EVALUATION AND COMPARISON OF THREE AIR POLLUTION PREDICTION MODELS

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This paper presents a brief discussion of the theoretical and mathematical development of a line-source dispersion model AIRPOL-4 designed by the Virginia Highway and Transportation Research Council to eliminate some of the problems encountered with existing models. It also comparatively evaluates the predictive and cost performances of AIRPOL-4 with those of the California Division of Highways and the U.S. Environmental Protection Agency models. The predictive performances of these models are evaluated, against measured data, in relation to wind speed, road-wind angle, atmospheric stability class, source height, and receptor location. The results demonstrate that the predictive capability and reliability of AIRPOL-4 are generally superior to those of the other models. Comparison of cost performances for the models is based on operating costs determined for each of the models for air quality analyses involving identical input parameters. The results of this cost comparison demonstrate that AIRPOL-4 is significantly more cost effective than either of the other models.

•MOTOR vehicles are a major source of carbon monoxide (CO) pollution. Consequently, CO concentrations are often highest in the vicinity of roadways. As detailed in the Federal Aid Program Manual, the Virginia Department of Highways and Transportation is required to estimate the impact of proposed highway facilities on the air quality in the region of such facilities. Currently, the CALAIR (1) and HIWAY (2) air pollution prediction models, developed by the California Division of Highways and the U.S. Environmental Protection Agency respectively, are the two prediction models generally accepted by the Federal Highway Administration for use in complying with the above requirements. These models are, however, cumbersome and expensive to use. They are, furthermore, generally inaccurate and tend to severely overpredict pollution levels in the critical cases of low wind speeds and small road-wind angles.

The Virginia Highway and Transportation Research Council has developed an air pollution prediction model, AIRPOL-4 (3), which is essentially free of the problems afflicting CALAIR and HIWAY. The purpose of this paper is to introduce AIRPOL-4 and to firmly establish, based on extensive field data, its utility and integrity. To accomplish this, the paper first presents the mathematical development of AIRPOL-4 and then analyzes and evaluates AIRPOL-4, CALAIR, and HIWAY on the bases of their cost performances relative to each other and their predictive performances relative to observed field data and to each other. The paper thus presents the development of AIRPOL-4 and determines both absolute and relative measures of its performance.

MODEL DEVELOPMENT

This section discusses the mathematical and theoretical development of AIRPOL-4 only; information regarding the development of CALAIR and HIWAY respectively is found elsewhere (1, 2). More detailed information concerning the development of AIRPOL-4 can be found in another report (3).

Basic Formulation

The basic geometry and calculus necessary to express CO concentrations at a receptor, either upwind or downwind of a uniform continuous line source, by using a Gaussian formulation are discussed below. The discussion assumes an understanding of the basic Gaussian formulation.

Figure 1 contains two Euclidian coordinate systems; a roadway, assumed to be a uniform continuous line source; a receptor downwind of the roadway; and a wind direction vector. The receptor coordinate system, or the P, DIST, Z system, is aligned so that the DIST axis is parallel to the wind direction vector with positive DIST measured upwind. The positive Z axis emanates from and is perpendicular to the surface of the earth. Within this system, the receptor coordinates are $(0, 0, z)_{\text{receptor}}$. The roadway coordinate system, or the D, R, H system, is oriented so that the R axis coincides with the roadway, the positive H axis emanates from and is perpendicular to the earth's surface, positive D is measured on the downwind side of the roadway, and the receptor lies in the DH plane. The observer location relative to this system is $(d, 0, z)_{\text{roadway}}$.

Given this information and α, the acute angle between the roadway and the wind vector, it can easily be determined that the roadway coordinate system may be mapped into the receptor coordinate system by

$$p = -d \times \cos(\alpha) + r \times \sin(\alpha) \tag{1}$$

$$\text{dist} = d \times \sin(\alpha) + r \times \cos(\alpha) \tag{2}$$

and

$$z = h \tag{3}$$

This technique allows the total CO concentration at a receptor to be expressed as a simple integral of all roadway points having nonnegative DIST coordinates, i.e.,

$$\text{CO} = \frac{Q_L}{2\pi\mu} \int_M^{\text{ULENGH}} \frac{\exp\left[-\frac{1}{2}\left(\frac{p}{\sigma_p}\right)^2\right]}{\sigma_p} \times \left\{ \frac{\exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]}{\sigma_z} \right\} dr \tag{4}$$

where Q_L is the uniform line-source emission rate.

The upper bound of integration ULENGH is the distance the roadway extends, in a nearly straight line, upwind from point $(0, 0, h)_{\text{roadway}}$. The lower bound M is found by first determining M′, the distance between $(0, 0, h)_{\text{roadway}}$ and $[0, -d \times \tan(\alpha), h]_{\text{roadway}}$, the intersection of the R and P axes. The latter point is the natural lower bound of integration since, as equation 2 demonstrates, it is the greatest lower bound of all roadway points having nonnegative DIST coordinates in the receptor coordinate system. However, the possibility that this point will lie farther along the R axis than the road actually extends must be accounted for. Since the receptor is downwind of the road, which implies $d \geq 0$, and since $0 \text{ deg} \leq \alpha \leq 90 \text{ deg}$, equation 2 requires that $M' \leq 0$. Therefore M must be defined as M = max (M′, -DLENGH), where DLENGH is the distance the roadway extends in a nearly straight line downwind from the point $(0, 0, h)_{roadway}$.

