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Diesel exhaust plume studies:
wind tunnel experiments and modeling

DIESEL EXHAUST PLUME STUDIES: WIND TUNNEL EXPERIMENTS AND MODELING

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DILUTION RATIOS, AND PM SIZE DISTRIBUTION AND CONCENTRATION DATA FROM LANGLEY TUNNEL STUDY (CRC E-43)

(Data was reported at the 10th On-Road Vehicle Emissions Workshop, San Diego, Ca; March 27-29, 2000)

The experimental study at the Langley Wind Tunnel was funded by the Coordinating Research Council and DOE/NREL through the University of Minnesota. Co-sponsored by the Engine Manufacturers Association, South Coast Air Quality Management District, California Air Resources Board, Cummins Engine Company, Caterpillar and Volvo

WEST VIRGINIA UNIVERSITY TEAM FOR E-43 STUDY

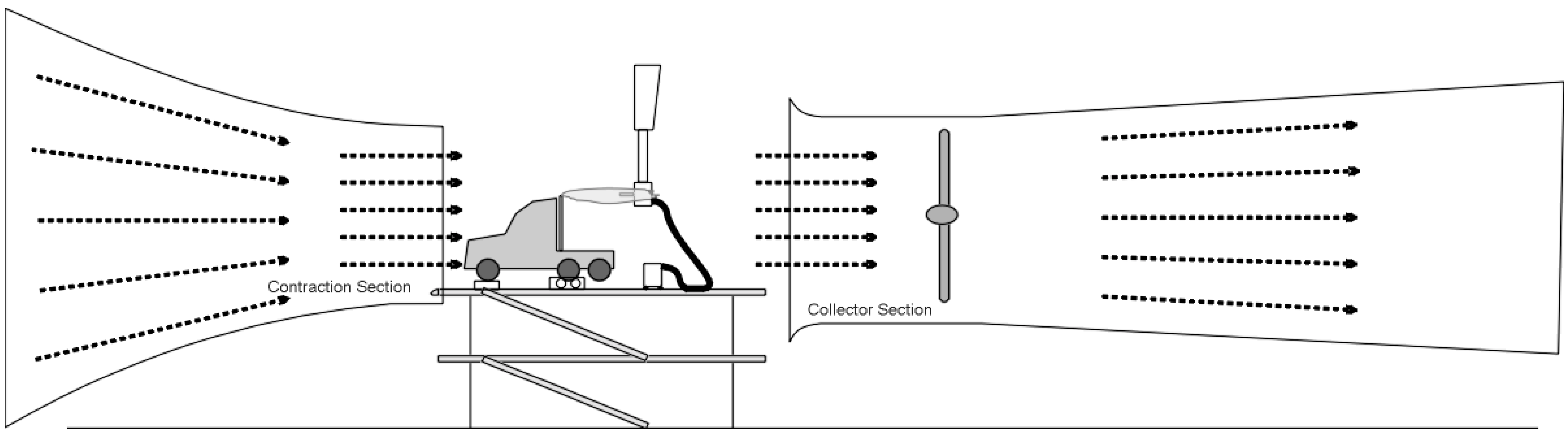
Alberto Ayala, James Boyce, Nigel Clark, Mridul Gautam, Don Lyons, Sandeep Mehta, Byron Rapp, Wenwei Xie, and Xu Zhuyun

OBJECTIVES

TO DEVELOP A SIMPLE PLUME DISPERSION MODEL TO PREDICT POLLUTANT CONCENTRATIONS IN A "REAL" HEAVY-DUTY TRUCK PLUME.

TO VALIDATE THE MODEL(S) WITH CO_2 CONCENTRATION DATA COLLECTED FROM A WIND TUNNEL STUDY USING A HEAVY-DUTY TRUCK, WITHOUT A TRACTOR, THAT WAS EXERCISED OVER A STEADY STATE MODE OF OPERATION.

WIND TUNNEL SIDE VIEW



Tunnel proportions and equipment layout

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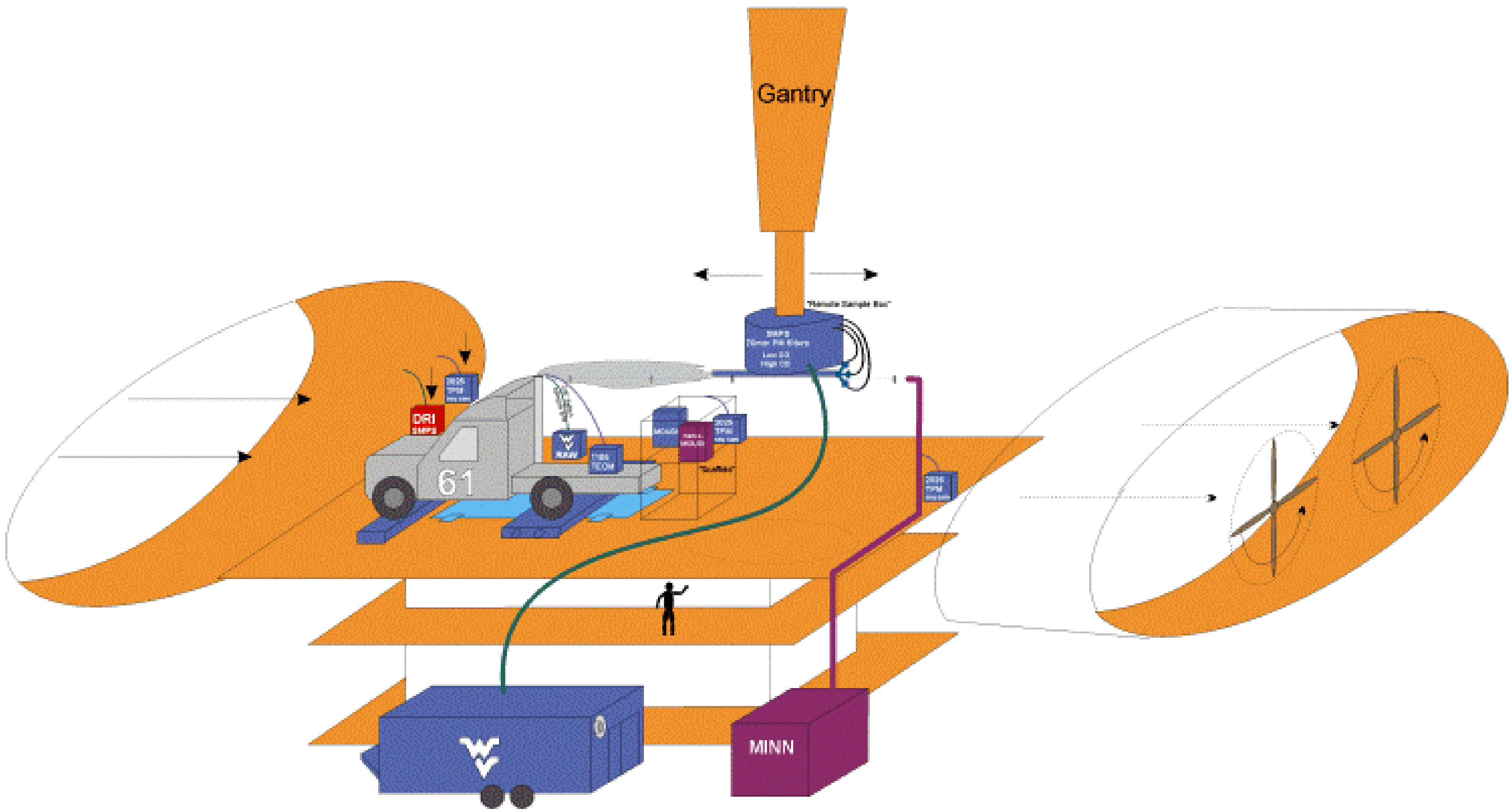
Source: 10th On-Road Vehicle Emissions Workshop, San Diego, Ca; March 27-29, 2000

