Fugitive Dust from Vehicles Travelling on Unpaved Roads

by THOMAS A. CUSCINO, ROBERT JENNINGS HEINSOHN, *and* CLOTWORTHY BIRNIE, JR., *respectively research assistant, Center for Air Environment Studies; associate professor of mechanical engineering, Center for Air Environment Studies; and associate professor of mechanical engineering, The Pennsylvania State University, University Park, Pa.*

ABSTRACT.—A model has been developed for estimating concentrations of fugitive dust downwind of an unpaved road within a factor of 2 for most cases. The model allows for winds oblique to the road and also for extraction of fugitive dust from the plume as it diffuses to the ground. Experiments were performed to determine the accuracy of the model in estimating downwind concentrations of fugitive dust generated by a vehicle travelling on a gravel road.

AN OFTEN NEGLECTED factor that contributes to the inadequacy of a region's air is fugitive dust. Fugitive dust is defined as any solid particulate matter that does not come from a stack or flue. It contributes to particulate concentrations in several Air Quality Control Regions that still exceed the National Ambient Air Quality Primary and Secondary Standards *(Environmental Protection Agency 1974)*.

There are several sources of fugitive dust in the urban environment:

1. Unpaved surfaces of travel; for example, roads, private driveways, and parking areas.
2. Paved roads, which yield a fine dust as their surfaces wear.
3. Building construction and demolition.
4. Highway construction and repair.
5. Tire and brake-lining wear.

By far the most significant contributor of fugitive dust to the total suspended particulate burden is vehicular travel on paved and unpaved surfaces. This paper is concerned solely with the prediction of fugitive dust concentrations downwind from unpaved roads, although the principles are applicable also to paved roads.

THE PREDICTIVE MODEL

As a vehicle travels over an unpaved surface, dust is elevated by two mechanisms. First, dust adheres to the tire as the tire rolls over the unpaved surface; the dust is then detached from the tire by centrifugal force and entrained in the turbulent wake of the vehicle. Second, turbulent eddies created by the passage of the vehicle sweep the fine dust from the ground and mix it upward. Both of these mechanisms cause the vehicle-road interaction to be a source of fugitive dust.

To develop an easy-to-use predictive scheme for estimating concentrations with reasonable accuracy, this source has been theoretically modeled as an elevated continuous line source of infinite extent. The assumptions inherent in this model are:

1. The particles distribute themselves in a Gaussian fashion in the vertical direction.
2. The fugitive dust is small enough that it moves exactly as the air.
3. The unpaved road is heavily travelled so that the generation of dust by traffic can be treated as a source that does not vary with time.

4. The wind speed and direction are not a function of height above the ground.
5. The car velocity greatly exceeds the wind velocity so that a line source essentially parallel to the road is generated.
6. The distance from the road at which concentrations are predicted is sufficiently small in comparison to the length of the road so that the road can be modeled as a line source of infinite length and end effects can be neglected.
7. The airborne fugitive dust particle-size distribution is such that it can be represented as a monodispersoid.

Fugitive road dust can be injected into the atmosphere continuously or instantaneously. A single vehicle travelling on a road at a speed much greater than the wind speed can be viewed as an instantaneous line source. On the other hand, many closely spaced cars travelling over the road can be modeled as a continuous line source.

Because the road dust is first of all mixed upward by the vortices trailing behind the moving vehicle, the vehicle-road interaction can be modeled as an elevated continuous line source. The turbulent wake region can be modeled as a volume of constant concentration called the mechanical mixing cell *(Beaton et al. 1972)*. Beaton references work by Eschenroder as the basis for the statement that the height of the mixing cell is approximately twice the height of the vehicle. The width of the cell is assumed to be the shouder-to-shoulder distance across the road, provided this distance is less than 30 feet. In an effort to develop a simplified model, the mixing cell, which is actually a volume source of dust, is modeled as a line source elevated to the height of the volume source and located above the center line of the road.