Figure 2 shows the geometry for a receptor upwind of a roadway. We can see that equations 1, 2, and 3 again transform any roadway point in the roadway coordinate system into the receptor coordinate system. Thus equation 4 may be used to determine the total pollution at an upwind receptor when the bounds of integration are chosen to include only those roadway points having nonnegative DIST coordinates.

ULENGH is determined in the upwind receptor case as it was in the downwind receptor case, by simple specification. The point $[0, -d \times \tan(\alpha), h]_{roadway}$, the intersection of the R and P axes, is again shown by equation 2 to be the greatest lower bound of all roadway points having nonnegative DIST coordinates. However, since the receptor is now upwind of the road, which implies $d \leq 0$, equation 2 shows that M', the distance from $(0, 0, h)_{roadway}$ to $[0, -d \times \tan(\alpha), h]_{roadway}$, must be $M' \geq 0$. Therefore M for an upwind receptor must be defined as $M = \min(M', ULENGH)$.

Consideration of the upwind formulation versus the downwind formulation reveals that, for the same absolute roadway to receptor distance, $|d|$, $M_U \geq M_D$. For any roadway point contained in both intervals, $p_U^2 \geq p_D^2$ and $dist_U \leq dist_D$. Only when $\alpha = 0$ deg does $M_U = M_D$, $p_U^2 = p_D^2$, and $dist_U = dist_D$. This is reassuring since the upwind and downwind sides of a roadway should be indistinguishable at $\alpha = 0$ deg.

We have shown that a single Gaussian formulation exists that is capable of expressing CO concentrations at receptor points either upwind or downwind from a uniform continuous line source.

Evaluation of Gaussian Line-Source Formulation

Equation 4 has no analytical solution, and solutions using general purpose numerical techniques are excessively expensive. AIRPOL-4 circumvents this problem by using a specialized segmentation technique in conjunction with Cote's method (6) of order six, C6, to solve equation 4.

Careful analysis of the integrand in equation 4 reveals that accurate numerical integration is difficult in only two neighborhoods, $p \simeq 0$ and $r \simeq M$. Thus AIRPOL-4 uses an interval segmentation technique that divides the total integration interval into 12 subintervals. Two of these subintervals cover the interval from M to M + 2, and 10 cover the remaining interval of integration with 5 on either side of the point $p = 0$. The lengths of these 10 subintervals increase away from the point $p = 0$ in the ratio of 1:2:3:5:10 with maximum constraints of 10, 20, 30, 50, and ∞ m. When the point $p = 0$ is not an element of the interval of integration, the midpoint of the interval is used to locate these subintervals. This technique in combination with C6 produces a maximum allowable error of 0.02 ppm (0.02 mg/m^3) of CO with a safety factor of about two orders of magnitude for a superposition of three line sources and yet requires the calculation of only 72 points.

Atmospheric Stability and Gaussian Dispersion Parameters

AIRPOL-4 uses a slightly modified Pasquill method of atmospheric stability classification (7) based on its superiority to the Turner classification method. AIRPOL-4 determines preliminary approximations to σ_y and σ_z by extrapolating Pasquill's empirical curves (8) to the points $\sigma_y = 3.0$ m and $\sigma_z = 1.5$ m and then by shifting these curves left such that $\sigma_{y_0} = 3.0$ m and $\sigma_{z_0} = 1.5$ m. AIRPOL-4 then translates these preliminary values, which are applicable only to rural areas and 3 to 10-min sampling times, to values applicable to urban areas and a sampling time specified by the user. This translation is based on Turner (5, 9) and empirical results obtained from the present study.

Figure 1. Geometry for downwind receptor.