WIND TUNNEL TEST EQUIPMENT LAYOUT



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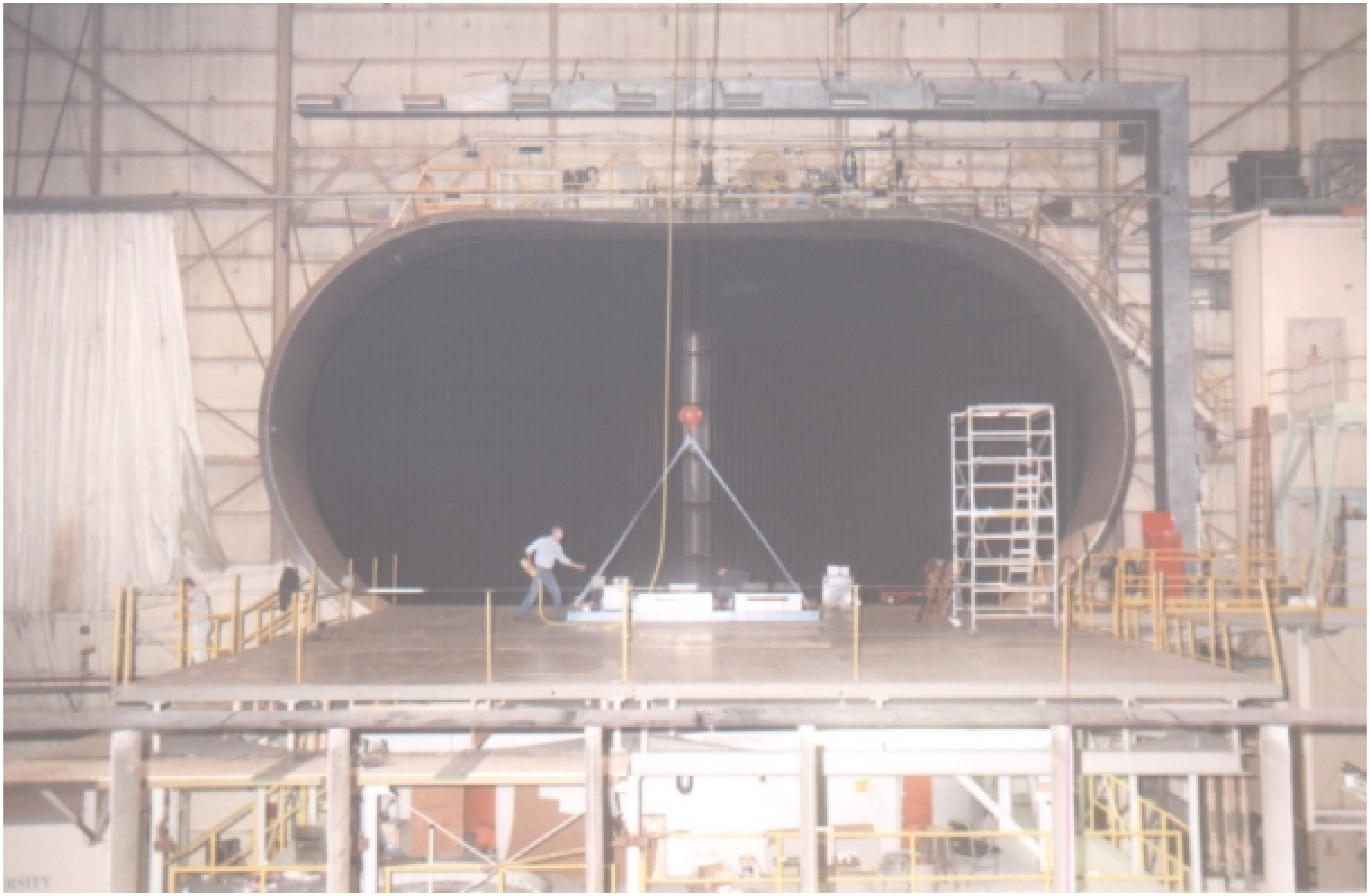
TEST PLATFORM AS VIEWED FROM COLLECTOR SECTION



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Source: 10th On-Road Vehicle Emissions Workshop, San Diego, Ca; March 27-29, 2000

DYNAMOMETER, TRUCK, AND INSTRUMENTATION ON PLATFORM

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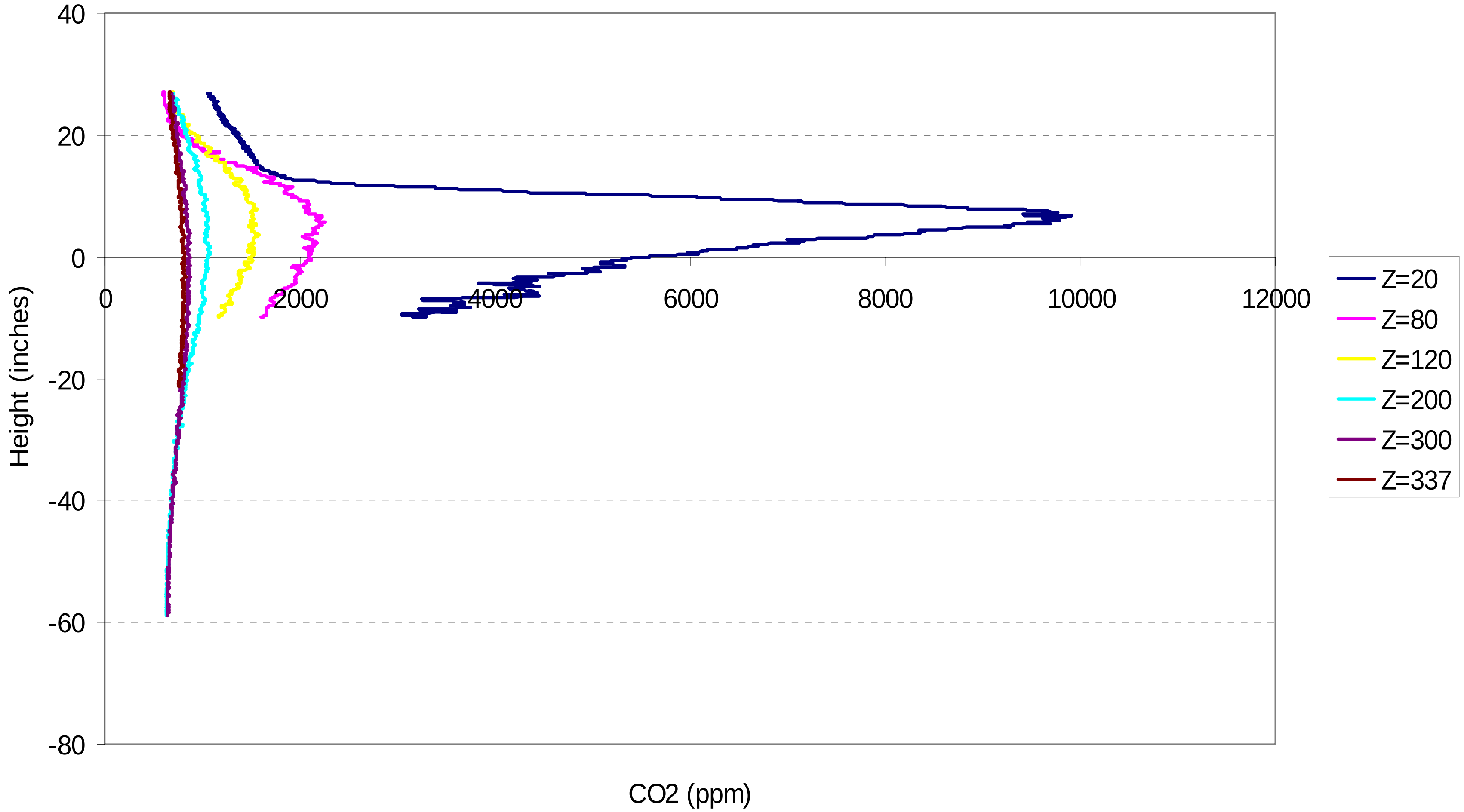
Source: 10th On-Road Vehicle Emissions Workshop, San Diego, Ca; March 27-29, 2000