The conventional equation *(Turner 1970)* for describing the concentration downwind from a continuous line source of infinite extent emitting a dust plume that expands in a semi-infinite medium is

$$c = \frac{Q_T}{u \bullet \sin\theta \bullet \sqrt{2\pi} \bullet \sigma_z(x)} \left\{ \exp\left(-\tfrac{1}{2}\left(\frac{z-h}{\sigma_z(x)}\right)^2\right) + \exp\left(-\tfrac{1}{2}\left(\frac{z+h}{\sigma_z(x)}\right)^2\right) \right\} \quad [1]$$

where

c = Concentration (g/m^3)
u = Mean wind speed (m/s)
Q_T = Total line source strength as measured at the road (g/m-sec)
θ = Angle between the wind vector and the road (degrees)
σ_z = Vertical dispersion parameter (m)
z = Height above ground (m)
x = Distance downwind of the source (m)
h = Height of the source above ground (m) $= 2 \cdot V_H$ (m)
V_H = Vehicle height (m)

This model is designed to allow for diffusion in an oblique wind and to neglect particulate settling (assumption 2).

Equation 1 can be further refined by allowing the ground to adsorb any particulate matter that diffuses to the surface. A model was proposed *(Johnstone 1949)* that postulated an infinitely thin layer at the earth's surface into which particles that diffused would be adsorbed. The adsorption process was modeled as a function of the Stokes terminal velocity of the particle, which is calculated by equating the drag and gravitational forces on the particle. To allow for this subtraction of particulate matter from the plume, an image source was postulated that emits less particulate than the image in equation 1. This was achieved by placing a deposition coefficient (α) before the image term as follows:

$$c=\frac{Q_T}{u \bullet \sin\theta \bullet \sqrt{2\pi} \bullet \sigma_z(x)} \left\{ \exp\left(-\tfrac{1}{2}\left(\frac{z-h}{\sigma_z(x)}\right)^2\right) + \alpha \bullet \exp\left(-\tfrac{1}{2}\left(\frac{z+h}{\sigma_z(x)}\right)^2\right) \right\} \quad [2]$$

Equation 2 contains two unknowns, α and c; and thus another relationship is needed. Johnstone postulated that the second relationship should be the continuity equation

$$Q_T={}_0\int^x V_s \cdot c\,(x',o)\,dx' + {}_0\int^\infty \bar{u}_\perp \cdot c\,(x',z)\,dz \quad [3]$$

where

- $u_\perp$ = The mean wind perpendicular to the road (m/sec)
- x' = A dummy variable representing downwind distance (m)
- V_s = The particle terminal velocity as determined by the Stokes equation (m/sec)

Equation 3 states that the total mass emitted from the source equals that which has diffused to the surface up to a distance x plus that which passes through a semi-infinite plane beginning at the ground and at a distance x downwind from the road.

Four factors must be known to solve equations 2 and 3 simultaneously. First, the mean wind speed and direction must be known at the site of the unpaved road. This must be obtained either by measurement or by review of climatological data. Second, the source strength must be known. The source strength can be defined as follows:

$$Q_T=E_T \times f \quad [4]$$

where

- E_T = Total emission factor measured at the road (g/vehicle-meter)
- f = Frequency of vehicle passage (vehicle/sec)

A useful estimate of the total emission factor has been obtained *(Roberts 1973)* for speeds from 10 to 30 mph on paved and unpaved surfaces (table 1). Third, the vertical dispersion must be acquired. The Pasquill-Gifford curves *(Turner 1970)* can be utilized for this purpose. Finally, the particle fall velocity must be attained. From measurements we have made, distributions of fugitive dust from gravel roads (density of limestone = 2.7 g/cc) have yielded an average number geometric mean diameter for fugitive dust of 1.6 micrometers, with an average standard deviation of 2.9. Representing the polydisperse aerosol as a monodispersoid with a diameter of 1.6 micrometers, the Stokes fall velocity can be calculated.

Table 1.—Emission factors for fugitive dust from vehicle-road interactions (Roberts 1973)

Vehicle speed (mph)	Type of road	LBS/VM* total particulate	LBS/VM below 10 microns	LBS/VM below 2 microns
10	Gravel road	3.5	0.58	0.10
20	Gravel road	7.0	1.9	.24
30	Gravel road	22.2	9.0	.77
20	Dusty paved road, no curbs	.83	.17	.022
20	Paved road with curbs, flushed weekly swept biweekly	.14	.0055	—

*LBS/VM=pounds mass per vehicle mile.

