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Warnard

55 mph speed added

X.7

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UNCERTAINTIES IN EMISSION FACTOR ESTIMATES OF DUST FROM UNPAVED ROADS

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For Presentation at the
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Anaheim, California
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INTRODUCTION

The emission of dust aerosol due to vehicular traffic on unpaved roads is a complex process involving a combination of mechanical and aerodynamic processes that are not well understood physically[1,2,3,4,5]. The AP-42 dust emission equation for PM-10 material is the result of an attempt to describe the dust emission process based on properties of the vehicle and road surface and is given as[6]

$$E = 5.9\ K\ (S/12)\ (V/30)\ (W/3)^{0.7}\ (w/4)^{0.5}\ (d/365) \qquad (1)$$

where:
- E = emission factor (lbs/vehicle-mile) of particles less than 10 microns in diameter (PM10)
- K = proportionality constant specific to the aerosol size range of emitted particles (.45 for PM10)
- S = silt content of road surface material (percent of mass smaller than 75 microns).
- V = vehicle speed in miles per hour (mph)
- W = vehicle weight in tons
- w = number of wheels on the vehicle
- d = number of dry days per year with less than .01 inches of rain.

Our current interest is to estimate the total mass of vehicular dust emitted nationally on an annual basis in order to estimate the acid rain neutralization potential of the alkaline material in the dust aerosol. Since cars, as opposed to trucks and other vehicles, account for a large fraction of the total traffic volume, particular attention has been given to measuring the dust emissions from this limited class of vehicles. For the experiments reported here, which were conducted on dry days using vehicles with four wheels and weighing about 1.25 tons, equation 1 becomes

$$E = .00113\ V\ S \qquad (2)$$

where E is in units of kg/veh-km and V in mph.

Our previously reported emission factor measurements[5,7] have failed to satisfactorily agree with the AP-42 formulation with respect to the coefficient in equation 2 as well as the exponents of V and S which are both equal to one in equation 2. The presently reported experimental results reflect improvements of the experimental design in an attempt to better evaluate the emission factor expression. For example, a fourth dichotomous sampler was added and the height of the roadside tower was extended to improve the dust plume measurement, additional measurements were made to better characterize the wind speed, the range of vehicle speeds was increased to include experiments at 55 mph, and more extensive sampling was made to improve the characterization of the road silt content. The results of 15 emission factor measurements and the associated analyses are reported.

EXPERIMENTAL DESCRIPTION

Road dust emission experiments were carried out on four different occasions during the summer of 1988. In each case dichotomous aerosol samplers were placed on a tower in the downwind direction of graveled roads while the prevailing wind was nearly perpendicular to the road. The vehicles for each experiment were light automobiles, which were driven past the sampling site one-hundred times at each speed of 25, 35 ,45, and 55 miles per hour. The data discussed here includes the PM-10 emission factor, defined as the mass of dust aerosol less than 10 microns in diameter (PM10) emitted per length of road during one vehicle pass. Before and after each set of 100 vehicle passes samples of the road surface material were collected for particle size analysis.

The emission factor was measured by collecting dust aerosol on the filters of dichotomous samplers placed on a tower at four different heights, from 1.5 to 6.1 meters, at a distance of 20 meters from the road. Gravimetric determination of the mass on the filters, in addition to the sampler flow rate and sampling time, are sufficient to determine the average PM10 concentration in the dust plume as a function of height. The wind speed as a function of height was determined by fitting the measured wind speeds at 1.5 meters, determined by an anemometer at the tower base, and the 10 meter wind speeds measured at a nearby meterological station to a logarithmic wind profile. The emission rate per length of road is then simply the integral from the ground to the top of the plume of the product of the wind speed and the PM10 concentration[5,7,8]. The emission factor equals the emission rate per length of road divided by the average rate at which vehicles pass the sampling site.

