The Effect of Vehicle Speed on Unpaved Road Emissions

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ABSTRACT

The AP-42 Supplement E unpaved road emission factor equation was developed in 1997 from a database of approximately 200 tests with widely varying source conditions. Since that time, not only have new test data become publicly available, but AP-42 users have gained operational experience with the emission factor model. This paper presents a reevaluation of the current factor with a focus on the effect of vehicle speed.

Everyday experience dictates that (all other things being equal) faster vehicles result in more dust than slower ones. As such, there is an understandable desire to include mean vehicle speed as a correction parameter. However, forcing that variable into a stepwise regression leads to the speed term being raised to a power much lower than what has been found in studies designed to isolate the effect of speed on individual roads. Additional complications arise because: (a) vehicle speed and road surface silt content are highly correlated in the available data base; and (b), the Supplement E background document discussed the factor's tendency to overpredict for travel speeds less than 15 mph.

This paper discusses and compares alternative methods to incorporate the effect of mean vehicle speed in a predictive emission factor equation for unpaved roads.

INTRODUCTION

The AP-42 Supplement E unpaved road emission factor equation was developed in 1997 from a database of approximately 200 tests with widely varying source conditions. Since that time, not only have new test data become publicly available, but AP-42 users have gained operational experience with the emission factor model. As a result, a reevaluation of the emission factor was undertaken.

The initial phase in the reevaluation began in 2000 and explored whether or not valid predictive models could be developed to address two distinct applications of the AP-42 unpaved road emission factor equation

- Public unpaved roads, traveled mostly by light-duty vehicles
- Industrial plant roads with a wide range of vehicle characteristics

Of particular interest was determining whether separate emission factor models would eliminate the following undesirable features of the Supplement E (September 1998) AP-42 emission factor:

- The current factor tends to overpredict emissions for mean vehicle speeds below 15 mph. – Both the AP-42 section and the 1998 background document [1] discussed this tendency. Although the AP-42 section suggested a reduction in emission estimates when applied to roads with travel speeds slower than 15 mph, this recommendation was not thoroughly supported by the available test data.

- The moisture term in the present model does not isolate the effect of watering a specific road. – The data base [1] included tests of emission from watered unpaved roads along with uncontrolled tests. The emission factor was found to have greatly improved (over the previous AP-42 emission factor) predictive accuracy when applied to independent data, with the increase presumably due to inclusion of a surface moisture content term. However, moisture was raised to only a very low power and did now allow one to isolate the effect of moisture content when the road is watered. Prior testing has shown that, on an individual road, watering to double the surface moisture content leads to control efficiency of approximately 75%. This is a far higher control than the 20% value one would obtain by doubling moisture in the emission factor in which moisture content is raised to the 0.3 power.

- Had a speed term been incorporated into the emission factor model in 1998, that term would not isolate the effect of reducing travel speeds on an individual road. – This is analogous to the above discussion on moisture content. The low power to which vehicle travel speed would have been raised does not allow one to predict the effect different speeds would have on emissions from an individual road.

The initial phase concluded by assembling a PM-10 data set of unpaved road emission factor tests. In contrast to the 1998 background document [1] ,only uncontrolled emission tests were included This approach was adopted to avoid possible confusion arising from use of a moisture term to estimate watering control efficiency.

Tests were identified as having been conducted on roads that either were publicly accessible or were located on private (industrial) property. It became apparent that there was no significant difference between light-duty vehicle tests on the two types of roads and that vehicle weight provided a more important classification than did ownership of road. The data set was thus divided as follows:

- Industrial (Plant) – Tests conducted on industrial plant roads, regardless of mean vehicle weight.

- Light-duty – Tests with mean vehicle weights less than 3 tons, regardless of whether or not the public has access to the road

PRELIMINARY MODEL DEVELOPMENT

The reevaluation continued in 2001 by exploring what predictive emission factor models could be developed from the two data bases described above. Model development activities began by developing the correlation matrices for (log-transformed) variables. For the "industrial plant" data set, the variables of interest were

- PM-10 or PM-30 emission factor
- Road surface material silt content
- Road surface material moisture content
- Mean vehicle weight
- Mean vehicle travel speed
- Mean number of wheels

For the "light-duty" data set, the variables of interest were

- PM-10 or PM-30 emission factor
- Road surface material silt content
- Road surface material moisture content
- Mean vehicle travel speed

Because of the limited types of vehicles that typically travel public roads, vehicle weight and the number of wheels were excluded from consideration because only slight variations in the fleet averages are present in the data sets.