Figure 1.—A comparison of the theoretical versus experimental results on 6 August at 18.3 m from the road.

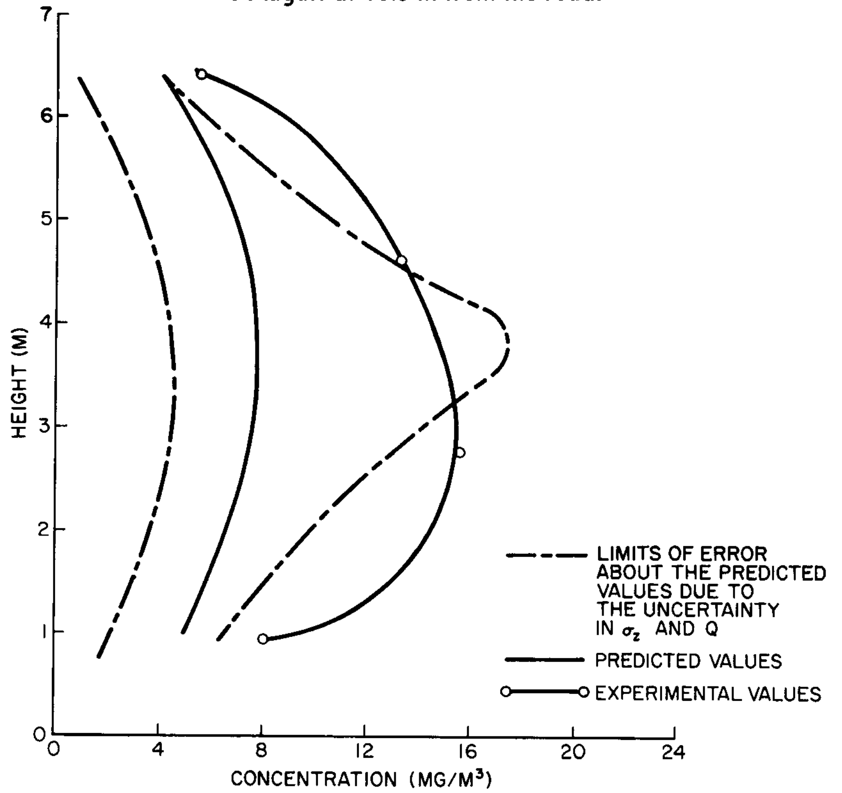


Figure 2.—A comparison of the theoretical versus experimental results on 6 August at 36.6 m from the road.