Samples of the road surface material were taken by two different procedures. Across the road samples were taken by collecting the loose material in a 12 cm wide strip from the center to the edge of the road. Another set of samples was collected from the material of the visible track or rut that occurs from repeated travel on a gravel road. In each case the material was taken from a known sized area, and all the loose material was removed from the sampled area. All surface material samples were obtained under dry conditions, so it was not deemed necessary to oven dry the samples which our experience has shown can lead to material handling problems due to electrostatic charge build-up. Three different samples each, from across the road and in the track, were collected before and after each set of 100 vehicle passes from approximately 50 meters of road adjacent to the sampling area. The average sample mass was .9 kg ranging from .3 kg to 2.9 kg. The samples were dry sieved into eight different size fractions ranging from greater than 4.75 mm to less than 50 microns. The mass of material in each size fraction per area of road surface, along with vehicle speed, were used to develop relations for the emission factor by multiple regression analysis.

* NOT OVEN DRIED 1ST

DISCUSSION OF RESULTS

The emission factor measurements are listed in Table I for each experiment along with the corresponding vehicle speed and silt content measured across the road. Other variables listed in Table I that were found to be related to the emission factor were: P, the percent of mass contained in the particle size range from .425 mm to 2 mm for the samples taken from the tire track and, H, the mass per unit area of particles with size less than 50 microns in samples

mass < 50 μm per area (across road)

Table I. Summary of emission factor measurements and variables used in models.

Exp #	Date (1988)	Time (CDT)	Gravel Type	Vehicle Speed (mph)	Emission Factor (kg/veh-km)	S(%)	H (gm/m²)	P(%)
15	6/30	11:30-12:42	Limestone	25	.70	5.30	287.18	40.14
15	6/30	15:04-15:45	Limestone	45	1.85	5.97	317.40	33.40
15	6/30	16:15-17:01	Limestone	55	1.68	5.26	257.94	34.33
16	8/3	11:07-11:88	Limestone	25	.49	4.57	203.88	39.39
16	8/3	12:27-13:10	Limestone	35	.72	5.17	209.02	50.11
16	8/3	13:42-14:24	Limestone	45	1 .05	5.73	225.98	50.16
16	8/3	14:46-15:30	Limestone	55	.95	4.92	201.41	46.94
17	8/4	11:11-11:45	Limestone	25	.50	4.82	200.74	45.67
17	8/4	12:46-13:14	Limestone	35	.64	5.28	199.30	44.89
17	8/4	13:39-14:16	Limestone	45	.94	5.21	192.29	48.44
17	8/4	14:39-15:14	Limestone	55	1 .00	5.07	205.49	50.86
18	9/8	11:15-11:42	Glacial	25	.42	3.87	245.56	43.06
18	9/8	12:07-12:34	Glacial	35	.73	3.74	258.41	40.31
18	9/8	12:57-13:33	Glacial	45	1.02	3.31	229.41	38.53
18	9/8	13:56-14:39	Glacial	55	.98	2.81	207.77	42.41

% 0.425 mm → 2 mm in rut

consecutive days

interesting time back there

are silt #'s before & after? cf. * p. 3

taken from across the road. Each surface material value represents an average of six samples, three taken before and three after the one-hundred vehicle passes at a given speed.

The locations were in a rural area southwest of Champaign, IL. The countryside is flat and almost exclusively cultivated in corn and soybeans. Of the four sets of experiments performed, three were on the same limestone graveled road and the fourth was on a glacial gravel road. Two of the three limestone graveled road experiments, labeled as experiments 16 and 17 in Table I, were performed on consecutive days at the same location.

In order to compare the present results to the AP-42 formulation, a regression analysis was performed to relate the measured emission factor to the product of silt content with vehicle speed, yielding the expression

$$E = .0045\ V\ S + .053 \qquad (3)$$

Comparison of equations 2 and 3 show that the current experimental values are larger than the AP-42 estimate by nearly a factor of 4. The average value of the ratio of the experimental values to the AP-42 estimate is 4.3 with a standard error of .3 and range of 6.1 to 3.1. The correlation between E and the product V S, leading to equation 3, was .76, so only about 58 percent of the variance of E is explained by this functional dependence. Figure 1 shows a plot of equation 2, multiplied by 4, versus the measured emission factor. The one-to-one line, also shown in figure 1, represents where the points would lie if the model, multiplied by 4, were a perfect prediction of the measured values.