Stepwise regression of the log-transformed data was used to develop multiplicative emission factor models. As a preliminary step, MRI first examined the correlation matrices for the log-transformed data. Several points should be noted about the correlations. In the light-duty, public road data sets:

- Vehicle speed was found to be highly intercorrelated with other independent variables - silt in the case of PM-10 and moisture content in the case of PM-30. (This remains the case even if one eliminates all tests in the data base that were directed toward isolating the effect of vehicle speed on a given road.)

- On the other hand, moisture and silt content were not significantly correlated in the data set for either particle size range.

Taken together, these two points would lead to development of a regression-based predictive equation based on silt and moisture contents. That is to say, because one usually cannot incorporate intercorrelated variables as independent inputs, straightforward stepwise regression would lead to PM-10 and PM-30 models that use silt and moisture as the input parameters.

Everyday experience dictates that (all other things being equal) faster vehicles result in more dust than slower ones. As such, there is an understandable desire to include mean vehicle speed as a correction parameter. However, the earlier work demonstrated that forcing that variable into the stepwise regression leads to the term being raised to a power much lower than that found in studies designed to isolate the effect of speed on individual roads. In 16 sets of "captive" traffic data, emissions vary with speed raised to a power typically between 1 and 1.5. Figure 1 shows that the exponent for the speed term in these 16 tests ranges from 0.85 to 2.85. In other words, with all other things being equal, one would expect that emissions on a particular road would tend to increase linearly with traffic speed.*

As a result of discussion with EPA staff, the decision was made to explore two ways to develop a light-duty unpaved road emission factor and to invite public review and comment. For that reason, the draft revised version of Section 13.2.2 includes two options. Option 1 forced the mean vehicle speed into a regression-based emission factor. Option 2 first developed a model based on regression against silt and moisture and then imposed a linear speed term. Both options are shown in Table 1.

In the case of the industrial plant road data sets, matters were more clear-cut. Examination of the correlation matrices revealed the following:

- As one would expect, emission factors are highly correlated with mean vehicle weight and road surface silt content. Furthermore, weight and silt are themselves not significantly correlated.

- Vehicle weight was found to be highly correlated with moisture content in both particle size ranges.

Taken together, these two points led to the straightforward development of a regression-based industrial unpaved road predictive equation based on silt and mean vehicle weight, as shown in Table 1.

PRELIMINARY MODEL VALIDATION

An initial series of validation studies were undertaken for the models shown in Table 1. Validation focused on PM-10 model performance primarily in terms of the predicted-to-measured ratio

$$\frac{\text{emission factor predicted by Table 1 equation}}{\text{measured emission factor}}$$

As a practical matter, because of the log-linear regression used to develop the predictive models, the log of the predicted-to-measured ratio is identical to the "residual" or error term associated with the regression:

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* At least one additional complication can be surmised. Imposition of a long-term change in the mean vehicle speed on a road may affect the equilibrium silt content. In other words, lowering the mean speed might be expected to raise the silt content. Past studies are not available to assess the effect of speed controls on the unpaved road surface. Earlier captive traffic tests lasted less than 1 week and do not provide any information on long-term effects.

$$\text{residual} = \log \{\text{predicted}\} - \log \{\text{measured}\} = \log \{\text{predicted/measured}\}$$

Plots of the residuals against the independent variables were made and examined for significant trends. Of particular interest was determining the models' performance for various travel speeds. (Recall Supplement E factor tends to overpredict for slow travel speeds.) Residuals for the industrial road model in Table 1 did not exhibit any tendency to over- or underpredict as speed varied. Figures 2 and 3 show the residuals plotted against travel speed for PM-10 and PM-30, respectively. In examining the residuals, only one systematic bias was observed for the industrial unpaved road emission factors. Both the PM-10 and PM-30 factors tend to overpredict for high (and underpredict for low) moisture contents (see the lower plots in Figures 2 and 3). This is not surprising -- one would expect that, all other factors being equal, very dry surfaces should emit more PM than damp surfaces. Although one could potentially remove this bias by including a surface moisture content term, the two factors noted earlier in connection with the correlation matrix caution against such an approach:

- Recall that moisture content is significantly correlated with vehicle weight in the industrial road data base. This restricts consideration of moisture as an additional independent variable.