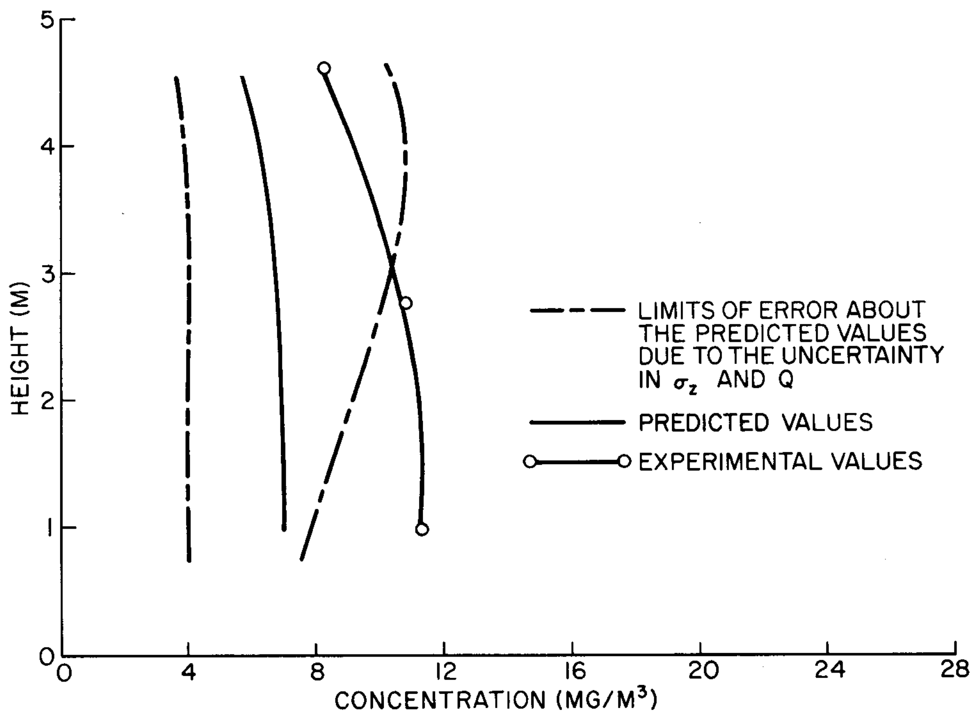


Figure 3.—A comparison of the theoretical versus experimental results on 15 August at 18.3 m from the road.

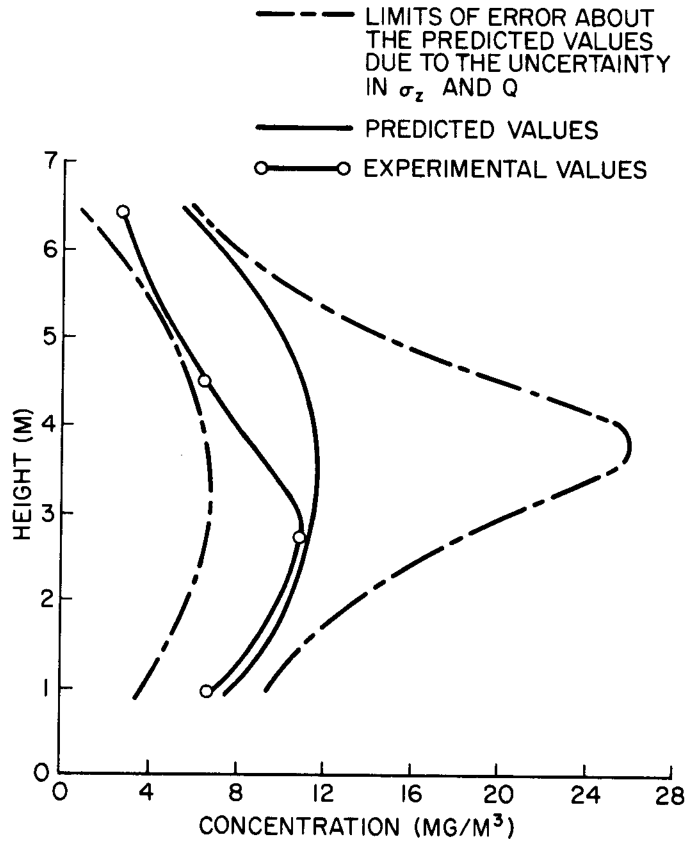
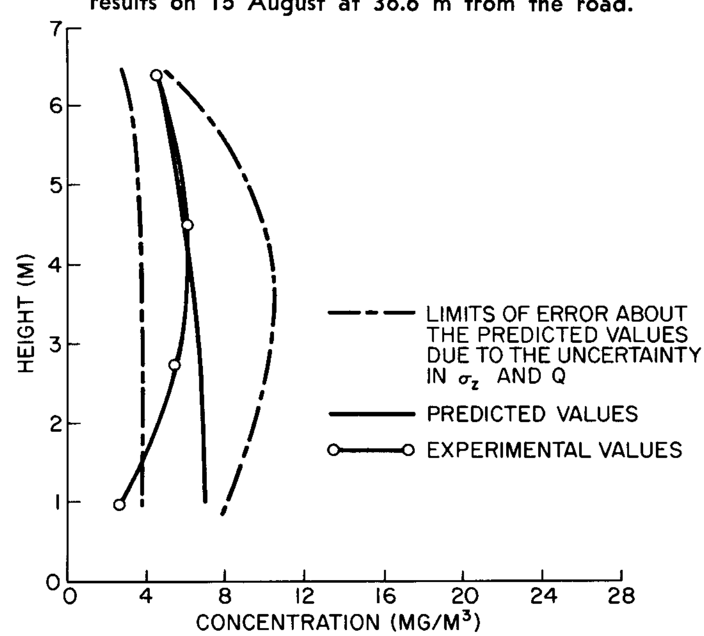


Figure 4.—A comparison of the theoretical versus experimental results on 15 August at 36.6 m from the road.



