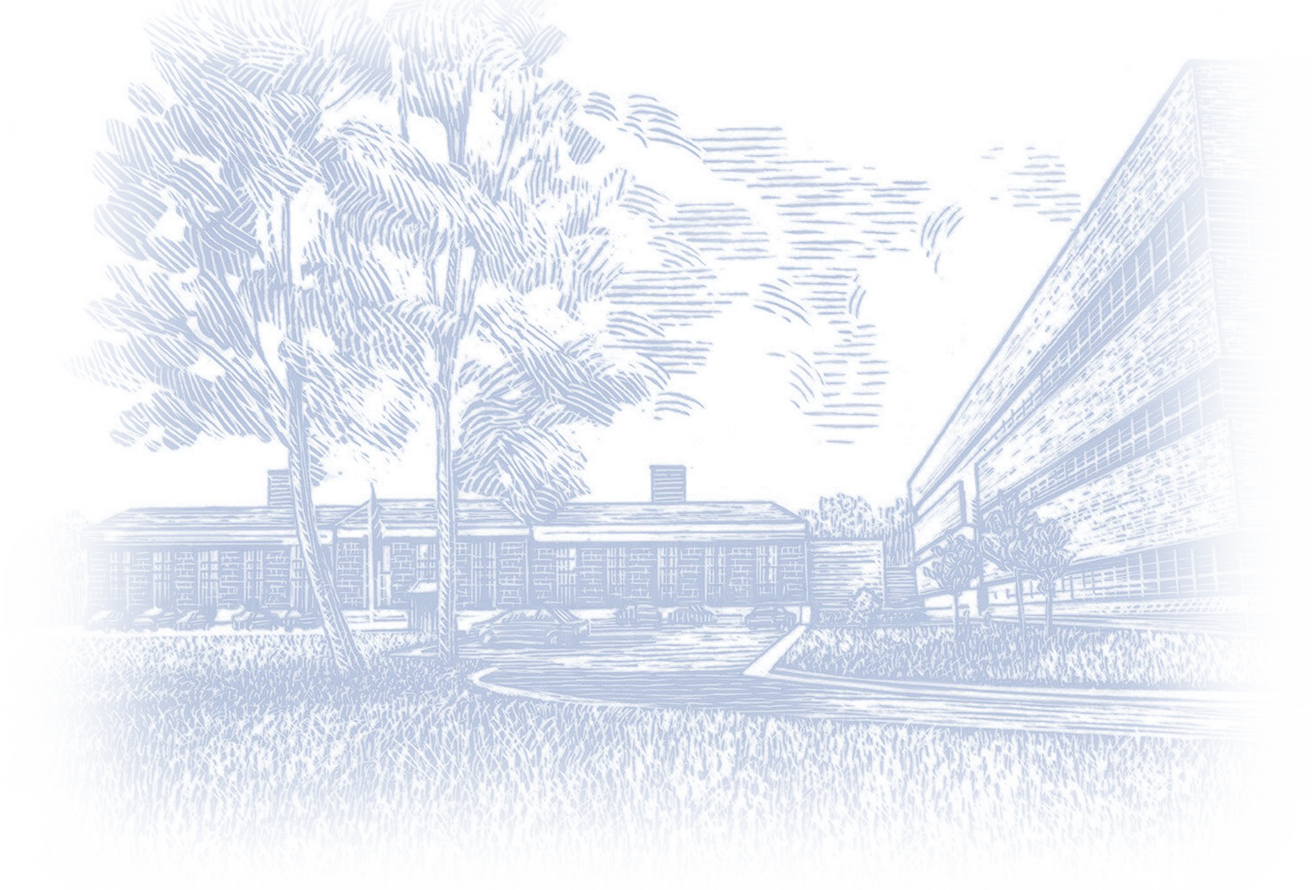
Modifications of Highway Air Pollution Models for Complex Site Geometrics (Canyon Plume Box Model [CPB 3.6])

Publication No.: FHWA-RD-02-036/037 **Month Year N/A**



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Volume I: Data Analyses And Model Development And Volume II: Wind Tunnel Test Program

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The Federal Highway Administration—in collaboration with the Transportation Research Board, the National Cooperative Highway Research Program, State departments of transportation, and other Federal agencies—has been investigating the effects of highway transportation on air quality. These investigations have primarily dealt with the evaluation of air-contaminant emissions produced by motor vehicles at various speeds and under various highway conditions. Dispersion of air-contaminant emissions in various areas has been analyzed.

Highway agencies are also mandated to evaluate whether mobile-source emissions conform to State implementation plans and to make adjustments, as required, to meet ambient air quality standards.

