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DEVELOPMENT OF A PM10 EMISSION FACTOR FROM UNPAVED ROADS

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ABSTRACT

This paper summarizes results of experiments designed to evaluate the PM10 emission factor for unpaved roads. Particulate matter from unpaved roads was generated by repeatedly driving vehicles in front of the samplers for a minimum of 100 passes in order to generate sufficient material. Particulate matter was collected using dichotomous aerosol samplers located in a vertical array downwind of the roads. Since the dichotomous samplers collect particles in the two size ranges of less than 2.5 microns and less than 10 microns, emission factors for both size ranges are found. The exposure profiling method was used to determine the emission factors for 21 separate experiments. The PM10 emission factors were found to be larger than expected, ranging from 1 to 10 lbs./vehicle-mile. A model that best fits the data yields the emission factor to vary approximately as the vehicle speed squared times the square root of the silt content. The model only explains about half of the variation of the data, indicating a more fundamental approach is needed for accurate prediction.

INTRODUCTION

The emission of dust into the air from travel on unpaved roads is commonly regarded as a significant source of fugitive emissions. Vehicle traffic on unpaved roads both grinds the dust from larger rocks by the force of the tires against the road surface, and emits dust to the atmosphere during dry conditions. Particle formation by grinding, termed comminution[1], is not a very efficient mechanism for the production of PM10 particles, which are defined as particles ten microns and smaller in diameter. However, the unpaved road environment, where the surface material is subjected to frequent grinding by vehicle traffic under a variety of moisture conditions, and, in many instances, during repeated freeze-thaw cycles, is extremely harsh. Although one would not expect many sub-micron particles to be produced in this way, the potential does exist for the formation of significant numbers of PM10 particles.

Once produced by grinding of the road surface material, the PM10 particles are susceptible to being ejected into the atmosphere by the action of the passing vehicle. The particle ejection mechanisms are not well formulated, although several mechanisms are recognized as important[1,2,3]. Among those that may be important are the following:(1) particle entrainment by the intense air flow that is undoubtedly produced at the region where the tire contacts the road surface, (2) wheel slippage[1], that causes particles to adhere to the tire or tread, and the subsequent ejection of particles from the tire surface by the centrifugal force associated with tire rotation, (3) entrainment by the motion of the air due to the aerodynamic shape of the moving vehicle, (4) saltation, the ejection of small particles from the road surface by large particles that become partially entrained and ,subsequently, strike the surface, (5) the force of the tire, as it compacts the road surface, may force some air and entrained particles from the surface material, and (6) under moist conditions small particles might agglomerate with larger ones[1,3] thus changing the character of

the emissions, and (7) static charge could build up on the tire, and eject particles into the air by electrical repulsion, or make them adhere to the tire for subsequent centrifugal ejection.

The combined processes of dust formation and emission to the atmosphere by vehicular traffic on unpaved roads is obviously complex. Particle size would appear to be a key parameter in that many of the ejection mechanisms are particle size dependent. The recent history of the road may be important in that traffic during wet conditions or frozen conditions might produce more small particles then are ejected, and cause unexpectedly large emissions at a latter date. Heavy vehicles might prepare the road surface to influence the emissions of subsequent lighter vehicles. A reasonable first step to describing the process of dust emission is to parameterize particle size influences by measurement of the silt content of the road surface material, defined as the per cent mass of the material less than 75 microns in diameter, although additional properties of the surface material particle distribution could be specified as well. The velocity, weight, and number of wheels of the vehicle, similarly appear to be important variables for parameterization. There appears to be room for improvement in the selection of descriptive variables, however, since the parameterization is hardly specific to any of the number of processes that are responsible for emissions.

Considerable attention has been given to developing equations to describe the fugitive dust emissions from unpaved roads[4,6,7,8,9,10,11,12]. Typically, the emission factor, defined as the amount of dust suspended in the air by a vehicle per distance of road traveled (lbs./vehicle-mile), is measured for representative ranges of the underlying variables. A model is then developed based on the correlation of the emission factor and the variables. The model recommended by the EPA[12] for unpaved road emissions is,

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

where:
- E = PM10 emission factor (lbs/vehicle-mile)
- K = proportionality constant specific to size range of emitted particles (.45 for PM10)
- s = silt content (per cent by mass of particles smaller than 75 microns)
- v = vehicle speed (miles per hour)
- w = number of wheels on the vehicle
- W = vehicle weight (tons)
- d = number of days per year with less than .01 inches of rain.

