Modeling the Effects of Outdoor Use of Portable Gasoline Powered Generator Exhaust on Indoor Carbon Monoxide Exposure

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SUMMARY
The U.S. Centers for Disease Control and Prevention (CDC) has reported that up to half of non-fatal CO poisoning incidents during the hurricane seasons in 2004 and 2005 involved generators operated outdoors but within seven feet of the home. We conducted a computer simulation study to examine the impact of gasoline-powered portable electric generators on indoor CO exposure. This paper describes the use of the CONTAM indoor air quality model coupled with two computational fluid dynamics (CFD) models to predict CO concentrations near and within a home. A variety of parameters were considered including house style, weather, generator location and distance, and generator exhaust temperature and speed. With some exceptions, the simulations showed it was helpful to point the generator exhaust away from the house and position the generator at a distance of more than 4.6 m from the house.

IMPLICATIONS
CO poisoning is a major cause of morbidity and mortality in post-disaster situations, often owing to improper generator use. The findings of this study provide information to improve communication and education on a safe distance for generator placement.

KEYWORDS carbon monoxide; computational fluid dynamics; CONTAM; multizone airflow model; simulation

INTRODUCTION
The U.S. Centers for Disease Control and Prevention (CDC) has reported that up to half of non-fatal CO poisoning incidents during the hurricane seasons in 2004 and 2005 involved generators operated outdoors but within 2.1 m of the home (CDC 2006). The U.S. National Institute of Standards and Technology (NIST) conducted a study for CDC to examine the impact of distance of gasoline-powered portable electric generators on indoor CO exposure. The study was based on computer simulations of CO transport outdoors and subsequently within the building and included two phases. In the first phase (Wang and Emmerich 2009), it was found that for the one-story manufactured house modeled, a generator positioned 4.6 m away from open windows may not be far enough to limit CO entry into the house and that lower wind speeds generally led to more CO entry. To reduce CO entry, the generator should ideally be positioned outside the airflow recirculation region near the building. This paper presents the results of the second phase of the study (Wang et al. 2010).

METHODS
A series of numerical simulations of the entry of CO from a generator exhaust into a two-story house (see Figure 1(a) and 1(b)) was performed. A matrix of simulation scenarios considered multiple factors contributing to CO entry including the generator placement distance (from 1.8 m to 10.7 m) from the house, the exhaust direction (toward or away from the house), temperature and speed of the generator exhaust, location either upwind or downwind of the

house, wind speed (from 1 m/s to 10 m/s) and direction. Table 1 provides the input parameters that did not vary. Transient indoor CO profiles were predicted using the CONTAM indoor air quality model (Walton and Dols 2008), and the NIST Fire Dynamics Simulator (FDS) (McGrattan et al. 2010) was used to determine the outdoor CO profiles.

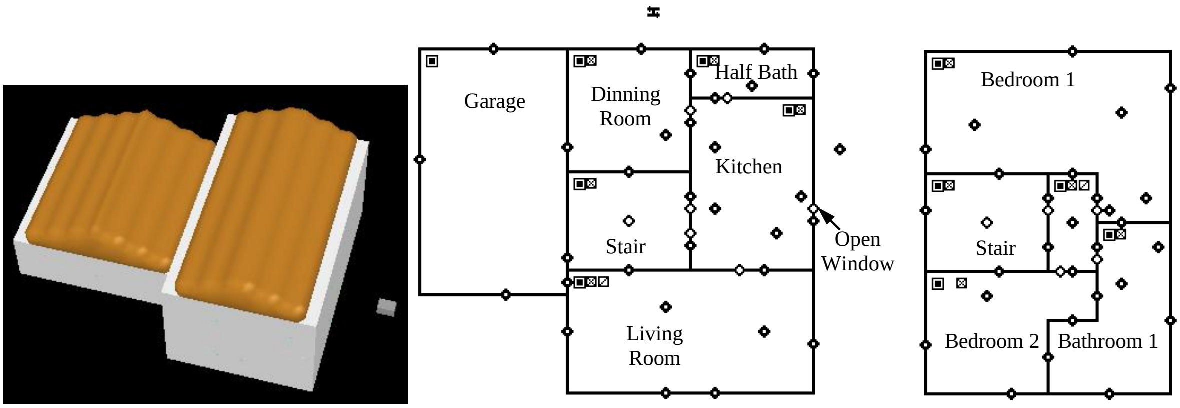

Figure 1(a) The two-story house modeled in FDS and (b) The house modeled in CONTAM