PLUME CO_2 CONCENTRATION (ppm)



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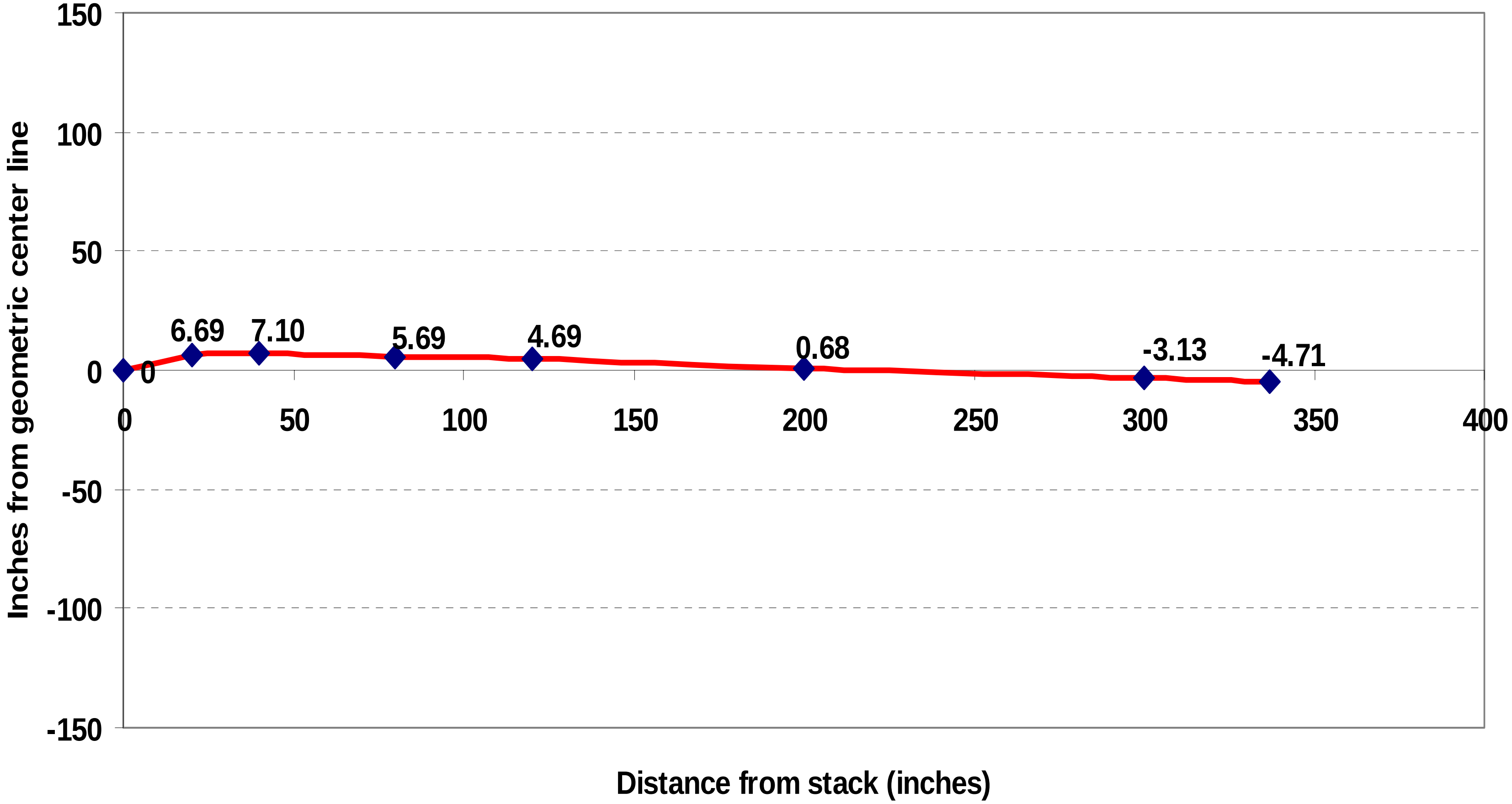
MEASURED CENTER LINE OF THE PLUME