The motivation behind our research[13,14] is to assess the extent that unpaved road dust emissions neutralize acid rain, the emphasis, therefore, being on crushed limestone gravel roads which are high in calcium. The emission of small particles that can stay airborne long enough to interact with precipitation is of primary concern. Emission factor calculations are presented for measurements by Barnard et.al.[15] of dust from unpaved, crushed limestone gravel roads, where particles in size fractions less than 10 and less than 2.5 microns were

but not replicate measurements

collected using dichotomous aerosol samplers. An attempt is made to estimate the error associated with the measurements. Correlations are presented to show the variation of the emission factor data with vehicle speed, and with the silt content of the road surface material.

DESCRIPTION OF EXPERIMENT

A full description of the experimental design is given by Barnard et.al.[15]. In a given experiment dichotomous and high volume aerosol samplers were placed upwind and downwind of an unpaved road to measure the background and road dust aerosol concentrations, respectively. During each experiment vehicles were repeatedly driven past the sampler site at a particular speed, and the experiment was repeated at the same site for various speeds. Of particular interest here is the three stacked dichotomous samplers located at 20 meters downwind of the road, and positioned to sample at heights of 1.55, 3.05 and 4.88 meters, respectively, above the ground. Using mass concentration values from the dichotomous samplers, corrected for the background aerosol concentrations, and with a record of the wind speed during the course of the experiment, the total mass of PM10 particulate that passes above a point on the ground downwind of the road can be estimated. This method, known as exposure profiling[16], enables one to calculate the emission factor without recourse to atmospheric dispersion modeling, and is further free of the assumption of continuous traffic volume on the road.

what wind measurements taken?

Both the coarse and fine particle filter samples from each dichotomous sampler were analyzed by gravimetric techniques. The aerosol mass concentrations of the 0-2.5 micron diameter particles, and the concentrations of the 2.5 to 10 micron particles were obtained. A PM10 emission factor as well as a 0-2.5 micron emission factor was calculated.

Filter weights were obtained using a Cahn 31 microbalance enclosed in a constant humidity chamber. The accuracy of the balance is judged to be about one microgram. Although the filters were always placed in the humidity chamber for at least 24 hours prior to weighing, both for the tare weight and loaded weight measurements, the adsorption of moisture onto the filters is considered to be the major source of error in the weighing procedure. An upper limit on the uncertainty due to the moisture problem is considered to be in the neighborhood of 10 micrograms for the loading of any particular filter. Considering the most lightly exposed filters, those from the top sampler of the stacked array, the coarse filter loading averaged about 500 micrograms leading to an experimental uncertainty of about 2 percent. The average loading for the corresponding fine filters was about 50 micrograms leading to an estimated weighing error of about 20 per cent. An additional uncertainty is introduced when a correction is made for the background aerosol, especially on the fine particle filters, since there the background aerosol mass concentrations average almost 20 per cent of the corresponding dust concentrations.

RESULTS AND DISCUSSION

In previous exposure profiling experiments[16], the sampling surface was placed so the wind flow was normal to the surface, while the sampler flow was adjusted to match the wind flow in order to establish isokinetic conditions. Under such conditions, the mass deposited per unit area of filter represents the mass that would pass through a unit area of the plume, and is termed the exposure. By an appropriate geometrical arrangement of the exposure measurements, an estimate of the exposure over the whole cross section of the plume was established. Considering the road emissions to be a line source, all points at a given height along the road should have the same exposure, so the measurements can be made at several heights above a given point. The vertical integral of the exposure over the height of the plume, divided by the number of vehicle passes gives the emission factor.

what's isokinetic for a dichot inlet?

Dichotomous samplers intake air at a fixed rate, and are designed to compensate for the departure from isokinetic flow conditions in order to obtain an unbiased sample over a wide range of air speeds. By measuring the mass deposited on the filters, and knowing both the flow rate and sampling time the aerosol concentration can be determined from the dichotomous sampler data. That concentration, multiplied by the wind speed, yields a mass flux, and, further multiplied by the sampling time gives the exposure.

In each of the twenty-one different cases analyzed, the three PM10 exposure values decreased linearly with height; the smallest correlation coefficient being .91, and in only three cases falling below .97. Accordingly, the exposure profiles were taken as linear. The profile was extrapolated upward, to find the height at which the background exposure occurred, and extrapolated downward to predict the ground level value. The profile integrated from the ground to the top of the plume, and divided by the number of vehicle passes, gives the emission factor.