Table 1. Simulation Parameters

House dimensions (m)	9.76 × 6.22 × 6.1
Garage dimensions (m)	7.32 × 7.32 × 3.86
Window opening (m^2)	0.31
Indoor temperature (˚C)	20.9
Outdoor temp (˚C)	20.9
Exhaust temp (˚C)	288.0
Exhaust speed (m/s)	7.0
Run time modeled (h)	8

RESULTS

Figures 2 and 3 show predicted CO levels at the vertical plane of the middle of the house (where the open window is located) with the generator exhaust pointed towards and away from the house, respectively. The wind direction is indicated by the arrow, and the generator distance and wind speed are reported in brackets following the simulation case number.

The results lead to several interesting observations. When the exhaust points towards the house (Figure 2):

- For low wind speed, the buoyancy effect of the jet tends to lift the CO plume above the house. For greater distances from the house, the CO near the house is lower (S1 through S4). Increased wind speed may help to dilute the CO, but it also pushes the CO plume down around the house as illustrated by S5 through S8. However, when the wind speed is high enough, as in S9 through S12, the CO can be effectively diluted.
- When the generator is located upwind of the house, generator positions further away from the house may allow enough space for the CO jet to develop better. When the generator is located too close to the house, the jet may impact the house wall such that CO is dispersed horizontally along the wall more easily than vertically by the buoyancy. S5 through S12 show that the vertical distribution of CO levels increase with the generator distance.
- When the generator is located downwind of the house (S13 through S24), a distance of 10.7 m may not be enough to avoid high CO levels at some locations near the house for some cases. The size of the leeward recirculation zone can be estimated as

$$R_{lw} = B_S^{0.67} B_L^{0.33} \quad (1)$$

where B_S is the smaller of upwind building face dimensions; B_L is the larger of upwind building face dimensions of building height and width(ASHRAE 2005). Application of this empirical relationship is discussed further in Wang and Emmerich (2009). Apparently, the exhaust jet affects the formation of the leeward recirculation zone unfavorably so a greater generator operating distance may be required than the empirically calculated value. Moreover, when the wind speed increases from 1 m/s to 5 m/s, more CO is entrained back towards the house for the same distance. However, these effects are limited for higher speeds, such as 10 m/s (S21 through S24), when the dilution effect of the wind takes over.