This TechBrief announces the two volumes in this series documenting the study entitled "Modifications of Highway Air Pollution Models for Complex Site Geometries":

Modifications of Highway Air Pollution Models for Complex Site Geometries, Volume I: Data Analyses and Model Development and Volume II: Wind Tunnel Test Program (Publication Nos. FHWA-RD-02-036 and -037)

This study's purpose was the evaluation of the limitations of flat, open terrain highway air pollution dispersion models for complex site geometries such as found within semi-confined spaces, such as highway cut-sections and street canyons. This included the development of modifications or the refinement of existing models or new models applicable to these situations and more appropriate than open terrain, straight-line highway air pollutant models, typically represented by Gaussian plume formulations. A major component of this study involved an extensive wind tunnel measurement program of the flows, turbulent velocity variances, and concentration fields within a wide range of street canyon and highway cut-section geometries. This wind tunnel study was undertaken at Boston University's fluid modeling facility and was designed to clarify the basic phenomena that control atmospheric dispersion in these complex flow environments, such as street canyons, and to provide the data needed for the development of an applicable pollutant dispersion model. Model refinements were carried out by a subcontractor with a well-established model for such semi-confined environments.

This Federal Highway Administration (FHWA) investigation was subsequently augmented to address the concerns of the Federal Aviation Administration (FAA) and the U.S. Air Force, who have concerns about the wind-perturbing environmental impacts of buildings at airports and air bases. At airports, many of the highest air contaminant concentrations and population exposures occur at the curbsides of access roads at the terminal. Hence, this study was expanded to consider wind flow and air pollutant dispersion complexities, as typified at the Seattle-Tacoma [commercial] International Airport (SeaTac) in Washington State. Both wind tunnel simulations and full-scale site measurements were made for SeaTac. The specific topology investigated in-volved a curved access road and a semiporous parking garage.

It is well known that highway vehicle-emitted exhaust gases do not disperse within cut-sections and urban street canyons in the same manner as in open, flat terrain environments, for which conventional boundary-layer flow and turbulence theory are appropriate and for which many Gaussian plume models of contaminant dispersion exist. In such semi-confined locations, such as narrow highway cut-sections or street canyons, wind speeds are suppressed, and there are frequent occurrences of separated flow vortices, which can lead to pollutant recirculations and, consequently, areas of higher air contaminant concentrations resulting from vehicle emissions within these semi-confined spaces. The straight-line Gaussian dispersion models do not apply in regions where the flow is curved or recirculates and, thus, are not applicable within these canyons or immediately downwind of them. Highway traffic in such semi-confined locations and especially in urban street canyons can have higher pollutant emission rates due to low irregular vehicle speeds, prolonged queuing, and frequent accelerations. Consequently, high primary pollutant concentrations can develop in these depressions. This may not be true of secondary air contaminants.

The major differences between the cut-section/street canyon and flat terrain air pollutant potentials derive from basic differences between the airflow across and down into depressed or cut-sections and those associated with reasonably developed boundary layers. In the established boundary-layer flows, the wind velocity tends to increase logarithmically in height above the surface roughness elements from 5 to 100 times the height of the surface roughness (100 m in a typical city where surface roughness is on the order of 1 m), whereas the wind shear-induced turbulence, responsible for pollutant dispersion, decreases slowly with height. In the case of narrow cut-sections, especially those with abrupt vertical walls, flow separations occur just at the top of the cut-section with:

- An upper, skimming flow continuing on past the cut-section and remaining relatively unaffected downwind of the cut, except for a somewhat increased amount of turbulence.
- A cut-section-filling vortex flow exhibiting relatively weak turbulent flow at street level.

These two flow regimes are coupled via turbulent exchange at their interface, as well as by an advective exchange driven by a sinking of the separation streamline below the top of the downstream wall. This streamline impingement on the downwind wall drives fresher air from above down along the downwind wall. The return flow up the lee wall then partially forces its way into the skimming flow regime, helping to vent pollutants from the cut-section, while the remainder of this air continues across the notch top to undergo turbulent exchange or subsequent circulation. The advective component of air exchange between the within- and above-canyon flows becomes stronger as the separation streamline sinks deeper into the cut-section, as is the case with wider cut-sections (width-to-height [W/H] ratio values are higher) or for cases where the downstream wall is higher than the upstream wall.

For cases where the separation streamline actually hits the street before the opposite wall, the within-canyon vortex splits into distinct upstream and downstream corner vortices. This situation, which occurs for canyon W/H ratios exceeding 6, is not particularly well modeled by either the Gaussian models or by the models developed within this project.