Table I gives values of the predicted plume height and the resulting emission factor for each of the different experiments analyzed, along with their respective error estimates. The leading uncertainty in the emission factor values results from the uncertainty in predicting the exposure versus height. The error estimates, both in the predicted dust cloud height and in the predicted ground level exposure, are found from the standard error associated with the calculated slope and intercept of the exposure profile. The uncertainty introduced by the exposure integration procedure is larger than the uncertainty of the weighing procedure for the coarse filters.

Periodically, during the course of the dust sampling experiments, silt measurements were made on each road. The silt content of the road surface material was found to be quite variable, both along a single road and over the coarse of time. The extent of this variation is presently being studied. A silt value is presented for each experiment; where a silt measurement was not available for the day of the experiment, it was estimated by interpolating between measured values on that road taken before and after the experiment. The resulting silt values for each experiment are shown in Table I.

Table I. PM10 emission factor measurements and model predictions.

Experiment #	Road id.	Vehicle speed (mph)	Silt content (% wt)	Plume height (meters)	Emission factor	Model Predictions Eqn.(3) (lbs./vehicle-mile)	Eqn.(2)	Eqn.(1)
7	400E	25	9.60	8.86±.51	1.35±.12	2.67	3.18	.97
7	400E	35	9.60	6.75±.15	4.00±.17	5.01	5.27	1.35
7	400E	45	9.60	6.10±.30	7.13±.72	8.02	7.36	1.74
9	900N	25	3.60	6.82±.54	1.06±.16	1.62	1.52	.36
9	900N	35	3.60	6.62±.85	2.58±.63	3.04	3.61	.51
9	900N	45	3.60	7.94±1.08	5.06±1.15	4.86	5.70	.65
10	400E	25	7.00	7.43±.41	2.64±.26	2.27	2.46	.70
10	400E	35	7.00	5.73±1.12	3.47±1.44	4.27	4.55	.99
10	400E	45	7.00	6.70±1.01	8.12±2.29	6.83	6.64	1.27
11	900N	25	3.75	9.54±1.68	2.33±.62	1.65	1.56	.38
11	900N	35	3.75	8.06±.03	3.65±.02	3.10	3.65	.53
11	900N	45	3.75	7.84±.69	5.39±.81	4.97	5.74	.68
12	400E	25	6.00	6.46±.73	3.28±.72	2.10	2.18	.60
12	400E	35	6.00	6.01±.37	6.38±.82	3.94	4.27	.84
12	400E	45	6.00	6.72±.06	9.85±.17	6.31	6.36	1.09
13	400E	25	4.75	7.11±.40	3.53±.36	1.87	1.84	.48
13	400E	35	4.75	7.33±.39	5.41±.51	3.50	3.93	.67
13	400E	45	4.75	6.38±.28	6.69±.58	5.60	6.02	.86
14	900N	25	4.05	5.90±1.36	1.05±.49	1.72	1.64	.41
14	900N	35	4.05	5.62±1.17	1.65±.74	3.23	3.73	.57
14	900N	45	4.05	5.38±.29	2.25±.28	5.16	5.82	.73

The emission factors are highly correlated with vehicle speed for each experiment. In order to determine if the emission factor values for each experiment are otherwise statistically different, the they were tested against each other in a series of paired t-tests; emission factor values for corresponding velocities were paired in the tests. The null hypothesis, that the emission factor means of two experiments were equal, was rejected at the .05 significance level. The results indicated that experiments 12 and 13 were in a group by themselves, while the other experiments could be grouped together. Other groupings appear possible if the natural logarithm of the emission factor is used to calculate the test statistic. Physically this is not expected; one would rather expect the emission factor for a given road or for a similar range of silt values to group together. Such behavior suggests that additional variables need to be considered in the evaluation.

Further analysis was performed on the data set as a whole. Multiple regression calculations were performed on various functions of silt content and vehicle speed. Two different models were found which have about the same statistical validity. In one model the emission factor, E, varies as a linear sum of the vehicle speed, v, and silt content, s, and is given by,

$$E = .209\ v + .279\ s - 4.71 \qquad (2)$$

The multiple correlation coefficient of equation (2) is .75. This model must be considered physically unreasonable at very small values of v or s, but it has the virtue of simplicity.