In the context of a model in which the emission factor varies as

$$E = C\ V^a\ S^b \qquad (4)$$

the values of the constants C, a, and b can be found by multiple regression analysis of ln(E) with ln(V) and ln(S). Such an analysis yields a=1.09 and b=.52 with the 95% confidence interval of the constant, a, ranging from .7 to 1.5 and that of b between .12 and 1.2. Accepting the calculated values of a=1.09 and b=.52, a regression of the product $V^a\ S^b$ versus the emission factor measurements only accounts for 59% of the variation of E. It appears that the variables of velocity and silt, as they appear in equation 4, do not rigorously predict E regardless of the values of a and b. If b=0 and a=1.09 then 48% of the variation of E is explained, so a model which does not include silt is almost as good as one with velocity and silt. Correlation of the measured emission factor with $V^{1.09}$ yields:

but there is little real variation in ~~S~~ in their tests

$$E = .0156\ V^{1.09} + .03 \qquad (5)$$

A particular concern regarding the vehicle speed is whether the dependance is linear or as velocity to a higher power[5,9]. Through repeated model evaluations with different variables the exponent of the velocity term remains in the neighborhood of 1 with a 95% confidence interval in the range of .7 to 1.5 as suggested above.

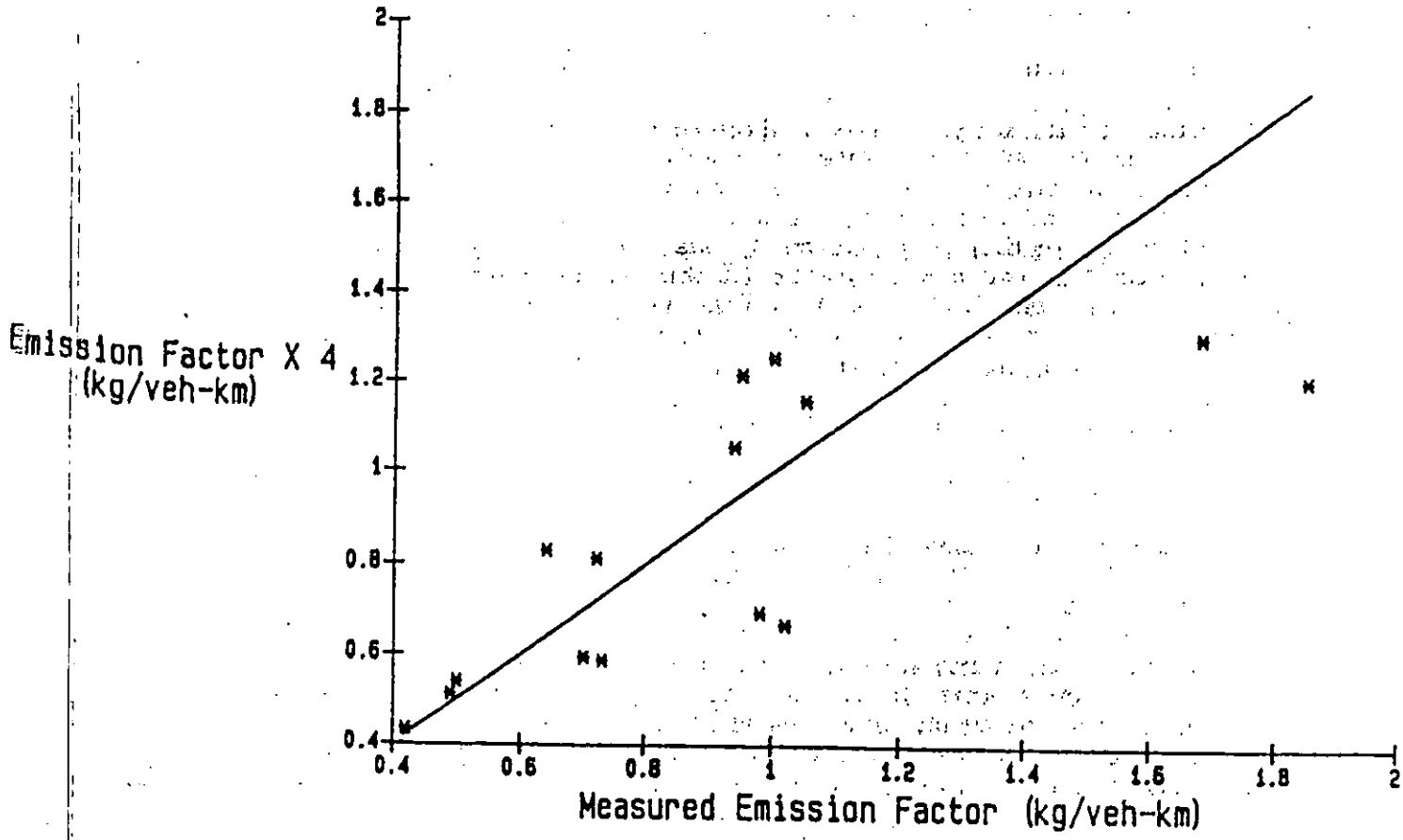

Figure 1. AP-42 Emission Factor Multiplied by 4 Versus Measured Emission Factor (line represents one-to-one correspondence)

Figure 2 shows the natural logarithm of the measured emission factor plotted against the logarithm of the velocity for each of the experiments. According to the model described by equation 4, the slope of the best fit line for each experiment equals the exponent, a. Figure 2 shows that each experiment displays a relatively constant slope over the velocity range from 25 to 45 mph. In each experiment the slope changes for the 55 mph case, suggesting that another dust suspension mechanism with weakened velocity dependance becomes important at high speeds. The average of the slopes of the best fit line for each of the four experiments described in figure 2 is a=1.06, and becomes a=1.37 if the 55 mph point is not included in the calculation.