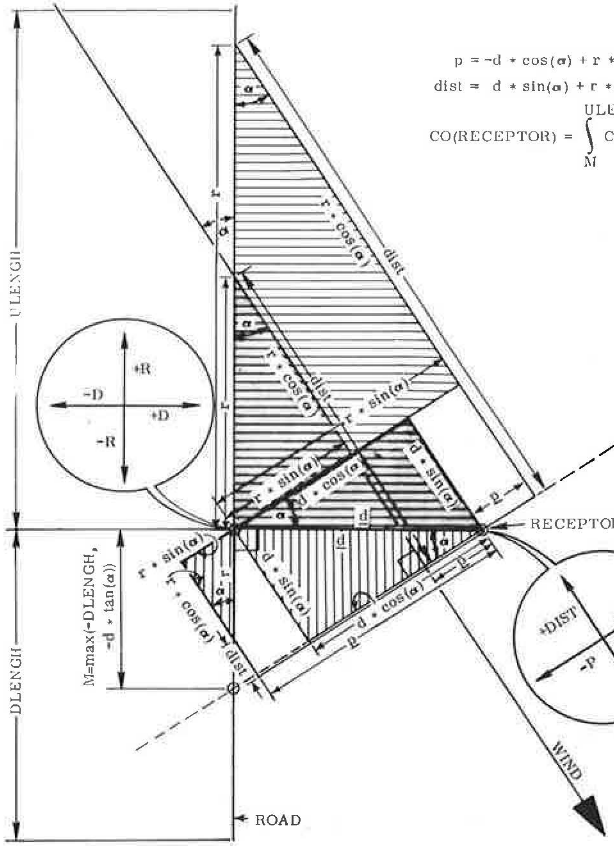
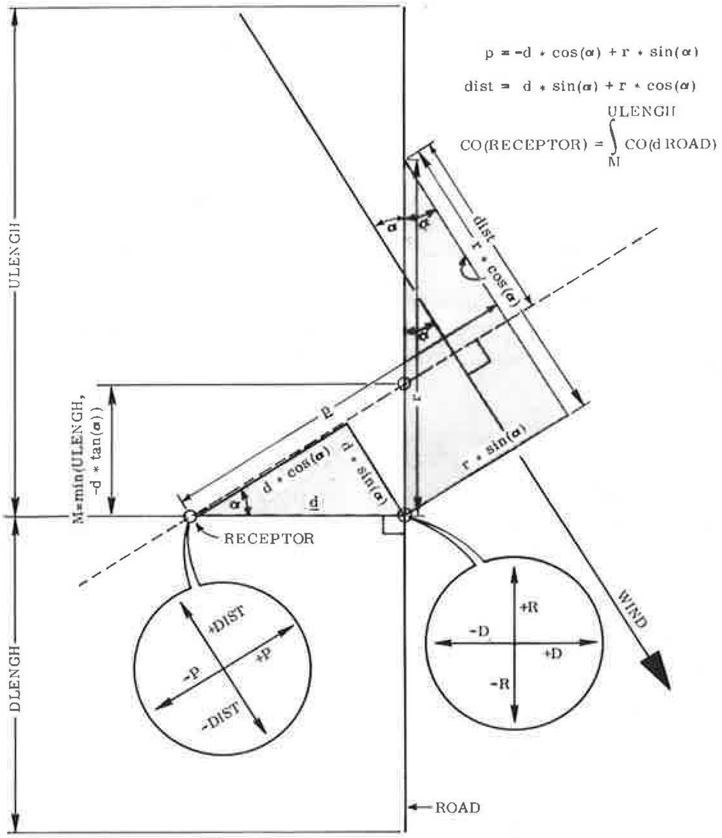


Figure 2. Geometry for upwind receptor.



Wind Speed Dilemma

The basic Gaussian dispersion theory is based entirely on the effect of macroscale air movement and its induced eddy effects exclusive of localized-eddy and molecular dispersion effects. Therefore, this theory indicates an inverse linear relationship, CO $\propto (1/\mu)$, between wind speed and pollutant levels when examined in the context of a mass balance. This relationship, however, requires that CO asymptotically approach infinity as μ approaches zero. This situation is, of course, intuitively and empirically false.

Field data verify that, although an inverse linear relationship yields reasonable predictions at higher wind speeds (greater than approximately 3 m/s), it produces progressively poorer estimates as wind speeds decrease (4, 10). The reason for this behavior is that, as wind speeds decrease, the dispersion effects of molecular diffusion, vertical thermal transport, and localized mixing replace the decreasing dispersion effects produced by macroscale air movement.

Empirical modeling of this residual turbulence concept resulted in the relationship

$$\mathrm{CO} \propto [\mu + 1.92 \times \exp(-0.22 \times \mu)]^{-1} \tag{5}$$

which produces accurate CO predictions over the entire range of feasible wind speeds. Note that equation 5 specifies that CO becomes inversely proportional to μ for $\mu > 3$ m/s.

Treatment of Elevated Roadways

Although the Gaussian formulation is capable of analyzing elevated sources, it is not directly capable of analyzing highway fill sections. The basic Gaussian stack equations assume that a smokestack does not materially obstruct or alter air flow. A fill section of highway does, however, drastically alter surface wind flows since it forms a physical barrier over which air must circulate.

Wind flows over barriers produce vertical turbulence to a height of 1.5 to 2.0 times the height of the barrier (19). Thus, AIRPOL-4 models the effect of a highway fill section, HEIGHT in meters, by increasing σ_{z_0} to

$$\sigma_{z_0} = 1.5 + \mathrm{HEIGHT}/4 \tag{6}$$

which in turn increases all σ_z values by shifting Pasquill's σ_z curves to the right. Note that this modification accounts for only the increased vertical turbulence produced at the top of a fill and does not account for the eddies formed on the downwind and upwind slopes of the fill. Thus AIRPOL-4, or any other Gaussian model, will still underpredict CO levels for receptors within about $10 \times \sin(\alpha) \times$ HEIGHT meters of a fill.

Treatment of Depressed Roadways

AIRPOL-4 has been designed to analyze receptors either inside or outside a highway cut section. However, since no test data are available for geometries of depressed roadways, these aspects of the design of AIRPOL-4 have been omitted from this paper.