The other model predicts a variation given as,

$$E = .00205\ v^{1.87}\ s^{.51} \qquad (3)$$

Here, the multiple correlation coefficient, found by correlating the logarithms of E, v, and s, is .76. In both cases the adjusted R square value, a multiple regression statistic that estimates the fraction of the total variation of the dependant variable accounted for, is just slightly over one-half. If the data is separated into two groups as suggested above, the same multiple regression analysis as that leading to equation (3) gives a correlation of .94 for the two experiments 12 and 13 taken together; the exponent of v becomes 1.5 while that of s increases to .7. A multiple regression analysis of the other grouping, comprising the rest of the experiments, yields a multiple correlation coefficient of .83 and exponents of velocity and silt of 2 and .5 respectively. It is curious that the data permit such different models to yield such equally good fits. Physical principles of the dust ejection mechanisms ought to yield guidance as to the modeling parameterization; together the two methods could determine the dominant physical dust ejection mechanism, and suggest how these, and possibly other, parameters should be incorporated into the model.

A scatter plot of the measured emission factor versus equation (3) is shown in Figure 1. The variation is larger than the error estimates of the measurements which are shown in table 1. The line in Figure 1 is a least squares linear fit of the calculated to the measured values, having a correlation of .79, and gives an idea of the amount of error likely to be encountered for our experiments by relying on a single model for the emission factor estimates.

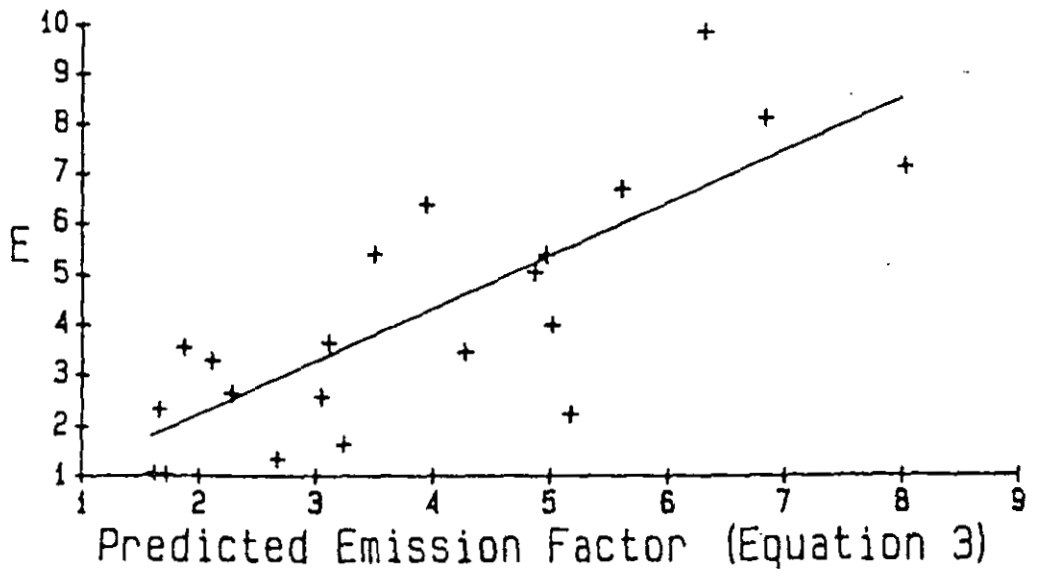

Figure 1. Predicted versus measured E emission factors

Values calculated from equation (1), the recommended EPA emission factor equation, are listed in the last column of Table (1). A value of W = 1.25 tons was used for the vehicle weights, the number of wheels was 4, and d/365 was taken as unity, since the experiments were only done on dry days. The value of K, the factor estimated to correct the total emissions to PM10 emissions, is taken as .45, and the corresponding values of vehicle speed and silt content are given in Table (1). The average of the ratio of the measured value to the EPA estimated value is 5.37, so our measurements are about 5 times higher than the those found using the EPA method. An earlier model by Cowherd et. al.[17], based on data taken over a restricted ranges of vehicle weight and number of wheels as in the present study, gives emission factors more in line with those reported here.

