Reevaluation of the Unpaved Road Emission Factor Model

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ABSTRACT

The current AP-42 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 review of the current factor in light of the newer developments.

Besides discussing how well the current factor predicts independent test data (in comparison to the earlier AP-42 model), this paper presents a thorough reevaluation of the expanded database. The reevaluation focuses on two distinctly different uses of the AP-42 model:

- Statewide or nationwide inventories of public unpaved roads
- Characterization of industrial plant roads for permitting and control planning purposes

The paper compares separate models developed to address those two distinct uses.

INTRODUCTION

The current AP-42[1] Section 13.2.2 unpaved road emission factor equation

$$e_{10} = 2.6\ (s/12)^{0.8}\ (W/3)^{0.4}\ /\ (M/0.2)^{0.3} \qquad (1)$$

where

e_{10} = PM-10 emission factor in pounds per vehicle-mile-traveled (lb/VMT)
s = surface material silt content (%)
W = mean vehicle weight (tons)
M = surface material moisture content (%)

was developed using a data base assembled in 1996. Although the AP-42 emission factor had undergone modification during the previous 20 years, all versions of the unpaved road model shared important common features. All were developed through multiple linear regression and consistently show the road's surface silt content to be of critical importance in predicting emissions. All versions included a roughly linear (power of 1) relationship between the emission factor and the road surface silt content.

Equation 1 shares those basic features of past models, but had three important distinctions

- First, Equation 1 was developed specifically for PM-10. All earlier versions referenced suspended particulate less than 30 μm and applied scaling factors for other size ranges.

- Second, Equation 1 addressed all types of vehicular traffic over unpaved surfaces. The development of previous models specifically excluded vehicles such as large mining haul trucks from consideration.

- Finally, Equation 1 was based on tests of both uncontrolled (dry) and watered surfaces.

This paper presents a reevaluation of Equation 1. The paper begins by exploring how well Equation 1 can predict independent test data that became publicly available after the AP-42 data set was assembled. In addition, several outstanding issues (such as default moisture content and the lack of a speed term in the equation) raised during the development and review of Equation 1 are discussed.

DISCUSSION

The evaluation began by assembling newer unpaved road emission test data, initially emphasizing the tests that led to a state-specific PM10 emission factor of 2.27 lb/vmt developed by the California Air Resources Board (CARB)[2]. This factor averages 22 emission tests of light-duty traffic on unpaved roads from two separate field studies in the San Joaquin Valley. The first study[3] was performed by the University of California at Davis (UCD) while the second[4] was conducted by Desert Research Institute (DRI). Note that CARB used some preliminary data in developing its factor. Had final data been used, an overall average PM-10 factor of 2.0 lb/vmt would have been found rather than the value of 2.27 lb/vmt. Tables 1 and 2 show the preliminary data used by CARB as well as the final values reported in References 3 and 4.

Besides the San Joaquin Valley tests, a Washington State University (WSU) report[5] [4] became publicly available after the AP-42 unpaved road factor data base was assembled. Although this study was directed primarily to paved road emissions, the report contained limited test data on unpaved roads. Furthermore, another 36 data points were compiled from two Illinois State Water Survey (ISWS) papers[6,7] from the 1980s. The ISWS tests were discussed in the Section 13.2.2 background document[8], but were not included in the final AP-42 data set because no test reports were available to describe the methodology or results.

Predictive Accuracy of Current Factor

To assess whether Equation 1 represented an improvement in predictive accuracy, it was necessary to also consider emission factor that immediately preceded Equation 1 in AP-42:

$$e_{10} = 2.1\ (s/12)\ (S/30)\ (W/3)^{0.7}\ (w / 4)^{0.5} \qquad (2)$$

where

e_{10} = PM-10 emission factor (lb/VMT)
s = surface material silt content (%)
S = mean vehicle speed (mph)
w = mean number of wheels
W = mean vehicle weight (tons)

This is the emission factor model to which the newer test data were originally compared. Equation 2 first appeared in AP-42 in 1983 as part of Supplement 14 to the third edition of AP-42. For clarity's sake, Equation 2 will be termed "old" model while Equation 1 represents the "new" (or "current") emission factor model.

Table 3 presents summary statistics for the predicted-to-observed ratios when both the old and new AP-42 emission factors are used to predict independent data in Table 2. The old AP-42 emission factor systematically underestimates the Table 2 data by factor of 2 on average. On the other hand, estimates based on Equation 1 are centered on the data, thus indicating acceptable performance by the new model. Presumably, the increase in predictive performance in the new AP-42 factor as compared to the old factor is principally due to inclusion of surface moisture content as an input parameter. (M in Equation 1). Furthermore, Equation 1 independently predicts the new California data at least as well as does the mean of the California data set. This is based on comparing the percentage of estimates within a factor of 2 of the measured value.