ANALYSIS OF PREDICTIVE PERFORMANCES

This section analyzes and compares the predictive performances of AIRPOL-4, CALAIR, and HIWAY relative to each other and relative to 436 one-hour field measurements. AIRPOL-4 is completely analyzed with respect to both the Pasquill and Turner stability classes to firmly establish AIRPOL-4 (Pasquill) as the superior version, although CALAIR and HIWAY are analyzed only with respect to the recommended Turner class.

Field Study

The AIRPOL project included a field study to collect data for validating the performance of AIRPOL-4. This study produced simultaneous measurements of CO levels and geometric, traffic, and meteorological parameters. One-hour data samples were measured intermittently at five test sites on random weekdays during either peak or off-peak hours over a period of approximately 1½ years to ensure representative ranges of geometric, traffic, and meteorological variables. During each test, several 1-hour bag samples were collected simultaneously on both sides of the roadway at distances ranging from 3.7 to 117.4 m from the edge of pavement and at elevations of 1.5 and 3.0 m above ground level; 3.0-m samples were taken only adjacent to the roadway.

Test Sites

An attempt was made to locate test sites typifying at-grade, fill, and cut sections of roadway meeting the following criteria:

1. Volume of traffic sufficient to produce detectable levels of CO,
2. Volume of traffic constituting the most significant source of CO in the immediate vicinity,
3. Terrain relatively free of physical barriers such as large buildings,
4. Adequate safe working area for personnel, and
5. Legal and physical accessibility to personnel and equipment.

Subject to these constraints, only one elevated and four at-grade satisfactory test sites were found. Since most of the major highway cut sections in Virginia are in sparsely traveled areas, no satisfactory test sites could be found for depressed roadways. The five selected sites and their measured data ranges are given in Table 1. Percentage breakdowns of the meteorologic and traffic conditions for all test sites are given in Table 2. Figures 3 through 7 show sites 1 through 5 respectively.

Data Collection

Meteorologic

Wind speeds and directions were measured continuously during each test hour by using a vectorvane and were recorded on strip-chart recorders. The strip-chart traces were manually digitized, and data were averaged over hourly intervals. The vectorvane was calibrated in a wind tunnel operated by the Department of Environmental Sciences, University of Virginia. At each of the test sites, the vectorvane was separated from the nearest of any physical obstructions that were present by a distance at least five times the height of the obstruction. The elevation of the vane was always 10 m above the ground.

Information such as cloud covers and ceiling heights needed for atmospheric stability classification was obtained for each 1-hour test interval from National Weather Service offices located at nearby airports. Each of the sites is within 12 km of a National Weather Service office. The atmospheric stability for each test period was determined by the classification schemes of both Turner (11) and Pasquill (7).

Table 1. Site, observed traffic, and meteorologic data.

Item	Site 1	Site 2	Site 3	Site 4	Site 5
Highway	I-495	I-64	I-95	I-264	I-64
County	Fairfax	Norfolk	Fairfax	Norfolk	Norfolk
U.S.G.S. topographic quadrant, 7.5-min map	Alexandria, Va.; D.C.; Md.	Kempsville, Va.	Annandale, Va.	Kempsville, Va.	Little Creek, Va.
UTM map coordinates, km					
North	4296.69	4081.07	4296.52	4078.23	4083.96
East	318.58	393.46	312.90	389.08	390.04
Relative highway elevation, m	0	0	0	10.7	0
Number of lanes	3,3 =6	3,3= 6	4,2,4 = 10	3,3 = 6	3,3 = 6
Median width, m	11.3	18.3	6.4 each	12.8	18.3
General highway direction	East-west	North-south	North-south	East-west	North-south
Land use	Low density, residential	Agricultural, two schools	Light commercial	Low density, residential, light industrial	Low density, residential
Distance to nearest significant external source, m	750	500	300	850	600
Traffic volume range, vehicles per hour					
Low	2,646	3,288	4,510	3,030	2,200
High	7,910	5,190	8,250	5,060	6,650
Traffic speed range, km/h					
Low	61	82	85	80	72
High	100	93	87	90	97
Range of percentage of heavy-duty vehicles					
Low	5	5	4	1	2
High	22	9	11	15	21
Road-wind angle range, deg					
Low	4	20	10	54	21
High	86	20	90	85	88
Wind speed range, m/s					
Low	0.18	1.88	0.58	2.19	0.27
High	4.83	3.08	2.06	3.22	3.80
Turner stability range					
Low	A	B	A	B	B
High	D	C	D	D	D
Pasquill stability range					
Low	A	B	A	A	B
High	D	C	B	C	C

Table 2. Percentage breakdown of experimental conditions.

Parameter	Range	Percent
Road-wind angle, deg	$0 \le \alpha \le 30$	27
	$30 < \alpha \le 60$	35
	$60 < \alpha \le 90$	38
Wind speed, m/s	$0.0 \le \mu \le 0.9$	21
	$0.9 < \mu \le 1.8$	31
	$1.8 < \mu \le 2.7$	25
	$2.7 < \mu$	23
Atmospheric stability class[a]	A	6, 10
	B	29, 63
	C	17, 17
	D	48, 10
Total traffic volume, vehicles per hour	$2{,}000 \le v \le 5{,}000$	58
	$5{,}000 < v \le 8{,}000$	40
	$8{,}000 < v$	2
Traffic speed, km/h	$56 \le s \le 72$	4
	$72 < s \le 88$	47
	$88 < s \le 100$	49
Percentage of heavy-duty vehicles	$0 \le h \le 10$	65
	$10 < h \le 20$	34
	$20 < h$	1

[a] Turner and Pasquill.