- Inclusion of a moisture term would again tempt AP-42 readers to (unsuccessfully) try to isolate the effect of watering to increase surface moisture content.

Furthermore, the degree of bias is fairly minor. Table 2 shows the geometric mean of the predicted-to-measured ratio for different ranges of moisture content. In each range, the average over/underprediction is within a factor of 2.

Not surprisingly, preliminary PM-10 validation results differ between two public road options in Table 1. As one would expect for a model based solely on regression, residuals for the Option 1 model do not exhibit any significant relationship between the independent variables. On the other hand, residuals for the Option 2 model (i.e., the one in which a linear speed term has been imposed) are positively correlated with speed and negatively correlated with silt content. In other words, the Option 2 model tends to significantly overpredict emissions at high mean vehicle speeds and to underpredict for high silt contents.

In summary, Option 1 offers marginally better predictive accuracy than Option 2 and does not exhibit the systematic biases evident in Option 2. However, the low power for the S term in Option 1 is not indicative of the isolated effect of vehicle speed on an individual road. For these reasons, public comment on the relative merits of Option 1 and Option 2 was sought by including both in the revised draft Section 13.2.2. The draft version, as well as background information, was posted in October 2001 on the CHIEF section of EPA's Technology Transfer Network.

SUMMARY AND CONCLUSIONS

Reexamination of the AP-42 unpaved road emission factor has shown that separate models can be developed to address two distinct applications – namely, public unpaved versus industrial plant roads. In the latter case, model development and validation proceeded in an unambiguous manner. The resulting emission factor model not only resembles the current (i.e., Supplement E) predictive equation in AP-42 Section 13.2.2 but exhibits roughly similar predictive accuracy. Importantly, the industrial road model as presented in Table 1 does not exhibit any tendency to over/underpredict for low/high vehicle travel speeds.

On the other hand, model development for public roads was not nearly as straightforward, given the desire to incorporate mean vehicle speed in the emission factor. Two distinct options were selected for evaluation – one forcing speed to enter the stepwise linear regression and the second imposing an assumed linear relationship between emissions and speed. The first option offers marginally better predictive accuracy and does not suffer from systematic biases. Nevertheless, the low power that results for the speed term under Option 1 is not indicative of the isolated effect of vehicle speed. Because unequivocal selection of a preferred approach could not be made, public comment has been invited by including both in a revised draft of Section 13.2.2 .

REFERENCE

1. Emission Factor Documentation for AP-42, Section 13.2.2, Unpaved Roads, Final Report, Midwest Research Institute, Kansas City, MO, September 1998.

Table 1. Preliminary emission factor models

Road Type/ Size Range	Emission Factor Model [a]	R^2	n[b]	Within factor of 2[c]	Within factor of 3[c]
Public Roads (option 1)					
PM-10	$e = 1.8\ (s/12)^{0.97}\ (S/30)^{0.46}\ /\ (M/0.5)^{0.23}$	0.286	87	56%	79%
PM-30	$e = 6.0\ (s/12)^{0.95}\ (S/30)^{0.31}\ /\ (M/0.5)^{0.34}$	0.514	22	54%	86%
Public Roads (option 2)					
PM-10	$e = 1.7\ (s/12)^{0.84}\ \mathbf{(S/30)^{1}}\ /\ (M/0.5)^{0.23}$	0.258[d]	87	46%	75%
PM-30	$e = 6.4\ (s/12)^{0.95}\ \mathbf{(S/30)^{1}}\ /\ (M/0.5)^{0.40}$	0.511[d]	22	41%	91%
Industrial Roads	$e = 1.5\ (s/12)^{0.87}\ (W/3)^{0.45}$	0.371	115	48%	72%
PM-30	$e = 4.3\ (s/12)^{0.68}\ (W/3)^{0.49}$	0.433	83	42%	71%

[a] In the expressions, "e" represents the emission factor in pounds per vehicle mile traveled (lb/vmt), "s" represents silt content (%), "W" represents mean vehicle weight (tons), and "M" is the surface moisture content (%).
[b] Number of data points
[c] Percentages of model predictions within stated factor.
[d] R-squared value for portion of model derived by stepwise regression (i.e., that not shown in **bold**).

