Critical Review of the Building Downwash Algorithms in AERMOD

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ABSTRACT

The only documentation on the building downwash algorithm in AERMOD, referred to as PRIME, is found in the 2000 A&WMA Journal article by Schulman, Strimaitis and Scire. Recent field and wind tunnel studies have shown that AERMOD overpredicts concentrations by factors of 2 to 8 for certain building configurations. While a wind tunnel equivalent building dimension study (EBD) can be conducted to approximately correct the overprediction bias, past field and wind tunnel studies indicate that there are notable flaws in the PRIME building downwash theory. A detailed review of the theory supported by CFD and wind tunnel simulations of flow over simple rectangular buildings revealed the following serious theoretical flaws: enhanced turbulence in the building wake starting at the wrong longitudinal location; constant enhanced turbulence extending up to the wake height; constant initial enhanced turbulence in the building wake (does not vary with roughness or stability); discontinuities in the streamline calculations; and no method to account for streamlined or porous structures.

This paper documents some of the theoretical flaws that have been found in PRIME and provides supporting CFD and wind tunnel observations that confirm these findings. A suggested path forward to correct these problems is also outlined in accordance to Appendix W's mandate that a model should be based on sound science and that its components are validated accordingly. In other words, corrections to the downwash theory in the model would ensure that the right answer is obtained for the right reason.

INTRODUCTION

In December 2006, AERMOD[1] officially became the EPA preferred model for regulatory dispersion modeling applications and replaced the predecessor ISC3.[2] Since then, AERMOD has been improved on a periodic basis. One of the major enhancements of AERMOD was the addition of the PRIME building downwash algorithm[3] to predict ground-level concentrations near structures more accurately. The PRIME algorithm (referred to as PRIME throughout this paper) incorporates enhanced plume dispersion due to the turbulent wake behind sharp-edged rectangular buildings and reduced plume rise due to descending streamlines behind these obstacles and entrainment of the plume in the building cavity.[3] PRIME calculates fields of turbulence intensity and wind speed, as well as the local slope of the mean streamlines as a function of the building dimensions, and, coupled with a numerical plume rise model, determines the change in plume centerline location with downwind distance.

The only documentation on PRIME is found in the 2000 A&WMA Journal article by Schulman, Strimaitis and Scire.[3] No improvements to the downwash algorithms in PRIME have been made in over 15 years. Because building downwash often causes concentration predictions that exceed ambient standards, it is critical that these estimates be accurate. Recent field and wind tunnel studies have shown, however, that AERMOD overpredicts concentrations by factors of 2 to 8 for certain building types.[4] For certain building and terrain configurations, PRIME can underpredict concentrations. While a wind tunnel equivalent building dimension study (EBD) can be conducted to approximately correct the overprediction or underprediction bias, it is critical that PRIME be updated based on the latest research.

This paper documents the theoretical flaws that have been found in PRIME and provides supporting CFD and wind tunnel observations that confirm these findings. A suggested path forward to correct these problems is also outlined in accordance to the mandate in Appendix W to 40 CFR part 51, the Guideline of Air Quality Models (hereafter referred to as Appendix W) that a model should be based on sound science and that its components are validated accordingly. In other words, corrections to the downwash theory in the model would ensure that the right answer is obtained for the right reason.

OBSERVED BUILDING DOWNWASH PREDICTION PROBLEMS

There are several recent examples where AERMOD has been shown to significantly overpredict maximum concentrations levels. Schulman and Scire[5] presented the following examples where AERMOD overpredicts concentrations.

- Stack height to building height ratios of 2.25 to 3.25 and building length (L) to height ratio (H_b) of 2.25: maximum concentrations with the building present are 3 to 14 times greater than those without the building present for W/H_b ratios ranging from 4 to 20.
- Stack height to building height ratio of 2.5 and W/H= 10: maximum concentrations with the building present are 3.5 to 9.5 times greater than those without the building present starting at $L/H_b = 3$ with the maximum at $L/H_b = 8.5$.
- AERMOD predicted maximum annual concentrations were 10 times or more greater than observations for a very wide and long smelter in Tennessee. Hourly AERMOD predicted maximums were 2 to 10 times greater than observations.