Figure 3. Site 1.

Figure 4. Site 2.

Traffic

Traffic information such as volumes, vehicle mixes, and speeds was measured at the sites during each of the hourly study periods. Traffic speeds were measured by radar and recorded on strip charts, from which hourly average speeds were manually reduced. The radar units were calibrated with tuning forks before use each day and after every 2 hours of continuous use. Traffic volumes and mixes were determined by manual counts. Vehicles with three or more axles or two-axle vehicles having a capacity of 2000 kg or more were considered to be heavy-duty vehicles; all others were considered to be passenger cars.

Site Geometric

Geometric data such as median, lane, and shoulder widths and roadway elevations were obtained from construction plans. The locations of receptor points were identified by measuring perpendicular distances from pavement edges and heights above ground. Line-source distances were obtained from topographic maps of the site areas.

Carbon Monoxide

One-hour air bag samples were collected simultaneously at several locations on both sides of the highway sites during each test hour and analyzed for CO by using a gas chromatograph. The chromatograph provided a precision of ±1 percent of full-scale setting, or ±0.1 ppm (0.115 mg/m^3) of CO for the 10-ppm (11.5-mg/m^3) full-scale setting used in this study.

The chromatograph was calibrated each day with span and zero gases. Even though these gases had certified CO concentrations, bag samples were taken from each tank before use for analysis by the Virginia State Air Pollution Control Board district office for added assurance.

Analyses

The meteorological, traffic, and physical site data taken for each test period were used as inputs to CALAIR, HIWAY, AIRPOL-4 (Turner), and AIRPOL-4 (Pasquill). Each of the models used emission factors derived from Virginia statistics in accordance with the procedure recommended by EPA (12).

The predicted CO concentrations were then compared with the measured values. The predictive powers of AIRPOL-4 (Turner), AIRPOL-4 (Pasquill), CALAIR, and HIWAY are evaluated in this paper based primarily on three criteria. The first and most important of these is the average squared error of prediction, which is often translated as an error bound. This criterion is the single most powerful test for model comparison since it yields a maximum likelihood measure of the discrepancy between observed and predicted behavior. The second and next most important performance measurement used is a comparison of the regression data generated by fitting the observed and predicted CO data to the SI statistical equation, OBSERVED = A × PREDICTED + B. These regression data indicate which models most closely approximate the ideal behavior, OBSERVED = PREDICTED, in their average performance. The third criterion used in this analysis is the 100 percent confidence limit on the prediction error. This test is demanding because it concentrates on the extreme behavior of the models as opposed to the average behavior; however, a measure of the extremes of a model's eccentricities is valuable to the potential user.

All tests for statistical significance were carried out at a 0.05 significance level. The tests for superiority of average squared errors (and all its transforms) and 100 percent confidence limits were one-sided F-tests of the hypothesis, H_0: average squared error of A > average squared error of B. The tests for regression lines were based

Figure 5. Site 3.

Figure 6. Site 4.

Figure 7. Site 5.

Table 3. Overall predictive performances of models for downwind receptors and upwind receptors.

	Downwind Receptors				Upwind Receptors	
Statistic	AIRPOL-4 (Turner)	AIRPOL-4 (Pasquill)	CALAIR (Turner)	HIWAY (Turner)	AIRPOL-4 (Turner)	AIRPOL-4 (Pasquill)
Number of data points	254	254	225	254	182	182
Average prediction error	-0.22	-0.45	0.75	0.55	-0.31	-0.31
Average squared error	1.28	1.16	5.02	7.22	0.58	0.50
Probable error	±0.76	±0.72	±1.50	±1.80	±0.51	±0.47
Correlation coefficient, percent	42	51	39	31	62	69
Regression slope	0.54	0.96	0.17	0.13	0.85	1.08
Regression intercept	0.70	0.49	0.83	1.02	0.35	0.29
Minimum error	-4.71	-4.71	-3.94	-4.36	-3.94	-3.94
Maximum error	3.81	1.41	13.38	20.05	3.15	1.20
100 percent error range	8.52	6.12	17.32	24.41	7.09	5.14
Minimum observation	0.0	0.0	0.0	0.0	0.0	0.0
Maximum observation	6.50	6.50	5.40	6.50	4.40	4.40
Observation range	6.50	6.50	5.40	6.50	4.40	4.40
Variance of observations	1.30	1.30	1.01	1.30	0.77	0.77
Expected percent within ± 1 ppm	62	65	35	29	81	84
Expected percent within ± 2 ppm	92	94	63	54	99	100

Note: 1 ppm = 1.15 mg/m^3 of CO.

on two-sided t-tests of the hypotheses, H_o: slope = 1 and H_o': slope (A) = slope (B).