Table 2. Bias in industrial road model due to moisture content

Range of Moisture Contents	Geometric Mean of Predicted-to-Measured Ratio	
	PM-10	PM-30
0.5 % or less	0.69	0.76
0.5 to 2 %	0.91	0.81
2 to 5 %	1.27	1.12
5 % and above	2.05	1.51

Figure 1. Emission variation with speed during 16 captive traffic test programs

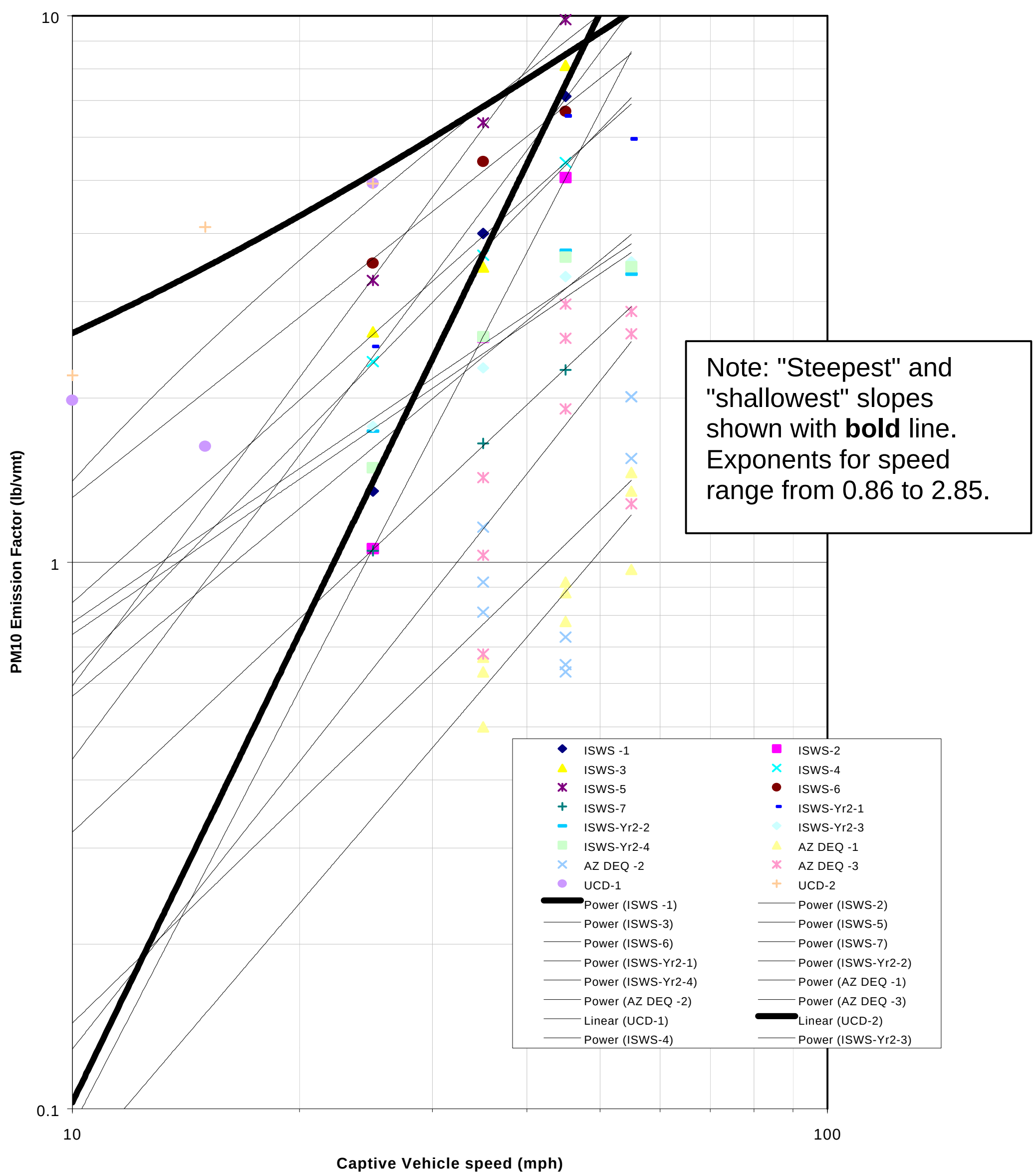
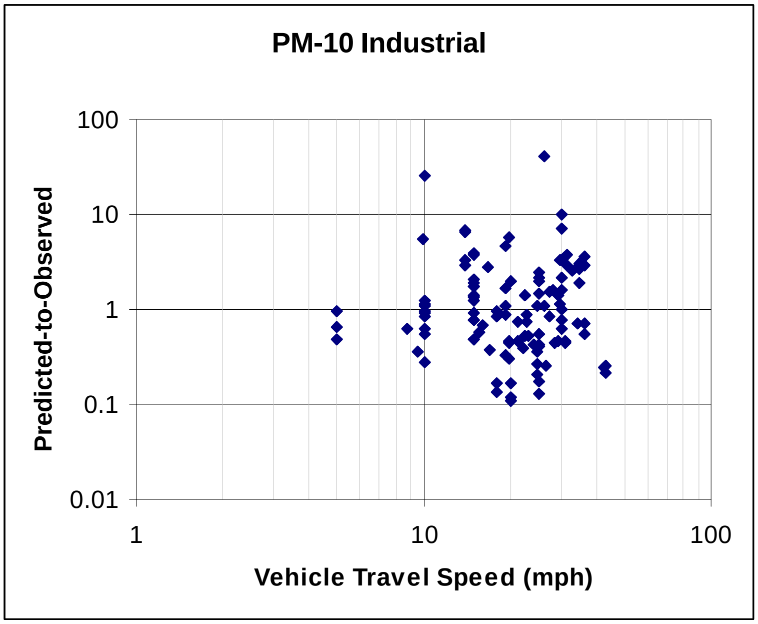