EXPERIMENTAL VERIFICATION OF THE PREDICTIVE MODEL

To test the validity of the predictive model, an experiment was designed to sample the dust cloud generated by a vehicle travelling on a gravel road. A 1000-foot straight section of gravel road giving access to farm lands provided the fugitive dust source. A vehicle of height equal to 6 feet travelled the road at a controlled speed of 30 mph and a frequency of two passes per minute. A classification of the gravel size was determined by sieving. The maximum size stone comprising the road was ½ inch, and 3.7 percent of the total sample mass was particles of less than 88 micrometers.

The dust plume was sampled in a plowed field downwind from the road. Concentrations in the plume were obtained at a fixed distance downwind by open-faced filters mounted at four elevations above the ground on a stationary support. Two vertical concentration profiles were attained on 6 August 1974 at 18.3 m (60 feet) and at 36.6 m (120 feet) downwind from the road. Again on 15 August, two vertical profiles were obtained at the same downwind distances. The samples were drawn for 10 minutes at 3.5 1pm on 6 August and for 20 minutes at 7.7 1pm on 15 August. Both sampling days could be classified as B stability with wind speeds of 2 m/sec.

A comparison of the concentrations as estimated with Equations 2 and 3 and the experimentally measured concentrations, both at the above given conditions, was made for all four experimental profiles (fig. 1 to 4). The predicted concentrations were found to be within a factor of 2 for 11 of the 15 measurements and within a factor of 3 for all measurements. The combined limits of accuracy suggested for σ_z *(Turner 1970)* and for the emission factor *(Roberts 1973)* accounted partially for the variation between experiment and theory. Turner suggested that σ_z may be expected to be correct within a factor of 2 in all stabilities provided one was only considering diffusion within approximately 200 m of the source. Roberts reported a mean emission factor of 9 pounds/vehicle-mile with a 95-percent confidence interval from 8 to 10 pounds/vehicle-mile. Thus, the source strength in the predictive model had an error band of ± 1 pound/vehicle-mile times the frequency of vehicle passage. The theoretical bands of error due to the uncertainty in both σ_z and Q are also portrayed in figures 1 to 4.

APPLICATION OF THE PREDICTIVE MODEL

Equations 2 and 3 were solved simultaneously under selected conditions (fig. 5 and 6). Figure 5 portrays the variation with x of the concentration at a height of 2.7 m for various wind-road angles. Two important conclusions can be drawn. First, the effect of wind-road angle on the downwind concentration under the given meteorological conditions and for the given aerosol parameters was negligible beyond 100 m. Second, up to 100 m from the road, the concentration increased as the wind direction shifted from perpendicular to parallel to the road. Figure 6 shows the variation with x of the concentration at a height of 2.7 m, given various particle sizes. The conclusion to be drawn from this graph is obvious. The concentration decreases with x more rapidly as the particle size increases. In terms of deposition, the above result can be understood by considering that larger particles are removed from the plume at a more rapid rate than smaller particles.

CONCLUSION

The predictive model yields concentrations within a factor of 3 of the actual concentrations. Given the meteorological conditions, a highway engineer or air-pollution engineer concerned with the local effect of a proposed unpaved surface on local inhabitants can use equa-

Figure 5.—The variation of concentration with distance perpendicular to the road for various wind-road angles.