Baugues[6] compared AERMOD predictions to observations at four monitors near the Gibson power plant, which is located in southwestern Indiana. 2010 actual hourly SO_2 emission rates and meteorological data from a nearby tower were used as model input. Baugues concluded that AERMOD over-predicts by more than a factor of two. He also showed that, when AERMOD predictions are paired in time and space with monitored concentrations, very poor agreement is shown (very low correction coefficient). This result suggests that good agreement is a random event rather than based on skill or model accuracy.

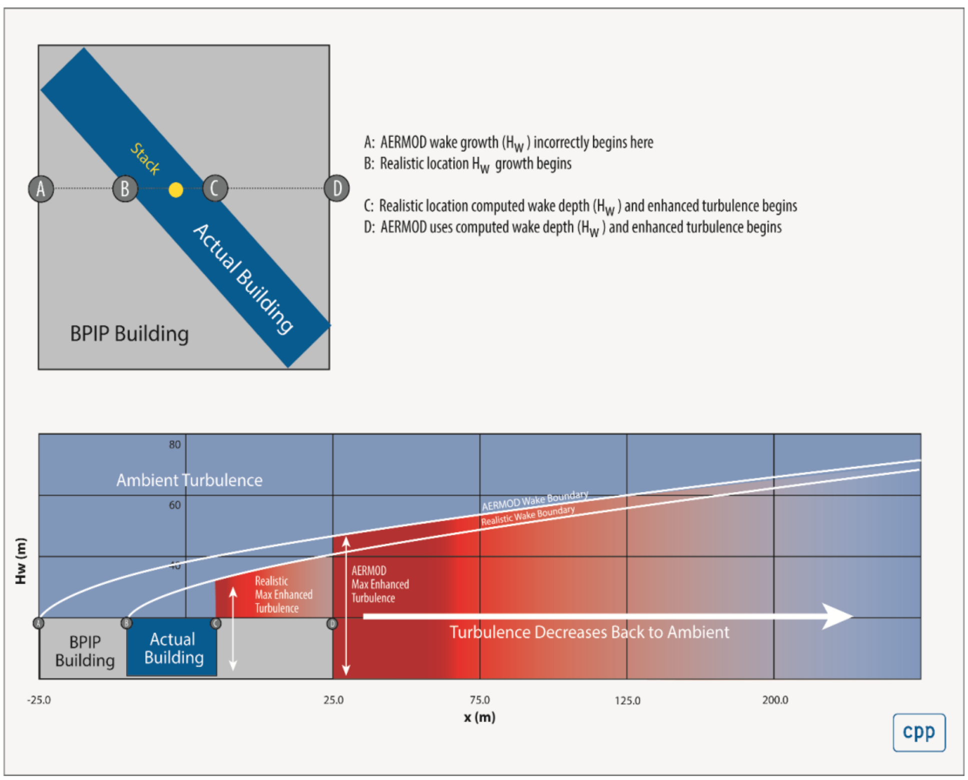
Shea[7] reported on a field study where SO_2 concentrations were monitored on a residential tower located near the Mirant Power Station. AERMOD predicted concentrations were an order of magnitude greater than actual observations. While the use of EBD as AERMOD inputs showed better agreement with observations, the best agreement was found when building downwash effects were turned off (i.e., no building was present).

The above results suggest that there are some theoretical problems with the building downwash algorithms in PRIME, several of which are outlined in the next section.