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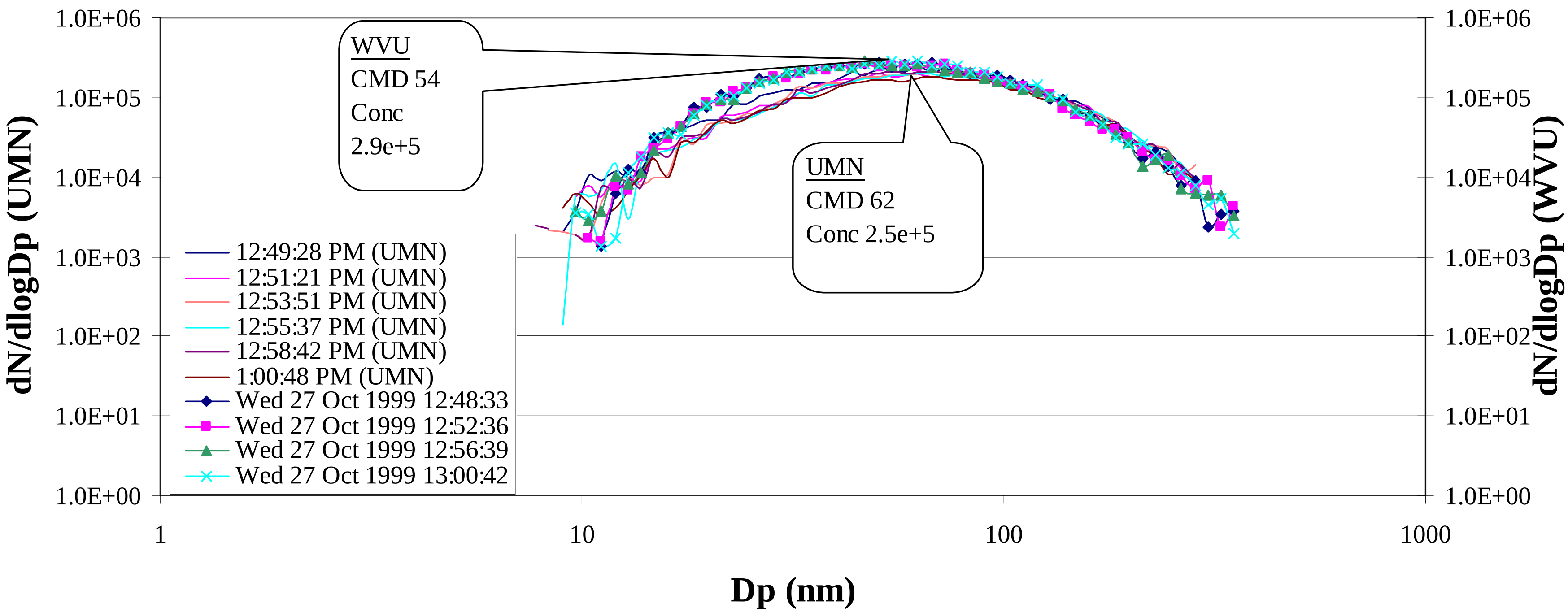
WVU LOCATION (337,-4.71); UMN LOCATION (430)



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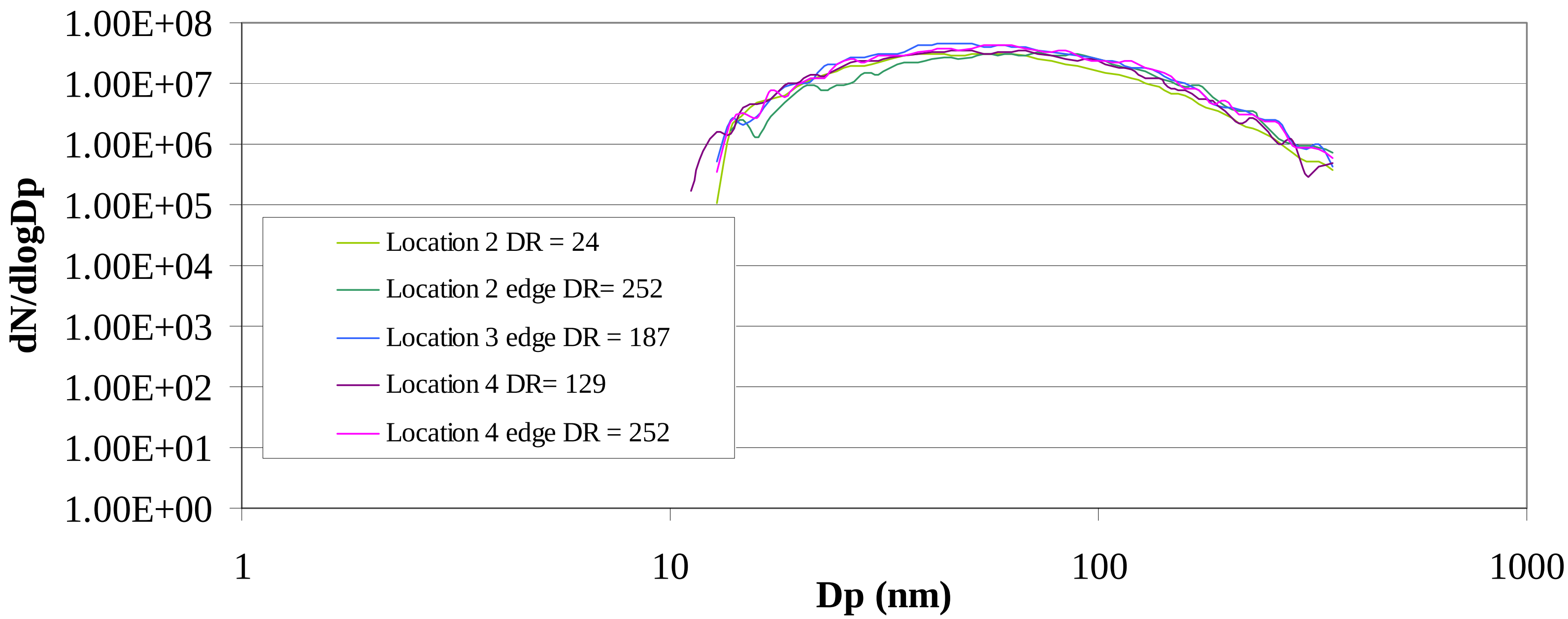
Source: 10th On-Road Vehicle Emissions Workshop, San Diego, Ca; March 27-29, 2000

EMISSIONS FROM VARIOUS LOCATIONS REDUCED BACK TO THE ENGINE



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Source: 10th On-Road Vehicle Emissions Workshop, San Diego, Ca; March 27-29, 2000

Concentration Distribution Equations

Contaminant concentration at a given position in the plume may be expressed by the well-known Gaussian plume equation (in the slender plume case):

$$c(x, y, z) = \frac{q}{2\pi u \sigma_y \sigma_z} \exp(-(\frac{y^2}{2\sigma_y{}^2} + \frac{z^2}{2\sigma_z{}^2}))$$

Where, $c(x,y,z)$ is the contaminant concentration, %V/V; u *is* the longitudinal average wind velocity, m/s; σ_y *is* the horizontal dispersion coefficient, m; σ_z *is* the vertical dispersion coefficient, m; x,y,z are the downwind, horizontal, and vertical distances, respectively, with the x-axis for the plume centerline, m; q is the source strength, g/s or m^3/s, expressed by

$$q = c_0 Q$$

Where, c_0—the raw concentration from the stack exit, %V/V;

Q—the exhaust airflow rate; m^3/s.

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Contaminant concentration distribution along the plume centerline:

$$c(x,0,0) = \frac{q}{2\pi u \sigma_y \sigma_z}$$

where, c(x,0,0)—the contaminant concentration along the plume centerline (ppm or g/m^3).