Model Performance Results

Downwind Receptors

The results of the analysis of model performance for all downwind receptors are given in Table 3. These statistics show the overall superiority of AIRPOL-4 (Pasquill). In particular, Table 3 demonstrates that for AIRPOL-4 (Pasquill) the average squared-error statistic, 1.16, is significantly less; the regression line is significantly closer to the ideal line, OBSERVED = PREDICTED; and the 100 percent error range is substantially less than those for the other models. Note that the CALAIR statistics in Table 3 are based on 29 fewer data points than are those for the other models. This difference results because CALAIR was incapable of analyzing any wind speeds less than 0.9 m/s. This is a reasonably serious deficiency in the model (the 10 percent of the sample points it is incapable of analyzing should reasonably constitute a worst case analysis) and should therefore be considered when examining its effectiveness.

Table 3 also gives the statistical error bounds. AIRPOL-4 (Pasquill) and even AIRPOL-4 (Turner) show comfortable probable errors of ±0.72 and ±0.76 ppm (0.83 and 0.87 mg/m^3) of CO, respectively, compared with ±1.50 ppm (±1.73 mg/m^3) of CO for CALAIR and ±1.80 ppm (±2.07 mg/m^3) of CO for HIWAY. Furthermore, the statistical expectations of the percentages of predictions within ±1 ppm (±1.15 mg/m^3) of CO, 62 and 65 percent, and within ±2 ppm (±2.3 mg/m^3) of CO, 92 and 94 percent, for the Turner and Pasquill versions of AIRPOL-4 are quite respectable and significantly superior to those for CALAIR and HIWAY, 35 and 29 percent within ±1 ppm (±1.15 mg/m^3) of CO, and 63 and 54 percent within ±2 ppm (±2.3 mg/m^3) of CO respectively.

Upwind Receptors

Table 3 also gives the performance results of the Virginia model based on field data for 182 receptors on the upwind sides of source roadways. (Because CALAIR and HIWAY are incapable of producing predictions for receptors upwind from a roadway, they have been excluded from this analysis.) These results firmly establish that AIRPOL-4 (Pasquill) yields reliable predictions of CO levels on the upwind sides of roadways. Specifically, they show that it has an average squared error of only 0.50, which is significantly superior to the Turner result and is certainly comparable to the downwind result. This average squared error translates to a probable error of ±0.47 ppm (0.54 mg/m^3) of CO and an expected prediction error of less than 1 ppm (1.12 mg/m^3) of CO 84 percent of the time and less than 2 ppm (2.3 mg/m^3) of CO almost 100 percent of the time. Furthermore, in its average performance, AIRPOL-4 (Pasquill) behaves almost perfectly. It has a regression slope of 1.08 and an intercept of 0.29 with a correlation of 69 percent. All of these observations demonstrate the statistical superiority of AIRPOL-4 (Pasquill) to the Turner regression results. Table 3 also demonstrates that the 100 percent error range of the Pasquill version is significantly less than that of the Turner version and that the Pasquill version has less of a tendency than the Turner version toward overprediction.

Predictive Performance Results

Relative to Wind Speed

Table 4 gives statistics obtained when the models were analyzed for performance relative to wind speed μ for downwind observers. These results indicate that the performances of all the models are statistically poorer for wind speeds below 0.9 m/s than for those above 0.9 m/s. However, the degradation of AIRPOL-4 is markedly less than that of HIWAY (note again that CALAIR cannot generate predictions for low wind speeds). These results demonstrate that AIRPOL-4 performs reliably even at low wind speeds.

Relative to Wind Angle

Results of the analyses relative to all downwind receptors for different ranges of road-wind angles α are given in Table 4. For 0 deg $\leq \alpha \leq$ 30 deg, AIRPOL-4 (Pasquill) is statistically superior to the other models. For 30 deg $< \alpha \leq$ 60 deg and 60 deg $< \alpha \leq$ 90 deg, AIRPOL-4 and CALAIR are nearly comparable; AIRPOL-4 (Pasquill) shows a slight advantage, and HIWAY is significantly inferior. The poor performance of HIWAY for $\alpha \geqslant 30$ deg is perhaps mitigated by the fact that 10 to 20 percent of the observations for this α range happened to be low wind speeds, for which HIWAY previously has given poor predictions. Similarly, the seemingly acceptable performance of CALAIR for this range of α should be tempered by the fact that the model was incapable of analyzing 10 to 20 percent of the data points.

Relative to Atmospheric Stability Class

Analytical results of the predictive performance of each model relative to stability classes A, B, C, and D for downwind receptors are given in Table 4. Two of the most interesting indirect statistics suggested by these analyses are the distributions of the Pasquill and Turner stability classes. From a total of 48 one-hour sampling intervals (A, B, C, D), distributions of 0.10, 0.63, 0.17, and 0.10 were determined by the Pasquill method, and distributions of 0.06, 0.29, 0.17, and 0.48 were determined by the Turner method. These distributions demonstrate that the Pasquill method tends to yield lower stability classes. Therefore, for urban areas where the atmosphere is more unstable than in rural areas, the Pasquill method should provide better estimates of atmospheric conditions than the Turner method. This is the principal reason for the overall superiority of AIRPOL-4 (Pasquill) over AIRPOL-4 (Turner).