Cut-sections having gently sloped sidewalls do not induce separated flow. Instead, the flow simply diverges to fill the cut-section (i.e., with flow streamline separation growing and flow speeds decreasing) and reconverges on the downstream upslope wall to produce flow speed-up and streamline compression. The report discusses the pollutant concentration changes as a result of recompression of surface flows.

Most of the findings of this study are consistent with the above simple concepts and different flow situations as illustrated in the reports. Hence, this study reflects the basic fluid mechanics of airflows in the presence of the complex building/ wall geometries that characterize typical highway cut-sections or urban street canyons. Variations considered in this study include a range of W/H ratios, unequal upwind and downwind heights, curved roads, porous walls, the effects of openings such as intersections, and the effects of large proximate high structures.

The analysis and interpretation of these and other data are documented in Publication No. FHWA-RD-02-036, Volume I: Data Analyses and Model Development. The model development and analyses of the problems were started before the wind tunnel test program was begun and continued during and after the completion of the wind tunnel and the use of full-scale field tests.

In this volume, the authors:

- Reviewed what is known from flat terrain highway modeling and experimental studies.
- Considered the status of street canyon modeling, field studies, and wind tunnel studies.
- Analyzed the experimental flow, turbulence, and concentration data obtained from this program to expand the useful validity range of the original Canyon Plume Box (CPB-1) developed by the lead author of this report and European experts for sites in Germany and The Netherlands.
- Created a more comprehensive model, CPB-3, that can simulate cut-sections and street canyons having W/H ratios ranging from ¼ to 6, geometries having unequal height sides, semi-open walls, and roadway curvature, and include wind direction variability.
- Evaluated the applicability limits of this new model, CPB-3, relative to existing roadway models, which are usually satisfactory for cuts with a W/H greater than 6.

Focusing on the data analyses and model development portion of the study, it was noted that the starting point for the modeling effort began with the CPB-1 model, under development since 1981 (reported by Yamartino and Wiegand, 1986), which was refined on the basis of this study. It was originally based primarily on a full-scale study of a single European street canyon having a $W/H^{a} \approx 1$. A primary objective was to extend this model concept to accommodate the many variables and geometric variations studied in the wind tunnel. Such a merger of wind tunnel and full-scale data yielded a useful dispersion model applicable to both scales and that involved the following analyses:

- Investigation of the spectral and probability density characteristics of output from the single hot-wire anemometer in highly turbulent environments to overcome its rectification (i.e., wind direction insensitivity) limitation.
- Development of an algorithm to convert hot-wire measures of mean flow and turbulence to those that are measured in the full scale using direction-sensitive probes such as u-v-w anemometers.
- Hot-wire measurements of flow and turbulence above and within depressed sections to create a series of correction functions for various canyon geometry variables and that are applicable, respectively, to an earlier quasi-analytic flow solution (Hotchkiss and Harlow [1973]) and an empirical turbulence model developed as part of the CPB-1 modeling effort.
- Implementation of the above flow and turbulence correction functions into CPB-1 modules to produce a new model version, CPB-3. In addition, this new model version contains modifications to the basic ventilation physics to account for semi-open bounding walls and meander of the above-roof wind direction.
- Comparison of CPB-3 concentration predictions with tracer concentrations measured in the wind tunnel with the objective of understanding the model's predictive power and its limitations (i.e., regimes where other models are more appropriate).

Among the many results of these analysis efforts, it was found that:

- Independent, multiplicative correction factors are generally reasonable for turbulence estimation, but are less satisfying for the flow velocity field. This may result from the flow field involving a sum of coherent processes, whereas the turbulence field involves a sum of incoherent processes.
- CPB-3 concentration predictions for various two-dimensional (2D) and three-dimensional (3D) idealized canyons are in generally good quantitative agreement (i.e., ±10 percent) with Boston University wind tunnel measurements.
- The W/H = 2 canyon shows anomalous behavior in flow, turbulence, and concentration fields and CPB-3 predictions fall more than 35 percent below observations.
- The downwind facing step (i.e., one-sided canyon) is well simulated by allowing a downwind wall of equal height to have 100-percent porosity, despite the fact that this value of porosity is well

beyond the maximum value of about 40 percent actually studied in the wind tunnel. This technique proved to be unsuccessful in treating the upwind-facing step.