Concentration vs. the z-axis (vertical direction) at given axial locations (x cross-sections) is expressed by:

$$c(x,0,z) = \frac{q}{2\pi u \sigma_y \sigma_z} \exp(-\frac{z^2}{2\sigma_z{}^2})$$

Concentration vs. the y-axis (horizontal direction) at given axial locations (x cross-sections is expressed by:

$$c(x,y,0) = \frac{q}{2\pi u \sigma_y \sigma_z} \exp(-\frac{y^2}{2\sigma_y{}^2})$$

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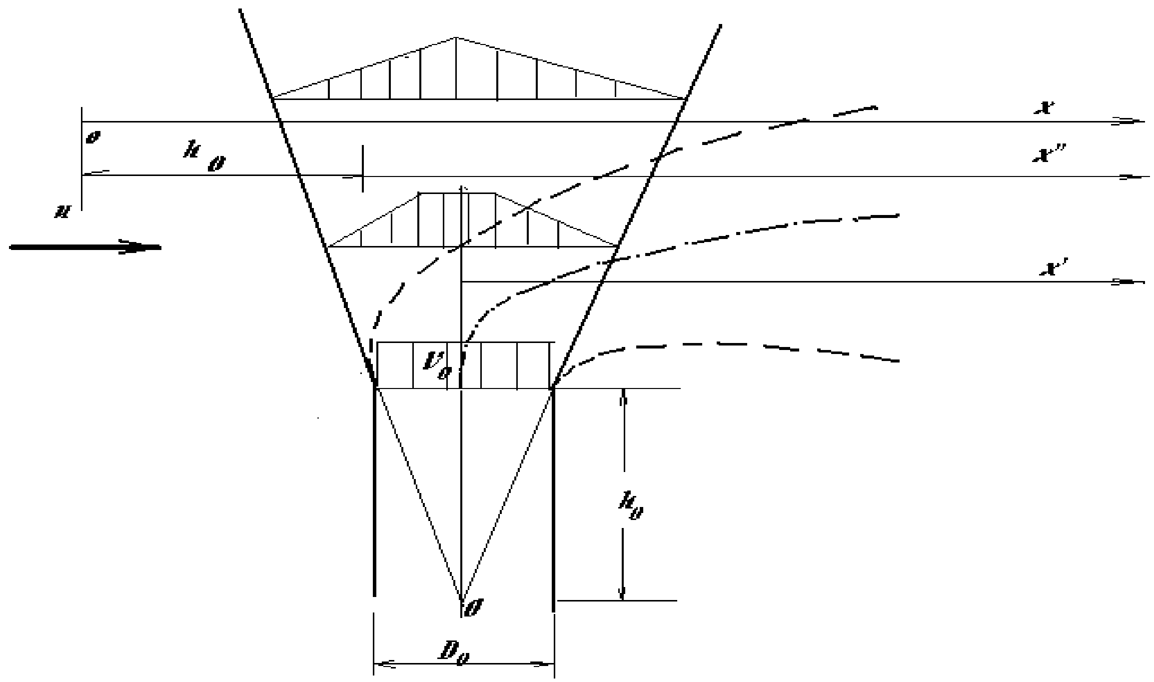
Circular Jet Velocity Field and Plume Construction



O—polar point; h_0— polar distance;
D_0— diameter of the stack; *u*—longitudinal wind velocity;
V_0—exhaust air velocity in the stack exit.

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Estimation of Dispersion Coefficients

The dispersion coefficients are functions of K_{yy} , K_{zz} and x, and may be expressed as:

$$\sigma_y{}^2 = 2K_{yy}x/u; \sigma_z{}^2 = 2K_{zz}x/u$$

where, K_{yy}, K_{zz}—diffusivities; x—downwind distance from the source, along the plume centerline.

Many of the empirically determined forms may be represented by power-law expressions,

$$\sigma_y = R_y x^{r_y}, \sigma_z = R_z x^{r_z}$$

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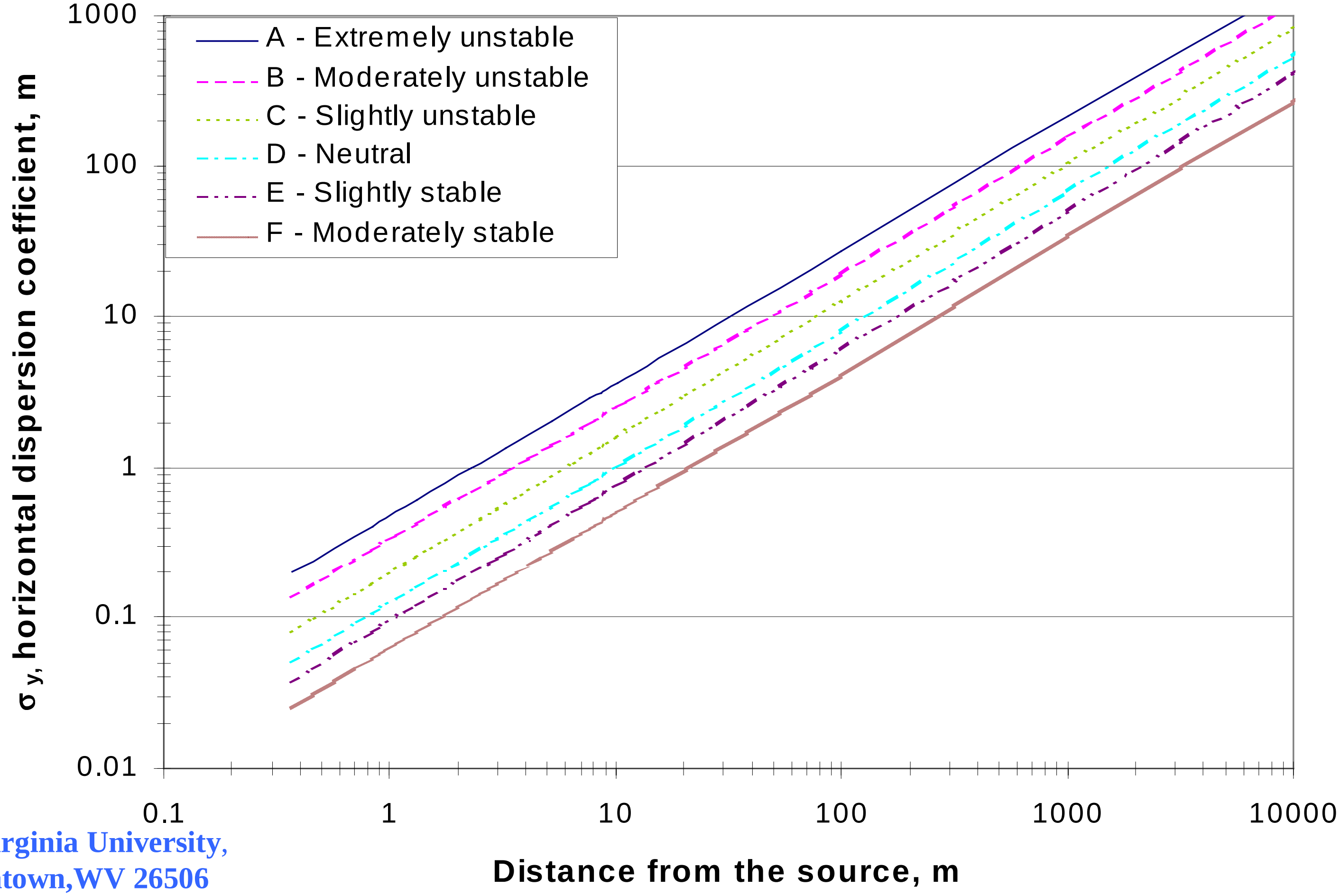
Extended Pasquill- Gifford Curve for the Horizontal Dispersion Coefficient