THEORETICAL PROBLEMS

The following summarizes some of the PRIME theoretical problems. First, the Building Profile Input Program[8] (BPIP) frequently creates artificially large buildings, as illustrated in Figure 1. Since an artificially large building is created, the starting point for the wake growth moves farther upwind (location A versus location B) which means that the height of the wake is much taller at the lee edge of the building than it should be if the wake growth started at location B. In addition, building wake turbulence enhancement should in reality start at location C while PRIME will have it start at location D. This results in an overstated wake height at location D

Figure 1. Diagram illustrating problems with BPIP building dimension inputs and wake height characterization

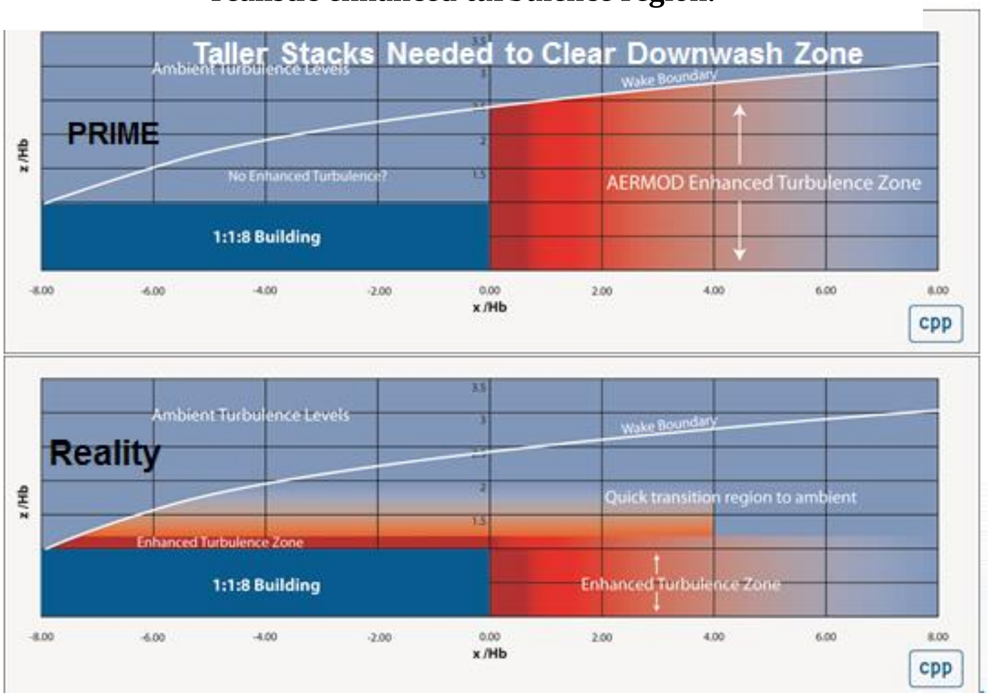


and an overstated amount of turbulence enhancement, both problems which will likely lead to higher ground-level concentrations than in reality.

A second problem relates to the height of the enhanced turbulence region calculated in PRIME. Figure 2 shows the turbulence enhancement region in PRIME versus the realistic enhancement region based on CFD simulations and wind tunnel measurements shown in Figures 3 and 4.

Figure 3 shows the mean wind field from a CFD simulation using open source code Fire Dynamics Simulator[9] (FDS) for a 15 m tall (H_b) building with H_b to W to L ratios of 1:1:2 run in large eddy simulation (LES) mode. The figure shows the velocity deficit (turbulence

Figure 2. Illustration of PRIME enhanced turbulence region and realistic enhanced turbulence region.

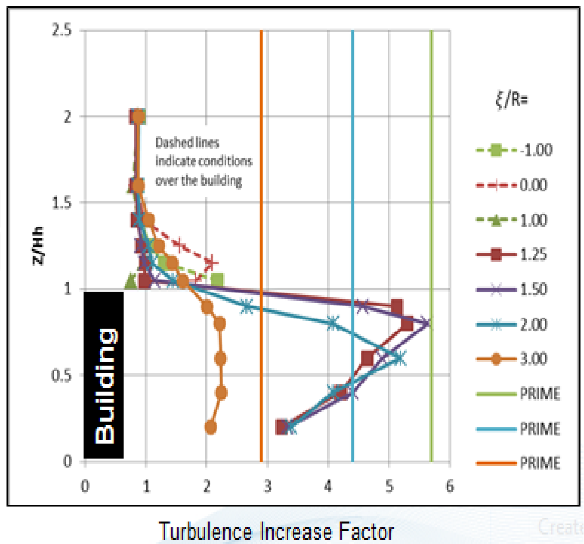


enhancement) only extends slightly above the top of the building versus extending up to the height of the wake.