Figure 2. Residuals for the PM-10 industrial roads model.



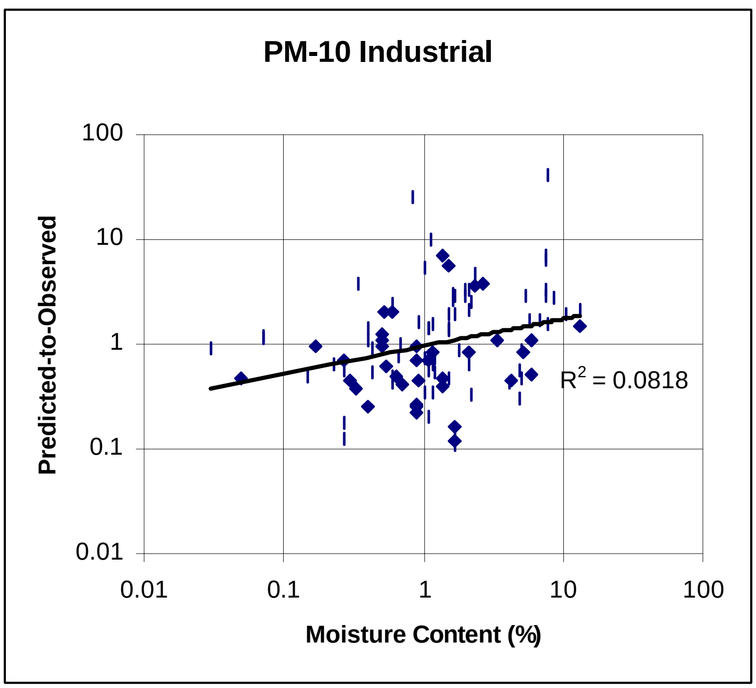


Figure 3. Residuals for the PM-30 industrial road model.