Insight into the dependance of E on the silt content can be gained by considering the variables from which the silt parameter is composed. The silt fraction can be represented as (G+H)/TM where G is the mass per unit area of road surface material between 75 and 50 microns, H is that for particles less than 50 microns, and TM the total surface material mass per unit area of road surface. From this standpoint the silt fraction is really a combination of three variables. It is found that the emission factor is strongly dependent on H (gm/m^2), which together with V explains 91% of the variance of the emission factor according to the relation:

$$E = 10^{-5}\ V^{1.15}\ H^{1.32} - .099 \qquad (6)$$

The parameter, H, has the advantage of not depending on the mass of large rocks in the surface material sample which can cause variations in the silt parameter. Since it is the emitted aerosol less than 10 microns diameter that is of interest, the mass of particles less than 10 microns diameter per area of road surface would intuitively be most directly related to the emission factor. Such a measurement is, however, difficult to make, and may well be directly related to H.

If the variables (H+G) and TM are considered in a regression analysis, along with V, the model explains 92% of the variance of the emission factor. It is interesting that (H+G) occurs to the power of 1.7 while the coefficient of TM is -.6. This explains why the ratio of these variables, the silt fraction, when considered as a single variable gives a poor correlation with the data. Such a model would add two more variables to the description given by equation 6 and only slightly improves the accuracy.

Another model, which keeps velocity and silt as variables while adding a third parameter P, the percent of millimeter sized particles in the tire track, is shown in equation 7:

$$E = .97\ V^{1.13}\ S^{.63}\ P^{-1.4} + .026 \qquad (7)$$

This model explains 93% of the variation of the measured emission factor and the approach is appealing because it relates the emission to road surface material properties of the road surface over which the tire actually passes. An extension of this approach might lead to a partitioning of the emissions into a part coming from the vicinity of the tire, and another part coming from the edge of the road. Mechanical suspension of dust by the movement of millimeter sized rocks in the track as the tire passes ought to increase with P because