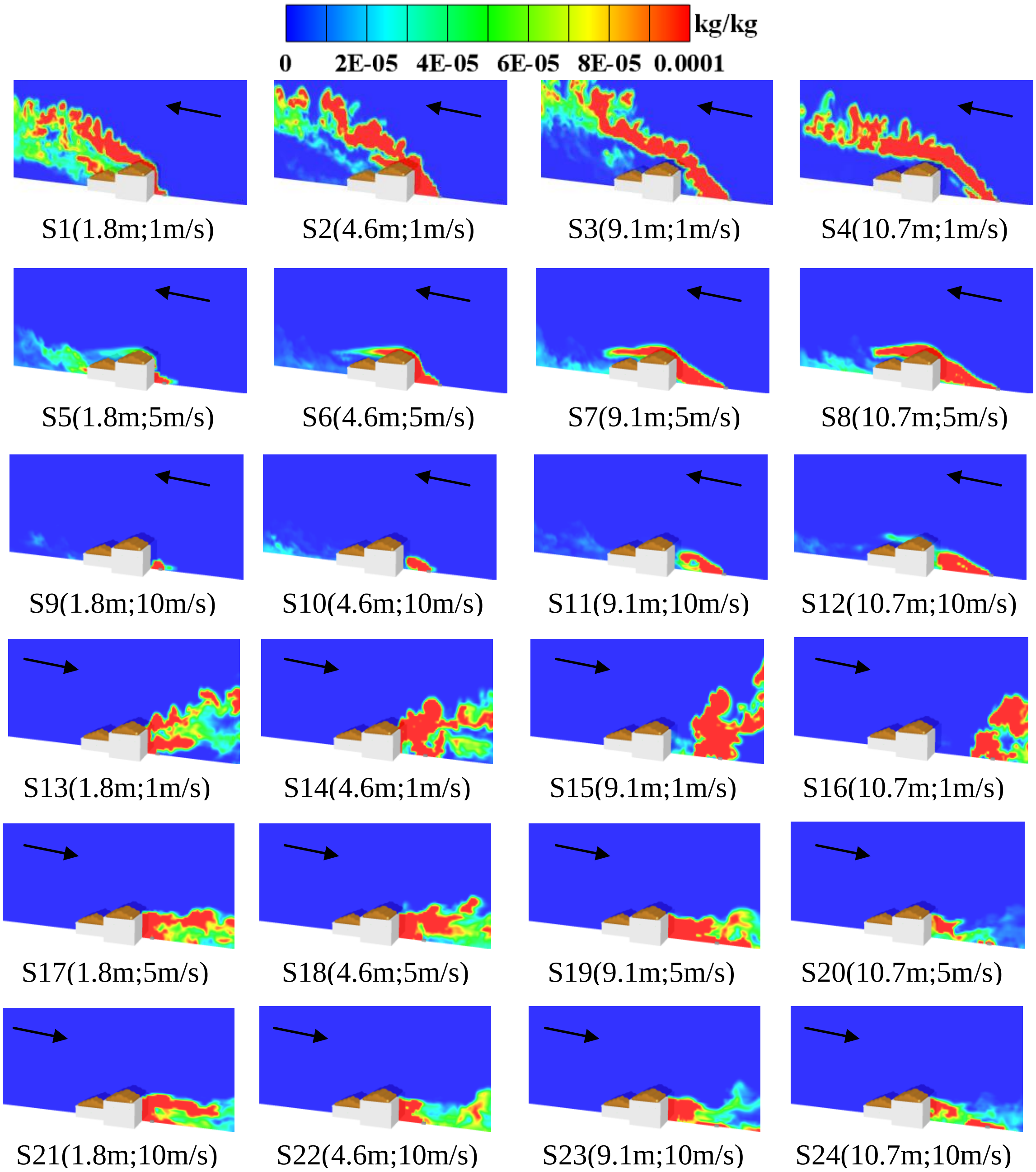

Figure 2. CO levels at the middle plane of house with exhaust pointed towards the house.

When the generator exhaust points away from the house (Figure 3),

- Generally, the CO levels near the house are lower than when the exhaust points towards the house. Such effects are more apparent for lower wind speeds when the generator is located upwind of the house (S25 through S28) and for all cases with the generator downwind (S37 through S48).
- For an upwind location, the wind may push the CO plume down close to the house for a wind speed of 5 m/s (S29 through S32) or dilute CO more effectively for a wind speed of 10 m/s (S33 through S36).
- For a downwind placement (S37 through S48), a distance of 9.1 m seems sufficient to avoid CO being entrained backwards near the house for any wind speed.