Direct comparisons for the other new test data were not possible because necessary information (moisture content in the case of the ISWS data and silt/moisture contents in the case of the WSU tests) were not reported.

Other Issues Related to the AP-42 Factor

At least two issues have been associated with Equation 1 since the time that it was incorporated into AP-42:

- What is a suitable default moisture content for use in Equation 1?
- What effect does the omission of a vehicle speed term have on the predictive accuracy of the AP-42 emission factor equation?

Both of these points were discussed in the background document. Upon further reflection, it became apparent that both issues are related to two distinct applications of Equation 1 – namely, development of areawide inventories of public unpaved roads versus characterization of industrial plant roads for permitting and control planning purposes. Each application has its own particular needs. For example, although the inclusion of the M term in Equation 1 permits greater geographic variation for public road emission estimates, the term does not isolate the effect of watering industrial roads. A preliminary analysis was undertaken to evaluate the merit of developing separate emission factor models for public and industrial roads.

The analysis began by supplementing the AP-42 emission factor data base with the newer tests discussed above. Tests were identified as having been conducted on roads that either were publicly accessible or were located on private (industrial) property. This classification was not as straightforward as one would have anticipated. For example, the UCD tests[3] are commonly viewed as representative of public (county) roads but were in fact conducted on agricultural (vineyard) roads.

It became apparent that vehicle weight provided a more important classification than did the ownership of the road. Figure 1 shows box plots for various groupings of tests conducted with mean vehicle weights less than 3 tons. (Box plots present a great deal of information in a compact space, with the most important feature being the two parentheses -- the parentheses bracket the 95% confidence interval for the median emission factor in each grouping.) Figure 1 shows that there is no significant difference between light-duty emissions from public or industrial roads, except that the ISWS results are significantly higher than tests in any other grouping. (This is in keeping with the remarks made in the AP-42 background document that ISWS data reduction scheme systematically biases results high.) For this reason and because there no test report was available, the ISWS tests were excluded from the final data set. Furthermore, only uncontrolled tests were retained.

The data set was thus divided as follows:

Data Set I. Light-duty – Tests with mean vehicle weights less than 3 tons, regardless of whether the road is publicly accessible or not.

Data Set II. Industrial – Tests conducted on industrial plant roads, regardless of mean vehicle weight.

There is some overlap between the two data sets because tests of light-duty vehicles on industrial plant roads are included in both sets.

Stepwise regression of the log-transformed data was used to develop multiplicative emission factor models for Data Sets I and II in the same way that Equation 1 was developed. Table 4 compares the results obtained with the current emission factor. Note that Options 1 and 2 for Data Set I refer to whether or not moisture content (M) was included as a possible "correction parameter" in the regression.

The preliminary models bear strong resemblance to the current AP-42 factor. Similarly, the preliminary models have comparable predictive accuracy, with roughly half the model estimates within a factor of 2 and 70% to 80% within a factor of 3. Figure 2 shows the cumulative frequency distribution of predicted-to-observed ratio for the three preliminary models.

Although the current AP-42 emission factor equation appears to have slightly greater predictive accuracy, none of the preliminary models exhibit the current model's tendency to overpredict for low vehicle speeds. Figure 3 plots the log-residuals (logarithm of the predicted-to-observed ratio) for the three preliminary models. For each model, the residuals form a broad, fairly horizontal band above and below the x-axis indicating equal likelihood of over- and underprediction.

SUMMARY AND RECOMMENDATIONS

The current AP-42 emission factor model (Equation 1) performed well in predicting newer test data. The increase in predictive accuracy over the "old" factor (Equation 2) is presumably due to inclusion of the surface moisture content term. In fact, the current emission factor predicts the newer, independent California data at least as well as the mean value of the data set.

Even though the current factor performs well in estimating independent test data, the two distinct uses for AP-42 estimates suggest that some shortcomings of the current factor can be overcome through the development of two separate models. The preliminary industrial plant road model

$$e = 1.6\ (s/12)^{0.72}\ (W/3)^{0.42} \qquad (3)$$

and the preliminary (Option 1) public road model

$$e = 1.8\ (s/12)^{0.80}\ /\ (M/0.5)^{0.19} \qquad (4)$$

are recommended for further evaluation for possible inclusion in AP-42. Compared to the current AP-42 unpaved road emission factor equation, these models sacrifice little in terms of predictive accuracy but remove the tendency to overpredict at low vehicle speeds.