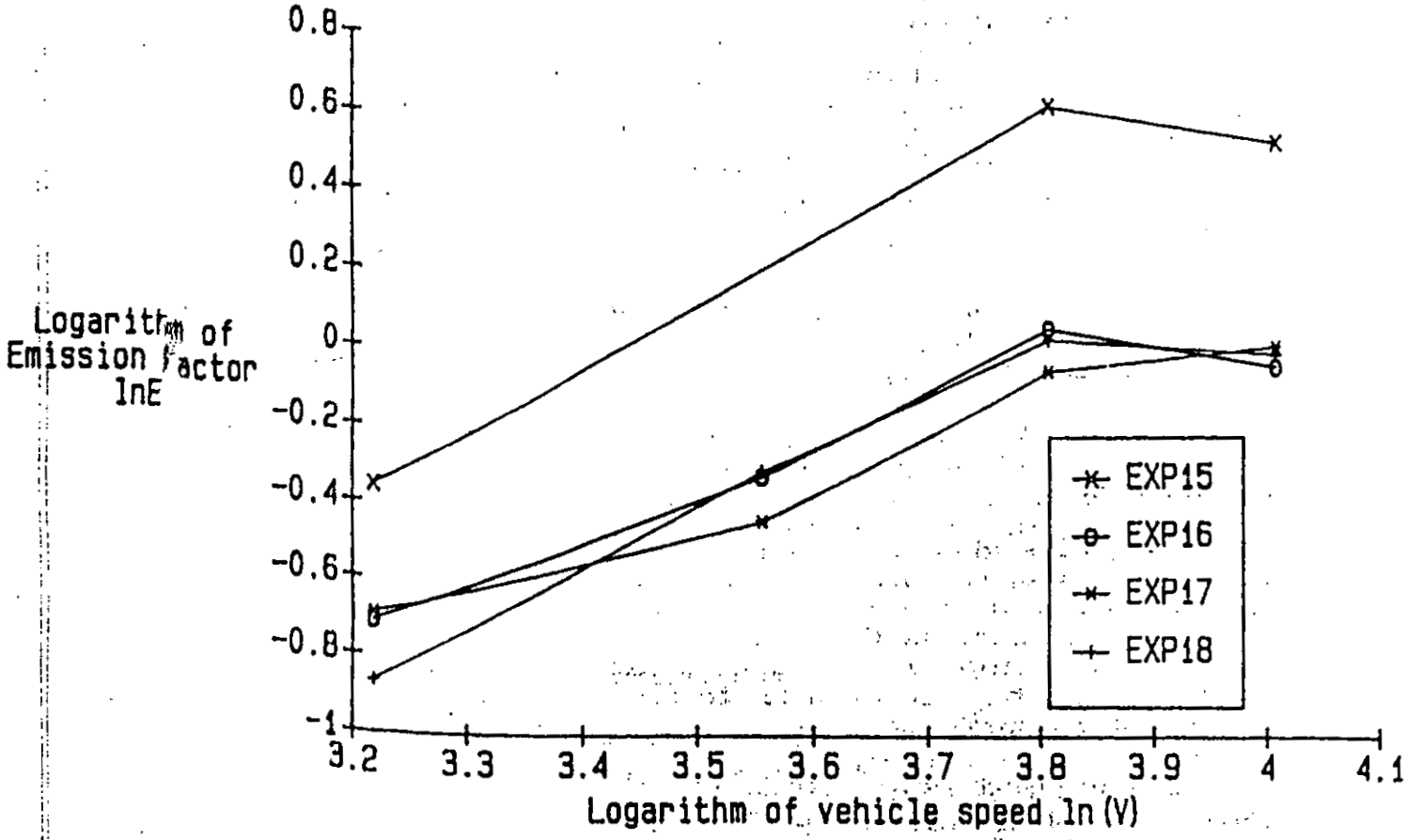

Figure 2. Logarithm of Emission Factor Versus Logarithm of Vehicle Speed for Experiments 15, 16, 17, and 18.

