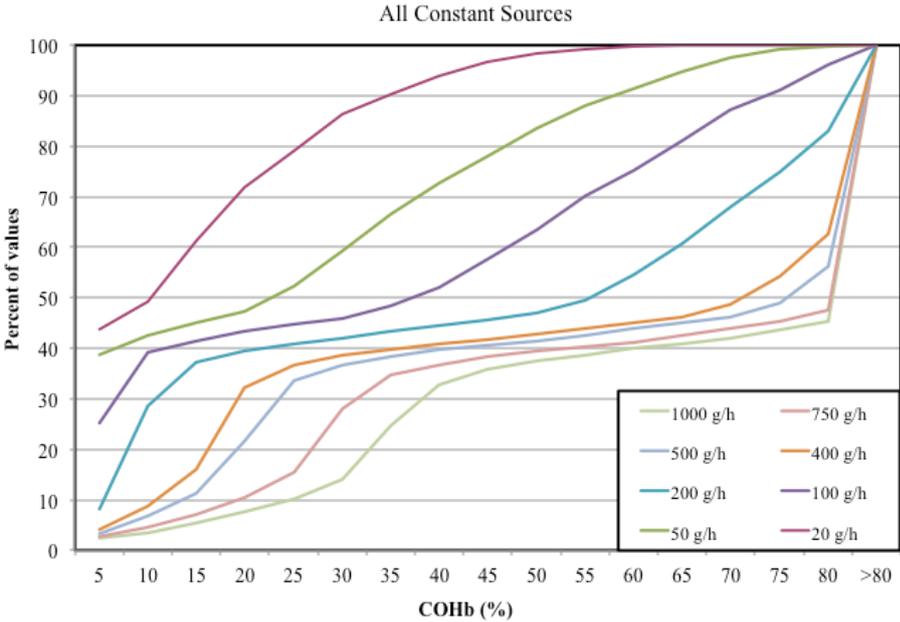


Figure 2. Frequency Distribution of % COHb for All Constant Sources

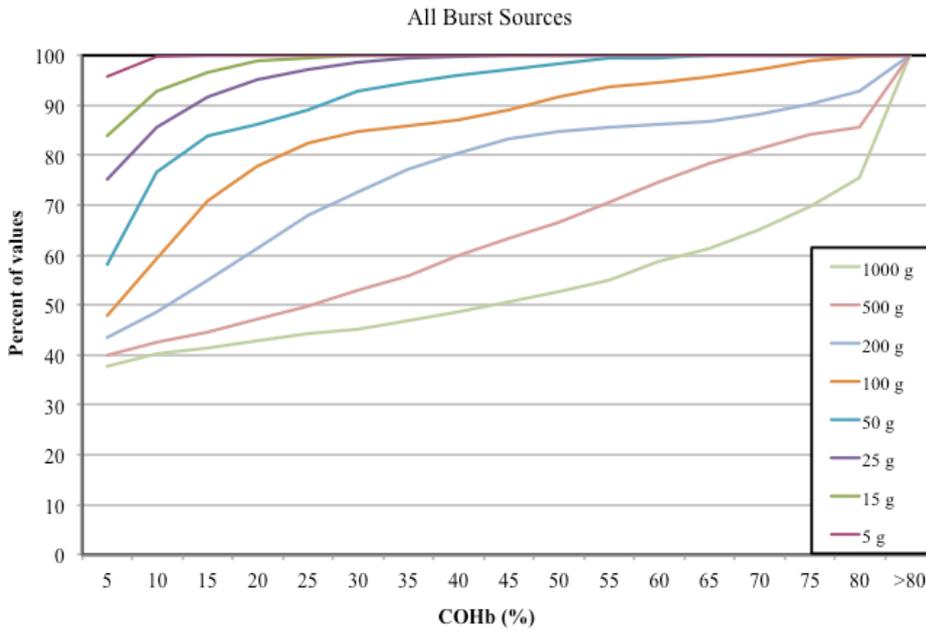


Figure 3. Frequency Distribution of % COHb for All Burst Sources

CONCLUSIONS

This simulation study was conducted to evaluate indoor CO exposures as a function of generator source location and CO emission rate in order to support life-safety based analyses of potential CO emission limits for generators. These simulations employed the multizone airflow and contaminant transport model CONTAM, which was applied to a collection of 87 dwellings that are representative of the U.S. housing stock. A total of almost one-hundred thousand individual 24-hour simulations were conducted that cover a range of house layouts and sizes, airtightness levels and weather conditions, as well as generator locations and CO source strengths. The locations include attached garages and basements, in the houses that have such spaces, and an interior room in all of the houses. This report presents the simulation results in terms of the maximum levels of percent carboxyhemoglobin for an individual located in the occupied portions of the dwellings as a function of CO emission rate for each source location.

It is important to note that the simulation results demonstrate the complexity of multizone airflow and contaminant transport in buildings, which in turn supports the value in considering a wide range of homes and weather conditions in addressing the objective of this study. Variations in house layout, source location, outdoor temperature and wind speed and direction can all have significant, and often complex, impacts on airflow and CO transport. This inherent variability means that considering only one or a small number of buildings under a limited range of conditions may not be adequate to fully understand the levels of CO exposure in residences as a function of generator location and CO release rate.

While operating portable generators indoors or near occupied buildings will be associated with significant residential CO exposure, reducing the CO emission rates of these devices or providing an effective shutoff mechanism will provide more time for occupants to recognize the existence of a problem and respond accordingly. This simulation study serves as the basis for determining a CO emission limit for portable generators in U.S. residences.

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