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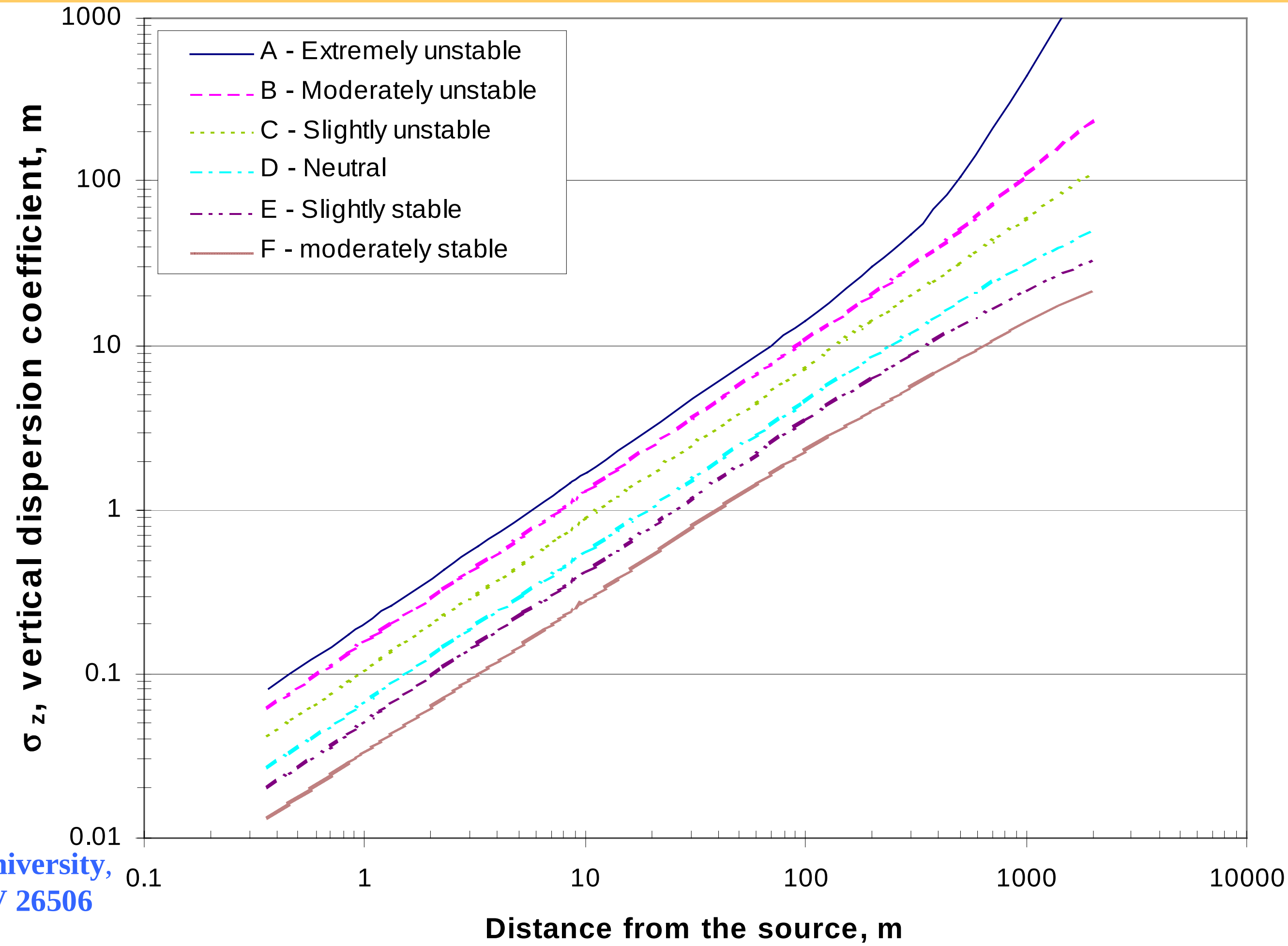
Extended Pasquill- Gifford Curve for the Vertical Dispersion Coefficient



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Relative Concentration

$$\frac{c(x,0,0)}{c_0} = \frac{Q}{2\pi\sigma_y\sigma_z}; \frac{c(x,0,z)}{c_0} = \frac{Q}{2\pi\sigma_y\sigma_z}\exp(-\frac{z^2}{2\sigma_z^2})$$

$$Q = V_m M_f (453.59)/(CMW_f D_{co_2} /100)$$

$$= 0.79072 * 88 * 453.6/13.8144 / 4.74*100 / 60 = 803\ ft^3 / \min$$

where, M_f—the mass flow rate of fuel used in the engine, lbs/hr;

V_m—the volume of one mole of gas at standard temperature and pressure, ft^3/mole;

CMF_f—the molecular weight of the fuel per carbon atom, g/moleC;

D_{CO2}—the CO_2 concentration in exhaust, % (dry).

Relative Concentration along Negative Z-Axis at Given Axial Locations

It was found that the model estimation did not agree very well with the experimental data along the negative z-axis, especially for the first 3 cross sections: x'=20, 40, and 80 inches. This was explained by the existence of a very large eddy behind the tractor. Flow visualization studies showed that the eddy extended nearly 100 inches behind the tractor.

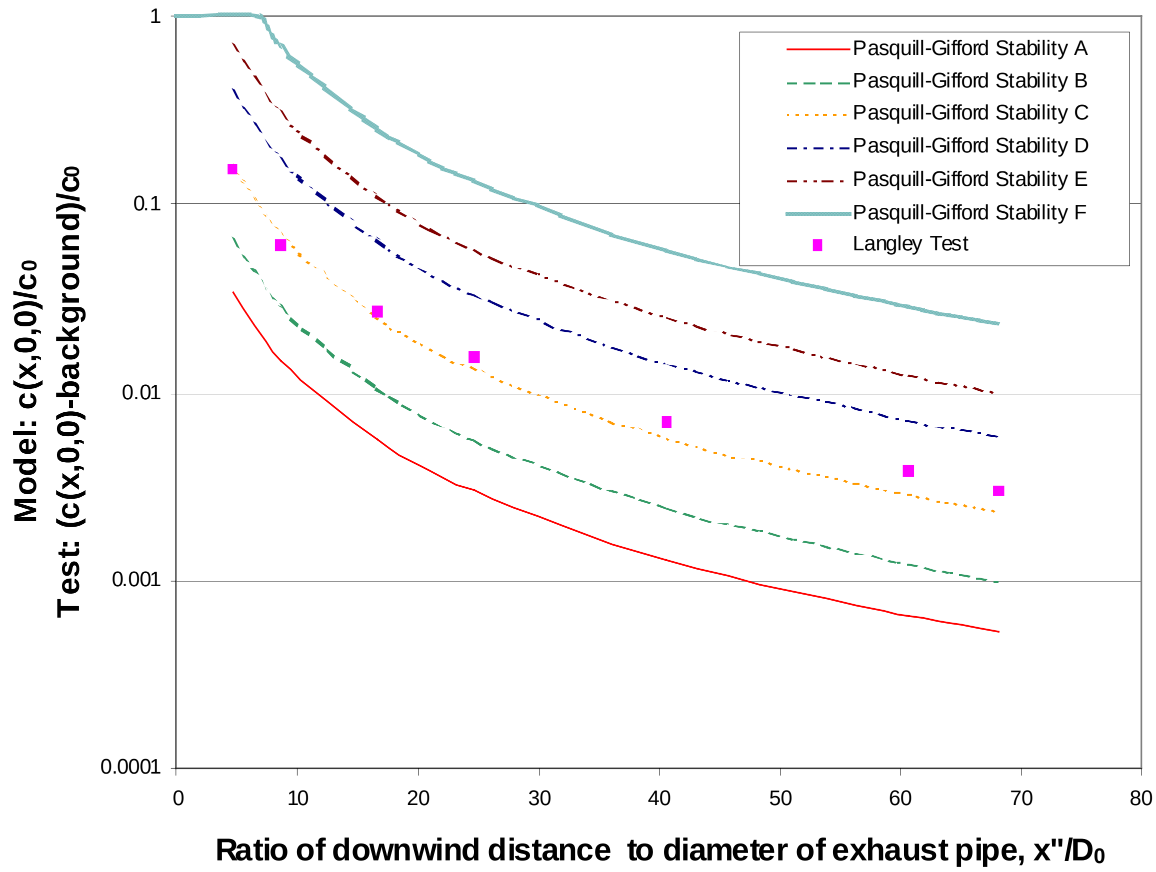
Analysis of the concentration profile in the wake region is not trivial. However, it is critical that this information be available. Hence, a modified equation was employed:

$$\frac{c(x,0,z)}{c_0} = \frac{Q}{2\pi u \sigma_y \sigma_z}\exp\left(-\frac{z^2}{2C_e\sigma_z^2}\right)$$

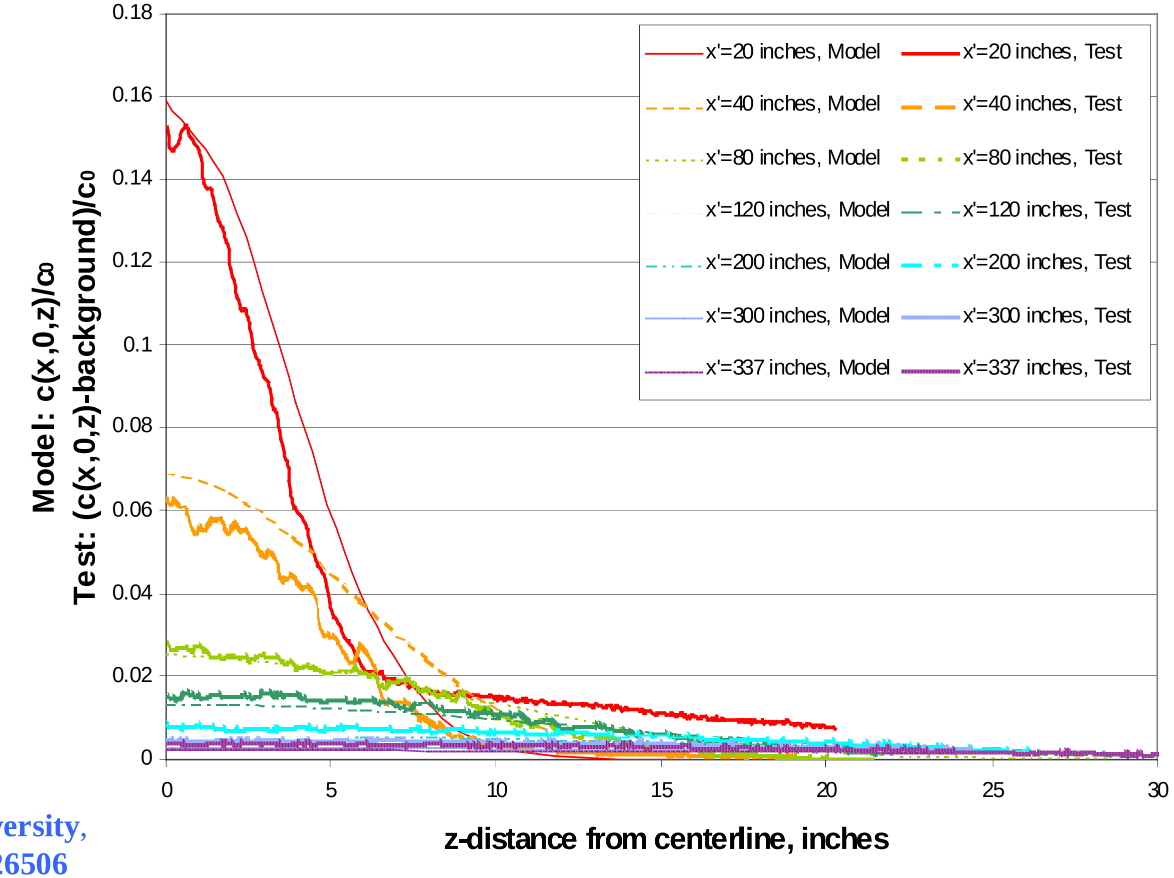
where, *Ce* :

$$C_e = 1 + \frac{50\,|z|}{x'}$$

Relative Concentration Along the Plume Centerline



Relative Concentration Profiles Along the Positive Vertical Axis Pasquill-Gifford Estimation (Stability C)