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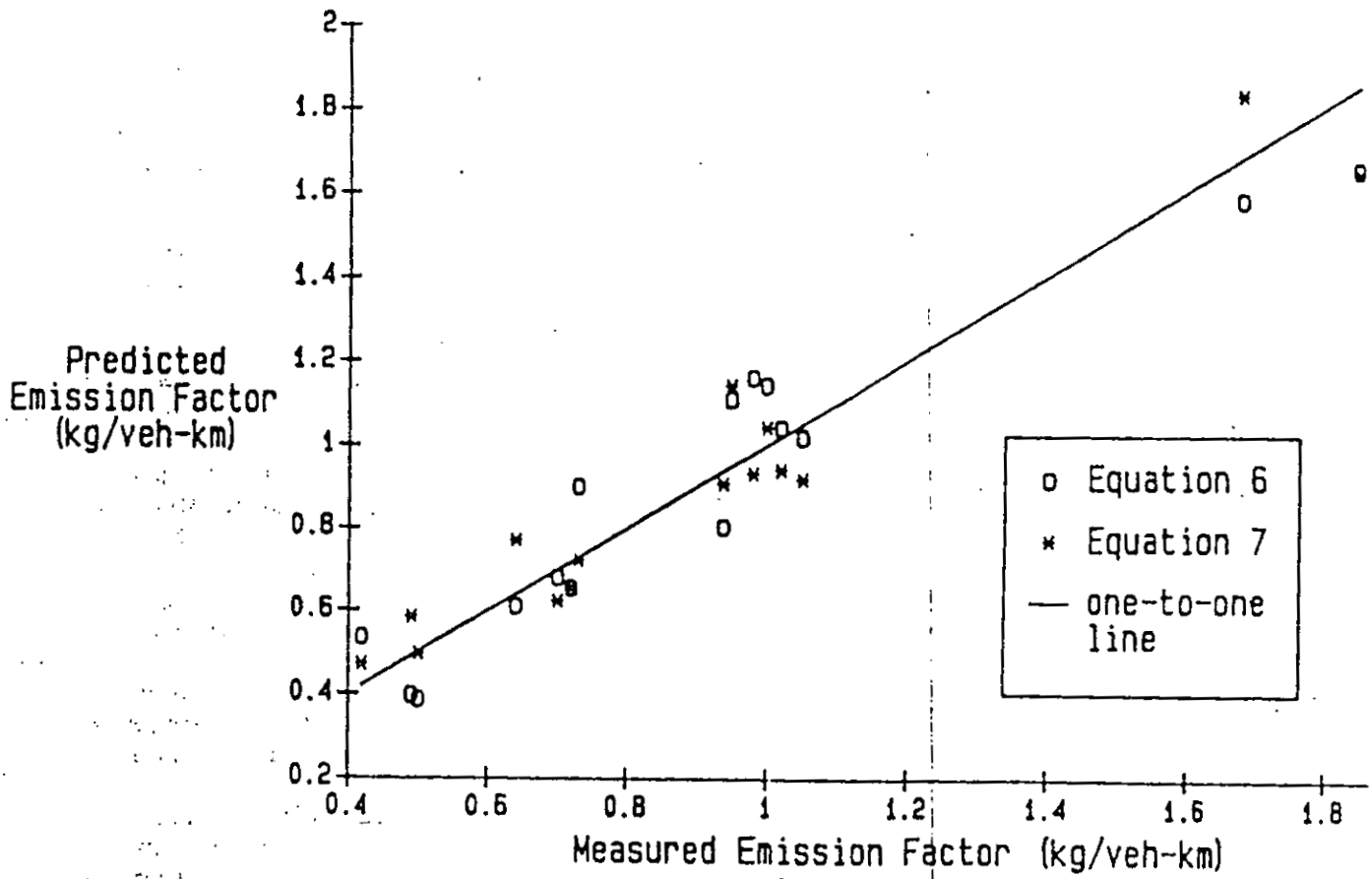

Figure 3. Predicted Emission Factors Versus Measured Values (kg/veh-km) for Two Different Models

more rocks would be disturbed. Since P occurs to a negative power in the equation, the model seems to be inconsistent with such a mechanical suspension mechanism. The observed P dependance does seem consistent with a pneumatic suspension mechanism since the viscous stresses, due to air motion under the tire at the moment of contact of the tire and road, would decrease as the flow channels between rocks are increasingly restricted by higher rock concentrations. The models given by equations 6 and 7 are compared to the measured emission factor in figure 3.