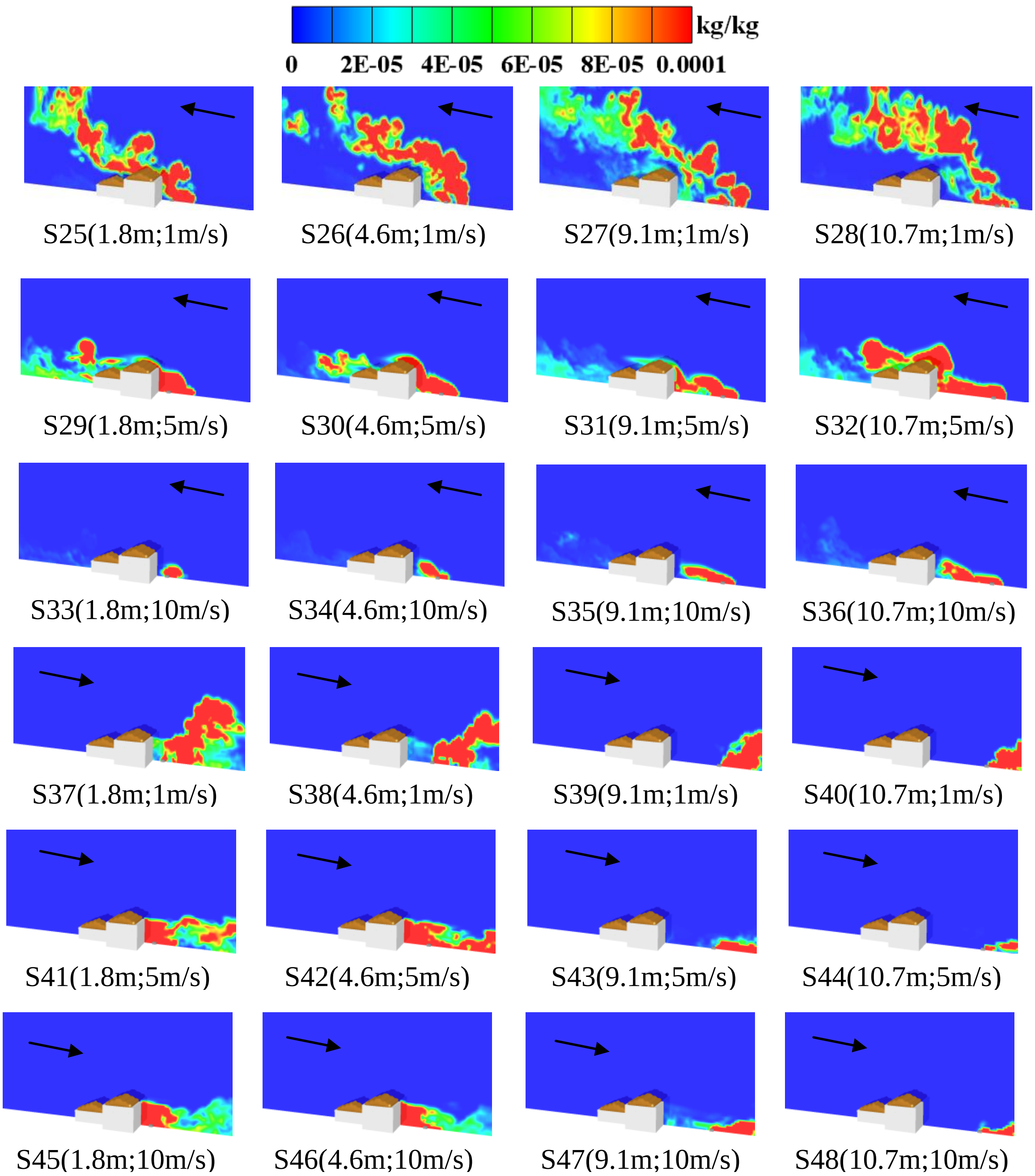

Figure 3. CO levels at the middle plane of the house with exhaust pointed away from house.

To examine CO entry to the house, Figure 4 compares the peak CO levels in any room of the house predicted by CONTAM when the generator operated for 8 hours and the indoor and outdoor temperature difference was zero. It is noted that when the generator was placed downwind of the house, the predicted CO levels in the house were minimal. This occurred because the predicted airflow direction at the open window was from the house to the outdoors, so the outdoor CO did not enter the house despite the presence of CO. Therefore, Figure 4 shows only the cases for the generator located upwind of the house.

It is found that pointing the exhaust away from the house can reduce indoor CO entry significantly. Even for a distance of 1.8 m, the indoor CO level can be reduced 97 % when the exhaust points away from the house (S29 in Figure 4) compared to when it points towards the house (S5 in Figure 4). Therefore, no matter whether the generator is upwind or downwind of the house, or the value of the wind speed, a generator exhaust pointing away from the house always results in a lower CO level both outdoors and indoors. It is also found that when the exhaust was pointed away from the house, a generator distance of 9.1 m appears to result in low CO entry indoors. The indoor CO can be 17 mg/m^3 for the wind speed of 1 m/s in S27 and 31 mg/m^3 for 10 m/s in S35. It appears the wind speed of 5 m/s is the worst case for the same generator distance (S31), where a maximum indoor CO level of 107 mg/m^3 is reached. Compared to 1 m/s or 10 m/s, the wind of 5 m/s is strong enough to push down the buoyancy-driven CO plume close to the house but not enough to dilute the CO outdoors. If the generator is placed further away to 10.7 m from the house, the CO appears to be still high, 84 mg/m^3 (S32). Therefore, the combination effects of wind direction and speed, generator distance, exhaust temperature and speed make it hard to develop a simple correlation of indoor CO entry with these factors. However, the bottom line is in most cases, to significantly reduce CO levels for the house and conditions modeled in this study, it was helpful to point the generator exhaust away from the house and position the generator at a distance more than 4.6 m.