For stability class A, the sample sizes unfortunately are small, but nonetheless they indicate that HIWAY is superior to the other models with respect to average performance characteristics. The analysis for stability class B shows that CALAIR and both versions of AIRPOL-4 are statistically equivalent and superior to HIWAY, which was again hampered by the presence of low wind speeds in 24 percent of the observations. The results of the analysis for stability class C show that the two versions of AIRPOL-4 are statistically equivalent and significantly superior to both CALAIR and HIWAY, and those for stability class D show that AIRPOL-4 (Pasquill) is significantly superior to the three other models.

Relative to Source Elevation

Results of the analyses relative to all downwind receptors for at-grade and elevated sources are given in Table 4. The results for at-grade roadways demonstrate that AIRPOL (Pasquill) is statistically superior to the other models. The results for elevated roadways reveal that the models are statistically equivalent to each other and that none of them performs satisfactorily.

COST PERFORMANCE

The total operating costs for AIRPOL-4, CALAIR, and HIWAY were determined for a typical project analysis consisting of four sites. Fill and at-grade sites were analyzed in a 25:75 ratio, as were source lengths of 1200 and 2000 m. Road-to-wind angles were assigned uniformly from 0 deg $\leq \alpha \leq$ 90 deg. Finally all sites consisted of four-lane, dual-divided facilities with 10.7-m medians and representative peak-hour traffic. Within each site, 16 receptors, 8 each at 0.0 and 1.5-m elevations, extending from 3 to 67 m from the downwind edge of the source road were analyzed. Each receptor was examined under both A and D stability classes for 3 prediction years (each having different traffic and emissions characteristics) at six wind speeds. Thus, a total of 576 receptor concentrations were determined per site.

All three models were bench marked on an IBM 370/158 with 1 megabyte of core running under OS release MFT 21.7 with Hasp II. The programs were all compiled to an object-code library by using an IBM FORTRAN IV, G-level compiler before testing. The machine costs cited are for the execution step only, and there is no system bias in the results.

Table 5 gives the resources required and their dollar equivalents, based on Virginia

Table 4. Predictive performances relative to wind speed, road-wind angle, stability class, and source elevation.

Item	Model	No. of Data Points	Probable Error	Regression Slope	Regression Intercept	Minimum Deviation	Maximum Deviation	Deviation Range
$\mu \geq 0.9$ m/s	AIRPOL-4 (Turner)	225	0.72	0.44	0.73	-4.43	3.81	8.24
	AIRPOL-4 (Pasquill)	225	0.67	0.83	0.56	-4.43	1.23	5.66
	CALAIR	225	1.50	0.17	0.83	-3.94	13.38	17.32
	HIWAY	225	0.90	0.26	0.84	-4.36	6.70	11.06
$\mu < 0.9$ m/s	AIRPOL-4 (Turner)	29	1.03	1.26	0.17	-4.71	1.41	6.12
	AIRPOL-4 (Pasquill)	29	1.04	1.24	0.24	-4.71	1.41	6.12
	CALAIR	—	—	—	—	—	—	—
	HIWAY	29	4.70	0.04	1.17	-2.45	20.05	22.50
0 deg $\leq \alpha \leq$ 30 deg	AIRPOL-4 (Turner)	69	0.75	0.50	0.56	-2.84	3.81	6.65
	AIRPOL-4 (Pasquill)	69	0.59	1.06	0.30	-2.84	1.07	3.91
	CALAIR	67	2.54	0.17	0.65	-0.65	13.38	14.03
	HIWAY	69	1.36	0.29	0.70	-2.01	6.70	8.71
30 deg $< \alpha \leq$ 60 deg	AIRPOL-4 (Turner)	90	0.80	0.87	0.39	-4.71	1.41	6.12
	AIRPOL-4 (Pasquill)	90	0.79	1.06	0.31	-4.71	1.41	6.12
	CALAIR	72	0.71	0.50	0.31	-3.03	2.12	5.15
	HIWAY	90	2.54	0.07	1.13	-3.81	20.05	23.86
60 deg $< \alpha \leq$ 90 deg	AIRPOL-4 (Turner)	95	0.73	0.70	0.69	-4.43	1.00	5.43
	AIRPOL-4 (Pasquill)	95	0.74	0.89	0.66	-4.43	0.83	5.26
	CALAIR	86	0.67	0.65	0.59	-3.94	2.17	6.11
	HIWAY	95	1.09	0.18	0.96	-4.36	7.80	12.16
Stability class A	AIRPOL-4 (Turner)	13	1.44	3.25	-0.80	-4.71	0.16	4.87
	AIRPOL-4 (Pasquill)	25	1.14	2.49	0.01	-4.71	1.03	5.74
	CALAIR	4	1.55	0.76	-1.50	1.86	3.01	1.15
	HIWAY	13	0.77	0.84	0.31	-2.45	2.18	4.63
Stability class B	AIRPOL-4 (Turner)	70	0.83	0.79	0.70	-4.43	1.41	5.84
	AIRPOL-4 (Pasquill)	154	0.75	0.96	0.60	-4.43	1.41	5.84
	CALAIR	53	0.83	0.48	0.71	-3.94	2.44	6.38
	HIWAY	70	3.08	0.07	1.16	-4.36	20.05	24.41
Stability class C	AIRPOL-4 (Turner)	46	0.47	0.74	0.45	-2.14	1.07	3.21
	AIRPOL-4 (Pasquill)	46	0.43	0.76	0.29	-1.62	1.07	2.69
	CALAIR	43	0.94	0.29	0.69	-1.75	4.64	6.39
	HIWAY	46	0.60	0.43	0.74	-2.08	1.91	3.99
Stability class D	AIRPOL-4 (Turner)	125	0.70	0.42	0.61	-4.07	3.81	7.88
	AIRPOL-4 (Pasquill)	29	0.43	1.48	-0.71	-1.92	1.23	3.15
	CALAIR	125	1.84	0.15	0.77	-3.03	13.38	16.41
	HIWAY	125	1.03	0.24	0.72	-3.81	6.70	10.51
At-grade source	AIRPOL-4 (Turner)	214	0.66	0.69	0.40	-4.71	3.81	8.52
	AIRPOL-4 (Pasquill)	214	0.61	1.24	0.09	-4.71	1.41	6.12
	CALAIR	185	1.60	0.20	0.66	-1.61	13.38	14.99
	HIWAY	214	1.90	0.14	0.92	-2.45	20.05	22.50
Elevated source	AIRPOL-4 (Turner)	40	1.15	9.52	-0.04	-4.43	0.13	4.56
	AIRPOL-4 (Pasquill)	40	1.15	10.45	-0.29	-4.43	0.14	4.57
	CALAIR	40	0.92	2.84	0.11	-3.94	0.25	4.19
	HIWAY	40	1.13	5.39	0.53	-4.36	0.15	4.51