CONCLUSIONS

The present results indicate that the AP-42 formulation when applied to graveled roads is too small by about a factor of 4. Further, the form of the equation, depending on the product of vehicle speed and silt content, is unable to explain more than about 60% of the variation of the emission factor measurements. It is found that a one parameter model with the emission factor a function only of vehicle speed is almost as good as the two parameter model depending on speed and road silt content. A model depending on vehicle speed and the mass per unit area of loose road surface material less than 50 microns, H, accounts for over 90% of the variation of the emission factor. Measured values of the parameter, H, should exhibit less scatter since the influence of large rocks is eliminated. Since the silt content is composed of several variables, including H, which may each vary differently with the emission factor, it is reasonable that E depends on H but the dependance of E on the combination of variables composing silt content be weak. The present results suggest the possibility of developing an improved predictive model for the emission factor based on surface density parameterizations.

If the variables of vehicle speed and silt content are retained in the model, over 90% of the variation of E can again be explained by including the percentage mass, P, of millimeter sized rocks measured in the tire track. A disadvantage of this approach is the measurement of P may be difficult on roads where a well defined track does not exist. However, extension of this approach might help sort out the different mechanisms responsible for dust suspension.

The question arises as to what is the most reasonable approach to use for calculating fugitive emissions in light of the present criticism of the AP-42 estimate. The conclusion that the AP-42 emission factor equation is low by a factor of 4 is consistent with earlier results[5], where 21 different emission factor measurements were reported. (In the earlier paper[5] the wind profile was considered constant with height which results in about a 20% increase in the emission factor as compared to that calculated with a logarithmic wind profile as presented here.) It is noted that the models presented here are based on only 15 additional emission factor measurements, for which the extended surface material measurements were made. Since the factors of vehicle weight, number of wheels, dust aerosol size, and number of dry days were constant in the present analysis there is no basis for changing the relation of E in equation 1 with these variables. In terms of the models proposed here, the emission factor can be written as

$$E = F\ K\ (W/3)^{0.7} (w/4)^{0.5} (d/365) \qquad (8)$$

where E is in units of kg/veh-km, K, W, w, and d are defined in equation 1, and F is defined as 4.12 times the emission factor expression in either equation 6 or 7.

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REFERENCES

1. R. A. Bagnold (1954) The physics of Wind Blown Sand and Desert Dunes, Methuen, London.

2. J. S. Kinsey and C. Cowherd, Jr., "Dust Generation in the Battlefield Environment", presented at the Battlefield Dust Symposium II, Vicksburg, MS (1985).

3. R.J. Dyck and J. J. Stukel, "Fugitive Dust Emissions from Trucks on Unpaved Roads," Environmental Science and Technology, 10(10): 1046-1048, (1976).

4. G. A. Sehmel, "Particle Resuspension from an Asphalt Road Caused by Car and Truck Traffic," Atmospheric Environment, 7: 291-309, (1973).

5. Williams, A.L., G.J. Stensland, D.F. Gatz, and W.R. Barnard, 1988: Development of a PM10 Emission Factor from Unpaved Roads. Preprint 88-71.4 in the Proceedings of the 81st Air Pollut. Control Assoc. Annual Meeting, Dallas, TX, 11 pp. SWS Reprint 839.

6. Midwest Research Institute, "Section 11.2, Fugitive Dust Sources: An AP-42 Update of Open Source Fugitive Dust Emissions," U. S. EPA, Research Triangle Park, NC, EPA-450/2-76-029, (1976).

7. W. R. Barnard, G. J. Stensland, and D.F. Gatz, "Development of Emission Factors for Area and Line Source Fugitive Dust Emissions: Implications of the New PM-10 Regulations", presented at the International Specialty Conference APCA/EPA PM-10: Implementation of Standards, San Francisco, CA (1988).

8. C. Cowherd, Jr., "Measurement of Fugitive Particulate," presented at the Second Symposium on Fugitive Emissions: Measurement and Control, Houston, Texas, (1977).

9. R.O. McCaldin and K.J. Heidel, "Particulate Emissions from Vehicle Travel over Unpaved Roads," presented at the 71st Annual Meeting of the Air Pollution Control Association, Houston, Texas, (1978).