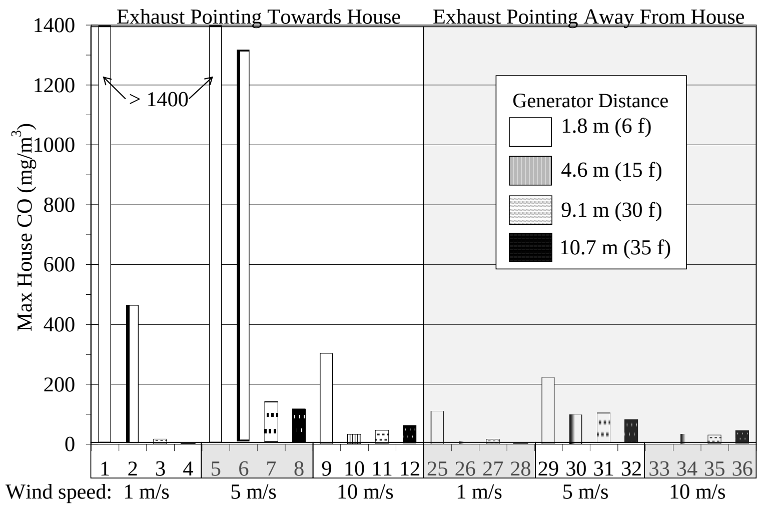

Figure 4. Maximum indoor CO in the house when the generator operated upwind of the house for 8 hours under zero indoor and outdoor temperature difference.

DISCUSSION

As a continued effort to provide information for determining safe distances for operating generators outside residences, this study investigated CO dispersion from a generator and its infiltration into a two-story house. In general, the results supported the conclusions of a first phase study which found that a distance of a generator positioned 4.6 m away from open windows may not be far enough to limit CO entry into a manufactured house. In phase two, it was also necessary to locate the generator further than 4.6 m from the two-story house to avoid high indoor CO concentrations (the next closest location modeled was 9.1 m). When the generator was moved further to 10.7 m, CO levels decreased but not significantly.

A new finding was that the generator exhaust temperature and speed may affect CO levels near the house significantly. Pointing the exhaust away from the house reduced the maximum CO at the house envelope to 17 % of that when the exhaust is pointing towards the house. With the exhaust pointing away, the peak indoor CO level can be reduced to be 3 % of the level with the exhaust pointing towards the house under the same wind speed. An exception was observed for a case with intermediate wind speed, where the CO could reach 107 mg/m^3. Therefore, the combined effects of wind direction and speed, generator distance, and exhaust temperature and speed make it hard to develop a simple correlation of indoor CO entry.

A few limitations to the interpretation of these results should be noted. While this study considered typical houses and a range of typical conditions, various factors could lead to higher indoor concentrations such as generators with higher CO emissions due to a larger size or poorly tuned engine and the additional openings. Some physical effects are not included such as variable wind direction and speed, impact of nearby structures, and elevation differences between house and generator. Thus, any conclusions drawn from this study will not apply to every possible situation. Additionally, it is strongly recommended that experimental work be pursued to further verify and strengthen the conclusions of this study.

CONCLUSIONS

CO poisoning is a major cause of morbidity and mortality in post-disaster situations, often owing to improper generator use. The findings of this study provide information to improve communication and education on a safe distance for generator placement. To significantly reduce CO levels for the conditions modeled in this study, the simulations showed it was helpful to point the generator exhaust away from the house and position the generator at a distance of more than 4.6 m from the house. If the generator is located more than 4.6 m with the exhaust pointing away from the house, then there is additional benefit in avoiding placing it upwind of the house. Ideally, the results suggest that the generator should be positioned outside of the airflow recirculation region which was around 7.6 m for the two-story house.

ACKNOWLEDGEMENT

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REFERENCES

ASHRAE. 2005. Airflow around buildings. *ASHRAE Handbook of Fundamentals*. Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers**:** 12.

CDC. 2006. Carbon monoxide poisonings after two major hurricanes - Alabama and Texas, August - October 2005. Morbidity and Mortality Weekly Report (MMWR), US CDC**:** 4.

McGrattan, K., R. McDermott, S. Hostikka, et al. 2010. Fire Dynamics Simulator (Version 5) User's Guide. Gaithersburg, MD NIST**:** 230.

Walton, G. N. and W. S. Dols. 2008. CONTAMW 2.4 user manual. Gaithersburg, MD, USA, National Institute of Standards and Technology**:** 286.

Wang, L. and S. J. Emmerich. 2009. Technical Note 1637: Modeling the effects of outdoor gasoline powered generator use on indoor carbon monoxide exposures. NIST**:** 23.

Wang, L., S. J. Emmerich and A. K. Persily. 2010. In situ experimental study of CO generation by gasoline-powered electricity generator in an enclosed space. *JAWMA*: 25.

Wang, L., S. J. Emmerich and R. Powell. 2010. TN 1666: Modeling the effects of outdoor gasoline powered generator use on indoor CO exposures - phase II. NIST**:** 20.