Figure 4 shows the vertical turbulence intensity enhancement based on measurements obtained in a boundary-layer wind tunnel for the same 1:1:2 building. This figure also shows that the turbulence enhancement only extends slightly above the top of the building and decays rapidly

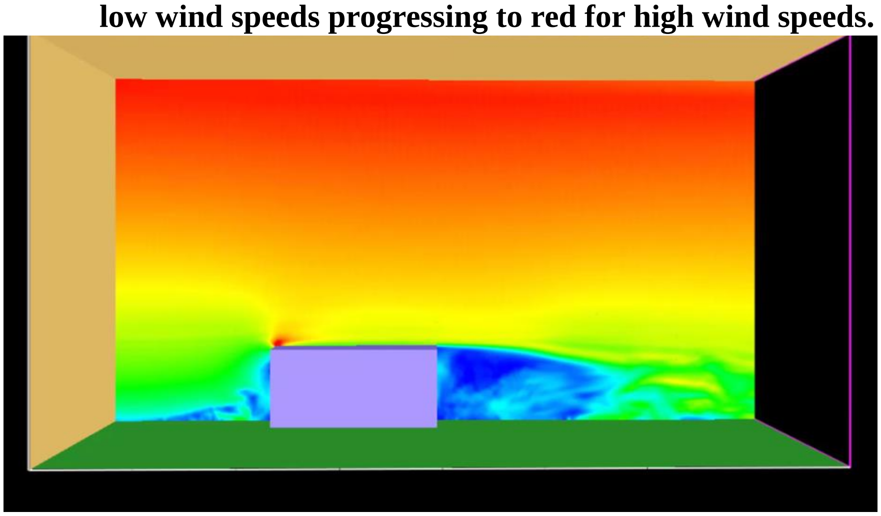
Figure 4. Vertical turbulence enhancement factor as measured in the wind tunnel for a building with aspect ratios of 1:1:2

Distance	Turbulence Increase Factor	
ξ/H_b	AERMOD	Observed
1	5.7	1.0 to 5.7
2	4.4	1.0 to 5.2
3	2.9	1.0 to 2.2



back to ambient turbulence levels. For long structures ($L/H_b>3$), the depth of the high turbulence region in PRIME can be well above the building roof as shown in Figure 2. This means that taller stacks and/or plume rise are required to escape the building downwash region than would be required in reality. This may explain the overprediction problems noted by Schulman[5] and

Figure 3. FDS LES simulation of airflow around a rectangular structure with building aspect ratios (H_b:W:L) of 1:1:2. Blue denotes low wind speeds progressing to red for high wind speeds.



Petersen[10] for long and/or wide structures.

Other problems with PRIME that have been identified are summarized below.

- The enhanced turbulence in the wake region starts at a constant value that does not vary with stability or surface roughness (see equation 30[3]). Values of 0.08 and 0.06 are assumed for the ambient lateral (i_{yo}) and vertical turbulence (i_{z0}) intensities based on Briggs dispersion formulas for neutral stability and rural conditions.[3] The starting point for the enhanced turbulence in the building wake is then assumed to be 1.7 times i_{yo} and i_{zo}. No basis is provided for this assumption and logic would suggest that the enhanced turbulence in the building wake would vary with surface roughness and atmospheric stability.
- Equations 14 and 15[3] should provide the same streamline slope at $x = 0$ (leading edge of the building) but they are different by a factor of two.
- The streamline and enhanced turbulence calculations are the same for lattice and streamlined structures as for rectangular structures. An obvious shortcoming that will most likely lead to model overpredictions.
- PRIME does not have any theory that accounts for the corner vortex. This oversight can cause PRIME to underpredict by a factor of two.[11] This suggests that when siting monitors to demonstrate compliance, agencies or concerned citizens should locate monitors in directions where a building corner is upwind of the stack.
- PRIME does not account for upwind terrain wake affects[12]. This suggests that when siting monitors to demonstrate compliance, agencies or concerned citizens should locate monitors in directions where terrain features are upwind of the stack. Guidance on where to locate the monitors can be found in Petersen.[12]