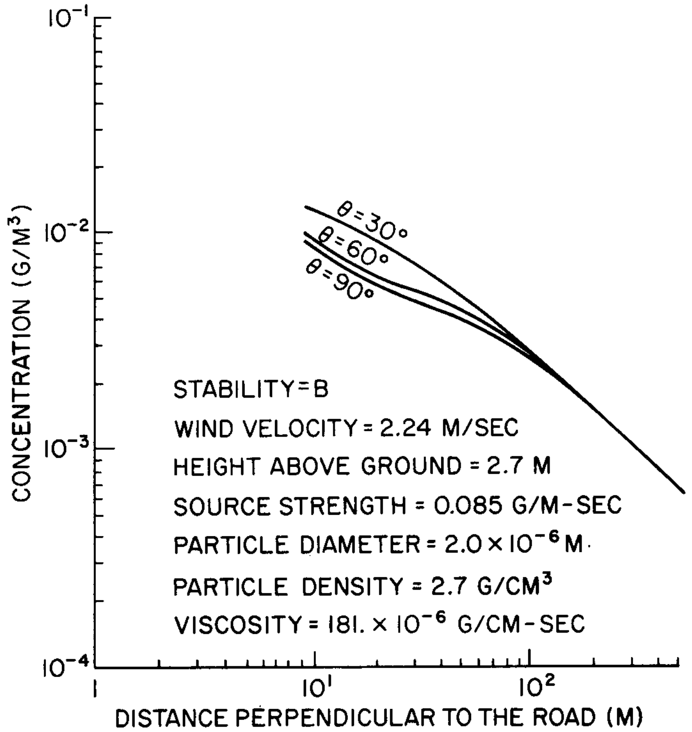
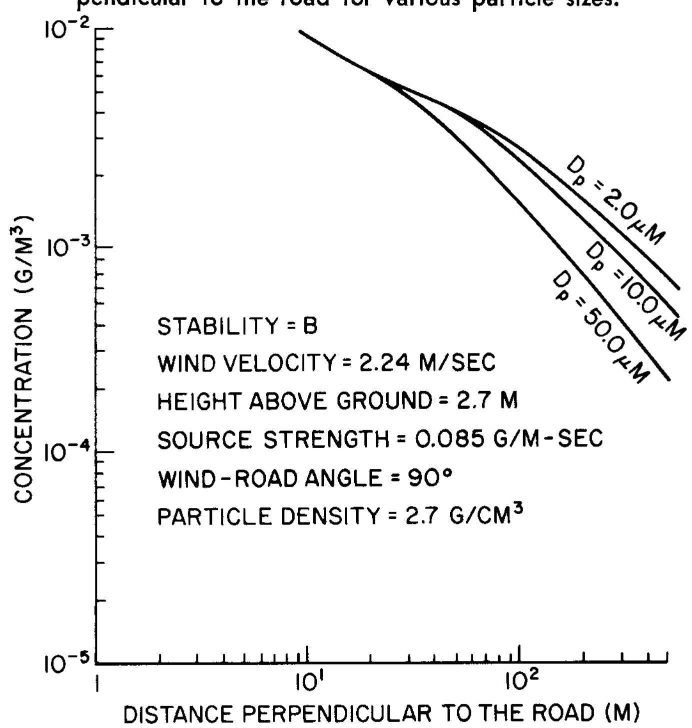


Figure 6.—The variation of concentration with distance perpendicular to the road for various particle sizes.



tions 2 and 3, along with Robert's total emission factors, to determine whether detrimental particulate concentrations might exist. Furthermore, this method can be applied just as readily to fugitive dust from paved surfaces. Roberts determined an emission from a paved surface travelled by a vehicle at 30 mph. More extensive research on emission factors from paved roads and at different vehicle speeds is needed before extensive application of this model can be made to paved surfaces.

LITERATURE CITED

Beaton, J. L., Skog, J. B., Shirley, E. C., and Ranzieri, A. J.
1972. MATHEMATICAL APPROACH TO ESTIMATING HIGHWAY IMPACT ON AIR QUALITY. Calif. State Div. Highw. Air Qual. Man. 4: 17.

Environmental Protection Agency.
1974. MONITORING AND AIR QUALITY TRENDS REPORT, 1973. EPA-450/1-74-007: 10.

Johnstone, H. F., Winsche, W. E., and Smith, L. W.
1949. THE DISPERSION AND DEPOSITION OF AEROSOLS. Chem. Rev. 1 44: 353.

Roberts, John Warren.
1973. THE MEASUREMENT, COST AND CONTROL OF AIR POLLUTION FROM UNPAVED ROADS AND PARKING LOTS IN SEATTLE'S DUWAMISH VALLEY. Master's thesis, Univ. Wash. 28 p.

Turner, D. Bruce.
1970. WORKBOOK OF ATMOSPHERIC DISPERSION ESTIMATES. Environ. Protect. Agency AP-26: 7-10.

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