- The CPB-3 model is able to qualitatively reproduce the concentration variations observed as a receptor approaches an intersection; however, two distinct concentration enhancement regions, thought to be due to vertical axis rotor and additional along-canyon mechanisms, are not identified by the model.
- The CPB-3 model generally produces the C* = 80 - 100 level of peak concentrations that are observed in wind tunnel, scale-model simulations of actual urban environments. (It should be noted that C* is a dimensionless, normalized concentration measure defined as the dimensional mass concentration (gm/m3) times the obstacle height (m), times the geostrophic or gradient wind velocity (m/s), and divided by the line source emission rate (gm/m/s)). Through the non-dimensionalization of concentrations, C* values determined in the wind tunnel should equal corresponding full-scale C* values, even though the mass concentration values differ by a large factor. Thus, C*'s are useful for comparing full-scale measurements with wind tunnel-scale results or for rescaling wind tunnel measurements to full-scale concentration estimates.
- The CPB-3 model is appropriate for steep-walled urban canyons (i.e., (45°), but not for the shallow-walled canyons that characterize some cut-section highways. While a precise wall-angle breakpoint has not been identified, the shallow-walled (i.e., (15.6°) Houston, TX, Katy Freeway cut-section highway is more appropriately described by a conventional, open highway dispersion model. The net effect of these cut-sections on subsequent downwind dispersion can be parameterized through an initial sigma, $\sigma_z(0)$; however, only an upper limit, $\sigma_z(0)\ ^{a}\approx$ 0.1 H for W/H = 1, was established in this study.
- The CPB-3 model is generally applicable when and where recirculation (i.e., vortices) is present, whereas open highway models are applicable well outside of any recirculation zones. Detailed discussion of the appropriate re-gimes is included.
- The resulting CPB-3 model is user-friendly and can be run easily on a personal computer. While it incorporates many of the mechanisms needed to model full-scale phenomena, there are opportunities to improve it in distinctly 3D environments.

Detailed descriptions of the wind tunnel experiments are documented in Publication No. FHWA-RD-02-037, Volume II: Wind Tunnel Test Program. The overall experimental strategy involved consideration of:

- Variations in the basic geometric variables, height (H), width (W), and length (L), of the simple rectangular-notch street canyon geometry.
- Influences of real-world 2D phenomena, such as unequal upwind/ downwind wall heights, sloping walls, roadway curvature (quasi-2D), and building porosity (to emulate semi-open garage structures).
- Influences of a few distinctly 3D phenomena, such as intersections and isolated tall buildings.
- Simulation of several specific geometries for which companion full-scale studies were available, including studies conducted in St. Paul, MN; New York City and Syracuse, NY; and Houston, TX.
- Full-scale field measurements for two complex sites at SeaTac.

Researchers— This TechBrief is based on a study performed by TIDG, Inc. with Richard E. Hayden, who was the president and the principal investigator of this study. Dr. Robert J. Yamartino, senior author of one of the reports, was employed by a subcontractor, Sigma Research Corporation of Westford, MA. Dr. George Succi was the leader of the wind tunnel measurements group for subcontractor Boston University.

Subsequent to this study, both TIDG and Sigma Research were acquired by larger corporations. Presently, Mr. Hayden (54 Brooks Road, Sudbury, MA 01776, (978) 443-3478), Dr. Succi (60 Second Street, Newburyport, MA, (978) 465-1237), and Dr.

Yamartino (509 Chandler's Wharf, Portland, ME 04101, (207) 780-0594) are independent consultants.

Howard M. Segal was the FAA contact for this study. He has retired from FAA and can be reached at (303) 494-5429.

With the retirement of Dr. Howard A. Jongedyk, FHWA monitor, questions should be referred to the others mentioned in this TechBrief, especially Dr. Yamartino, Mr. Hayden, Dr. Succi, Mr. Segal, Dr. Hosker, and Mr. Fleming.

The U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) has considerable interest in micro-scale airflow studies such as this. Dr. Rayford Hosker of the Atmospheric Turbulence and Diffusion Division of the NOAA Air Resources Laboratory provided advice before and during this study. He can be reached at: U.S. Department of Commerce, NOAA Air Resources Laboratory, Atmospheric Turbulence and Diffusion Division, P.O. Box 2456, Oak Ridge, TN 37831-2456, (865) 576-1233.

Also providing advice for this investigation were Dr. P. Builtjes of TNO (The Netherlands), Dr. G. Wiegand of Geomet (Germany), and the late T. Lockhart of Meteorological Standards Institute of Fox Island, WA.

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Availability—The publications are available now. Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. A limited number of copies are also available from the R&T Report Center, HRD-11, FHWA, 9701 Philadelphia Court, Unit Q, Lanham, MD 20706, Telephone: (301) 577-0818, Fax: (301) 577-1421.

Key Words—Air pollution, street canyons, highway cut, urban dispersion models, wind tunnel, and turbulence.

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