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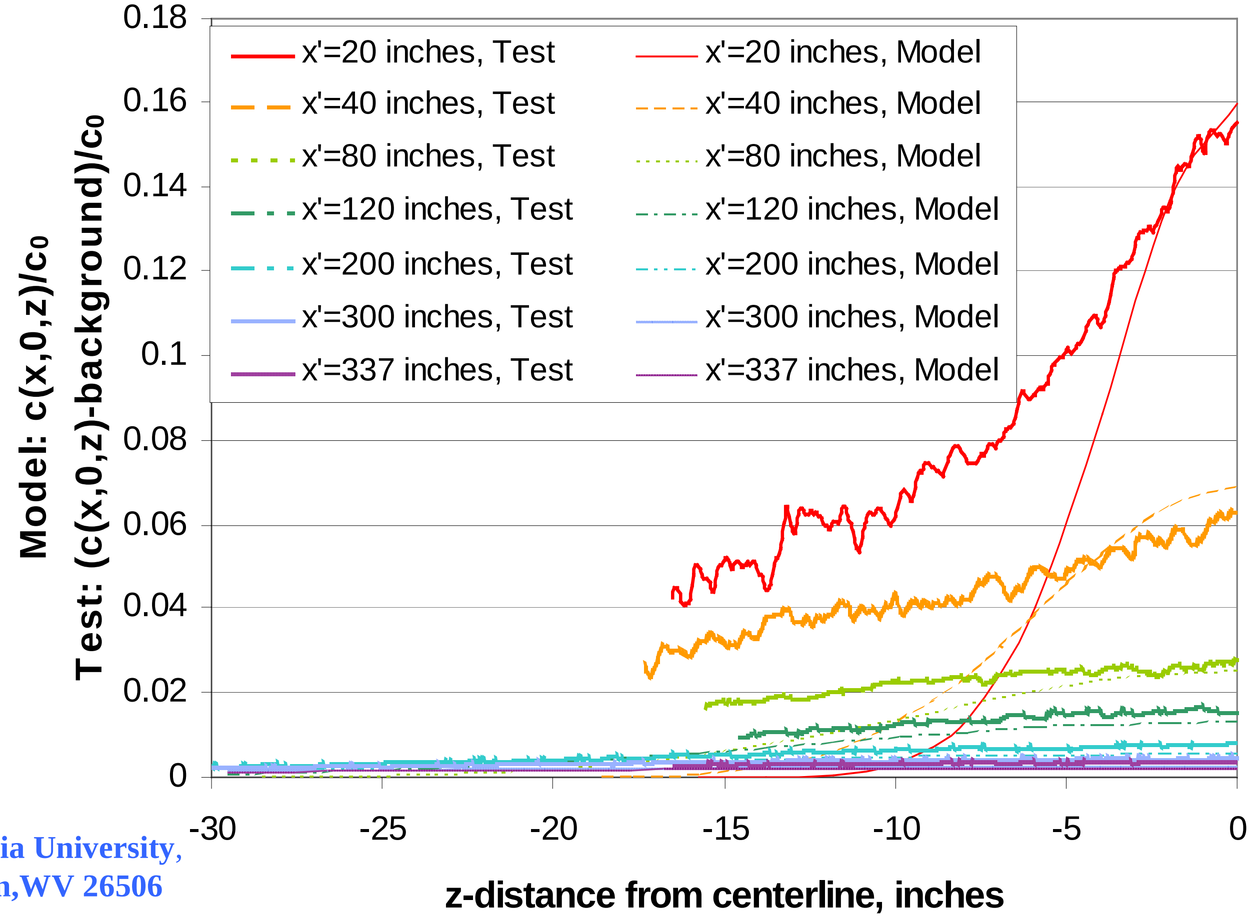
Relative Concentration Profiles Along Negative Vertical Axis Pasquill-Gifford Estimation (Stability C)



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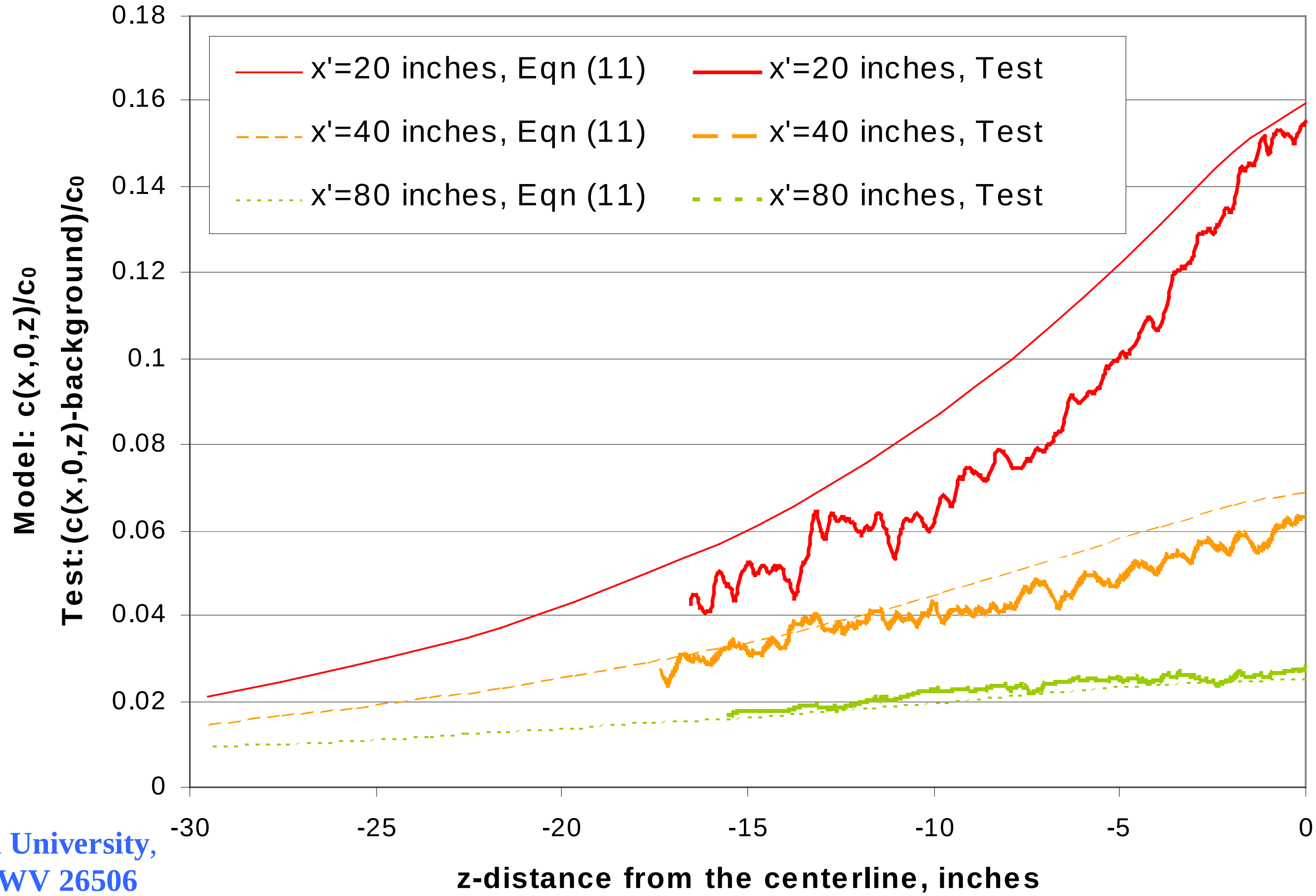
Modified Concentration Profile Model
(Along Negative Vertical Axis, Vertex Area)



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Conclusions

The dispersion of the exhaust plume near the stack can be well estimated by the Gaussian plume dispersion model. The horizontal dispersion coefficient can be calculated by Pasquill-Gifford formula:

$$\sigma_y = R_y x^{0.894}$$

The vertical dispersion coefficient can be calculated by

$$\sigma_z = R_z x^{0.9165}$$

(For cases with downwind distance <=100 m)

Conclusions

The eddy appearing behind the truck disturbs/modifies the contaminant concentration field.

The concentration distribution along positive z-axis can be estimated as follows:

$$c(x,0,z) = \frac{q}{2\ u\ {}_y\sigma_z}\exp\left(-\frac{z^2}{2\sigma_z^{\ 2}}\right)$$

and the concentration distribution along negative z-axis can be estimated by following empirical formula:

σ

$$c(x,0,z) = \frac{q}{2\ u\ {}_y\sigma_z}\exp\left(-\frac{z^2}{2C_e\sigma_z^{\ 2}}\right) \qquad C_e = 1 + \frac{50\,|\,z\,|}{x'}$$

π

σ

π