Table 5. Cost performances for analysis of four typical sites.

	Resource Requirements			Costs (dollars)		
Resource	AIRPOL-4	CALAIR	HIWAY	AIRPOL-4	CALAIR	HIWAY
CPU time, hour	0.004	0.022	0.565	0.82	4.52	115.80
Cards read	16	4,608	3,294	0.03	7.95	5.70
Lines printed	620	63,936	5,058	0.44	44.76	3.54
Computer memory, K-byte/hour	0.19	1.06	21.46	0.12	0.64	12.88
Input coding, hours	0.22	24.96	14.20	1.16	131.04	74.55
Keypunching, hours	0.05	5.62	3.20	0.18	20.50	11.66
Card stock	16	4,608	3,294	0.02	5.53	3.95
Paper stock, pages	8	2,304	144	0.04	11.52	0.72
Total				2.81	226.48	228.80

Department of Highways and Transportation cost factors, to fully analyze four typical sites. These figures show that the cost of using AIRPOL-4 was only \$2.81 compared to \$226.48 for CALAIR and \$228.80 for HIWAY. Thus the cost of using AIRPOL-4 is only about 1.2 percent of the cost of using either of the other models. In fact, even in those cases where a complete analysis is not desirable for one reason or another, AIRPOL-4 is still superior. For instance, consider the extreme example of four typical sites with only eight receptors per site, all analyzed for a combination of a single elevation, wind speed, stability class, and prediction year. Under these conditions, AIRPOL-4 would still cost only $2.34 compared with $3.15 for CALAIR and $3.18 for HIWAY. Thus, even under these conditions, AIRPOL-4 would cost only about 73.9 percent as much to use as either of the other two models.

Table 5 also demonstrates that CALAIR and HIWAY have nearly unmanageable volumes of input and output but that those for AIRPOL-4 are quite reasonable. Thus, since people are not generally capable of comprehending large volumes of data unless the data are available in some compact and meaningful form, there is an additional cost in using CALAIR or HIWAY that may be measured in terms of the errors and frustration generated by creating and analyzing unnecessarily expanded data sets. These results demonstrate that AIRPOL-4 is clearly a more cost-effective model than either of the other models.

CONCLUSIONS

The results of the statistical comparisons of overall downwind predictive performances have shown that AIRPOL-4 (Pasquill) is superior to AIRPOL-4 (Turner), CALAIR, and HIWAY. For upwind receptors, only AIRPOL-4 can be used, and the Pasquill version is significantly superior to the Turner version.

In the comparison of predictive performances for wind speeds greater than 0.9 m/s, CALAIR and HIWAY performed reasonably well, although AIRPOL-4 (Pasquill) performed better. For lower wind speeds, CALAIR cannot be used at all, and AIRPOL-4 is significantly superior to HIWAY.

AIRPOL-4 (Pasquill) is statistically superior to the other models for the road-wind angle range of 0 deg $\leq \alpha \leq$ 30 deg. However, for 30 deg $< \alpha \leq$ 90 deg, all models except HIWAY are about equivalent, and AIRPOL-4 (Pasquill) shows a slight statistical advantage.

For different atmospheric stabilities, AIRPOL-4 (Pasquill) shows a slight superiority over the other models with respect to average performance. The comparison of predicted and observed CO concentrations for elevated roadways showed that all the models performed poorly and thus need improvement. In addition, AIRPOL-4 proved to be significantly less expensive to use than either CALAIR or HIWAY.

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