The emission factor for particles smaller than 2.5 microns in diameter, e, was calculated, but an estimate of the error has not been determined. The main difficulty is that the scatter in exposure values is large enough that an accurate value of the plume height cannot uniformly be obtained; the fine particle exposure values do not always decrease linearly with height as do the PM10 exposures, and in a few cases they actually increase with height. For purposes of comparison, the method of calculation was to compute the emission factor for the particles from 2.5 to 10 microns in diameter, for which the exposure does linearly decrease with height, and subtract that result from the PM10 value. This avoids the question of determining a plume height for the 0-2.5 micron particles that differs substantially from the PM10 plume height, although it appears to underestimate the exposure integral for cases where the fine fraction exposures increase with height. Figure 2 shows a plot of e versus the PM10 emission factor, E. If the two large values of e are omitted from consideration, the correlation coefficient is .86, and the linear relation, shown by the line in Figure 2, becomes

$$e = .052\ E + .011 \qquad (4)$$

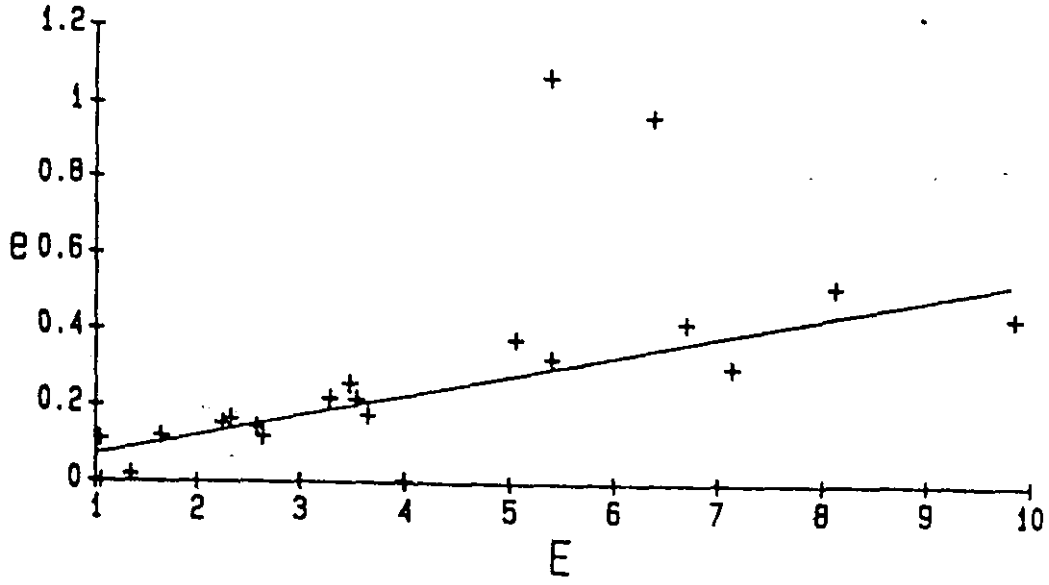

Figure 2. Fine particle, e, versus PM10, E, emission factors (lbs./vehicle-mile).

CONCLUSIONS

An important feature of the unpaved road emission factor data discussed here is that only about half of the variation of the emission factor is accounted for when vehicle speed and silt content are varied, while other parameters such as the vehicle weight and number of wheels are kept constant. This implies that all the important variables are not taken into account in the parameterization. Of the several mechanisms that are reported as being important, it is not known which ones really dominate the process; perhaps the identification of the important process and the development of emission estimate models based on the particular variables of that process would be a useful approach to future research.

The behavior of the silt content on a particular road relating to how it varies along the road, and with time, is an interesting question that arises in this analysis. If the silt variation is significant over tens of meters distance, a slight variation in the wind direction could bring dust to the samplers from parts of the road with different silt content. The question even arises as to whether the silt varies significantly during the 100 or so vehicle passes for each experiment, and if so does it increase due to additional grinding of the road surface material or does it decrease due to depletion? Some of these issues are being addressed in our ongoing research.

The dependance of the emission factor on silt content given in equation (3) varies nearly as the square root of the silt content which, if true, would tend to reduce the importance of silt content as a dominant variable; perhaps some other aspect of the road surface material particle distribution is more useful as a predictive variable. If the velocity dependence suggested by equation (3) can be supported by further experiments, then vehicle speed would become even more important as a determinant factor in predicting and, perhaps, controlling emissions.

The magnitude of emission factor for particles below 2.5 microns diameter is an interesting question. Present estimates put the value in the range of .1 to 1 lbs/vehicle-mile or about 10 per cent of the PM10 emission values. The number distribution of the road dust aerosol probably peaks in this region, and these particles ought to stay airborne even longer than the larger size fractions. It is perhaps this component of the road dust emission that has the most impact from a regional air pollution standpoint and from the standpoint of acid rain neutralization.

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NOTE TO EDITORS