SUMMARY AND CONCLUSIONS

This paper summarizes some of the problems found in PRIME. Clearly PRIME needs a major overhaul so that facility expansion and new construction decisions that rely in some way on AERMOD can be made based on more accurate information. Below is the suggested path forward:

- correct all the known bugs, some of which are noted above and in Petersen; [4]
- fix the known problems in the theory;
- incorporate the current state of science;
- advance the current state of science based on new CFD and wind tunnel modeling studies;
- expand PRIME theory to account for more structures types (e.g., long and wide, porous, streamlined);
- provide a well-documented and verified model formulation document;
- add a section to Appendix W that outlines a method all can use (versus just EPA) to update AERMOD and/or PRIME based on current research;

Of importance is for EPA to have a policy that encourages industrial and academic research and freely and openly collaborates during the execution of that research.

REFERENCES

1. Cimorelli, A.J.; S.G. Perry; A. Venkatram; J.C. Weil; R.J. Paine; R.B. Wilson; R.F. Lee; W.D. Peters; and R.W. Brode. *AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization*. JAM. **2005**, *44*, *682-693*.

2. EPA. *Users Guide for the Industrial Source Complex (ISC3) Dispersion Model*. U.S. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, EPA-454/B-95-003a, 1995.

3. Schulman, L., D. Strimaitis, J. Scire. Development and evaluation of the PRIME plume rise and building downwash model, *J. Air & Waste Manage. Assoc*. **2000**, *50, 378-390*. *ACS Style Guide*; Dodd, J.S.; American Chemical Society: Washington, DC, 1986.

4. Petersen, R.L. *Building downwash – problems, solutions and next generation*, 11th Conference on Air Quality Modeling, EPA Research Triangle Park, NC. 2015.

5. Schulman, L.L, J.S. Scire. *Building downwash modeling with AERMOD*. Presented at the 10th Conference on Air Quality Modeling, EPA Research Triangle Park, NC. 2012.

6. Baugues, K. *An assessment of the American Meteorological Society/U.S. EPA regulatory model's (AERMOD's) accuracy: a case study*. Indiana Department of Environmental Management Office of Air Quality. 2015.

7. Shea, D., O. Kostrova, A. MacNutt, R. Paine, D. Cramer, L. Labrie. *A model evaluation study of AERMOD using wind tunnel and ambient measurements at elevated locations*. 100th Annual AWMA Conference, Pittsburgh, PA. 2007.

8. EPA. *User's guide to the building profile input program*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Technical Support Division, Research Triangle Park, North Carolina 27711. 1993. EPA-454/R-93-038.

9. K. McGratten, McCermott, R., Weinschenk,C. *Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model*. National Institute of Standards and Technology Special Pulicatoin 1018-1. October 2013.

10. Petersen, R.L. and A. Beyer-Lout, 2009: "Is AERMOD/PRIME Overpredicting for Short Buildings with a Large Footprint?" 102nd Annual Conference and Exhibition of the Air &Waste Management Associate, Paper 517

11. Petersen, R.L., A. Beyer-Lout, R. J. Paine. *Evaluation of monitored SO_2 NAAQS exceedances due to the corner vortex.* 105th Annual Conference and Exhibition of the Air &Waste Management Associate, San Antonio, Texas, Paper 451. 2012.

12. Petersen, R.L., A. Beyer-Lout. *AERMOD building downwash theoretical limitations and possible solutions.* 105th Annual AWMA Conference, San Antonio, TX. 2012.

13. Snyder, W.H. and R.E. Lawson, 1994: Wind-tunnel measurements of flow fields in the vicinity of buildings, *Eighth Joint Conference on Applications of Air Pollution Meteorology with A&WMA*, American Meteorological Society, Boston, MA, pp. 244-250.