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Table 1. Data used to develop CARB factor

DRI Tests		UCD Tests	
Test Date	PM10 emission factor[a] (lb/VMT)	Test ID	PM10 emission factor[a] (lb/VMT)
21-Oct	5.04	A003	4.9
25-Jul	3.41	A015	4.9
23-Jul	3.37	A016	4.1
26-Jul	2.84	A017	2.2
Avg 07/95	2.34	A006	2
Avg 10/95	2.18	A004	1.6
22-Jul	1.67	A108	0.9
17-Oct	1.67	A109	0.7
24-Jul	1.53	A101	0.6
27-Jul	1.24	A106	0.6
20-Oct	1.17		
22-Oct	1.03		
Average	**2.29**	**Average**	**2.25**
Overall Average = 2.27 lb/vmt			

[a] As reported in January 12, 2000 project summary.

Table 2. Final data reported in References 2 and 3

DRI Tests		UCD Tests	
Test Date	PM10 emission factor (lb/VMT)	Test ID	PM10 emission factor (lb/VMT)
7/22/95	1.67	A003	4.94
7/23/95	3.37	A015	4.93
7/24/95	1.53	A016	4.11
7/25/95	3.41	A017	2.20
7/26/95	2.84	A006	1.98
7/27/95	1.24	A004	1.63
10/17/95	1.69	A108	0.91
10/18/95	0.86	A109	0.65
10/20/95	1.31	A101	0.60
10/21/95	5.22	A106	0.57
10/22/95	1.09		
6/13/96	0.67		
6/14/96	2.67		
6/15/96	0.67		
6/16/96	1.07		
6/17/96	1.83		
6/17/96	0.43		
Average	**1.86**	**Average**	**2.25**
Overall Average = 2.0 lb/vmt			

Table 3. Summary Statistics for Predicted-to-Observed Ratio for New California Data

	Old AP-42 Factor (Equation 2)	New AP-42 Factor (Equation 1)
Sample Size	n = 27	n = 32[a]
Geometric Mean	0.588	0.928
Median	0.488	0.929
Values within a factor of 2	33%	66%
Values within a factor of 3	85%	75%
Minimum	0.152	0.202
Maximum	2.58	5.48

[a] Includes 5 watered road data from UCD tests.

Table 4. Preliminary Emission Factor Models for Data Sets I and II

Data Set	**Emission Factor Model**[a]	R^2	**Sample Size, n**	**Within factor of 2**[b]	**Within factor of 3**[b]
Current AP-42 Unpaved Road Factor	$e = 2.6\,(s/12)^{0.8}\,(W/3)^{0.4} / (M/0.2)^{0.3}$	0.345	180	52%	73%
Data Set I Public/Light Duty (Option 1)	$e = 1.8\,(s/12)^{0.80} / (M/0.5)^{0.19}$	0.272	82	47%	79%
Data Set I Public/Light Duty (Option 2)	$e = 1.9\,(s/12)^{0.76}$	0.219	86	49%	80%
Data Set II Industrial Plant Roads	$e = 1.6\,(s/12)^{0.72}\,(W/3)^{0.42}$	0.325	119	48%	66%

[a] See Equation 1 in the text for explanation of variables.
[b] Percentages of model predictions within stated factor. Results for the current AP-42 model are based on cross-validation ("quasi-independent" predictions) and includes watered tests.

Figure 1. Box plots for the light-duty (< 3 tons) tests.

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                            PM-10 Emission Factor (lb/vmt)
               0.05   0.1    0.2      0.5     1      2        5     10     20


                                       (                )              AP-42Industrial

                                       (                 )             UCD Industrial
                                                                        (agricultural)
                                     0        (    )                   DRI Public

                                           (   )                 * **  AP-42 Public

                                  (            )                       WSU Public

                                                         (   )         ISWS Public


                            PM-10 Emission Factor (lb/vmt)
               0.05   0.1    0.2      0.5     1      2        5     10     20


                                           (        )                   All Industrial

                                           (   )                 * **   All non-ISWS Public

                                                         (   )          ISWS Public
AP-42   Equation 1 data base
UCD     Univ. of California – Davis
DRI     Desert Research Institute
WSU     Washington State Univ.
ISWS    Illinois State Water Survey
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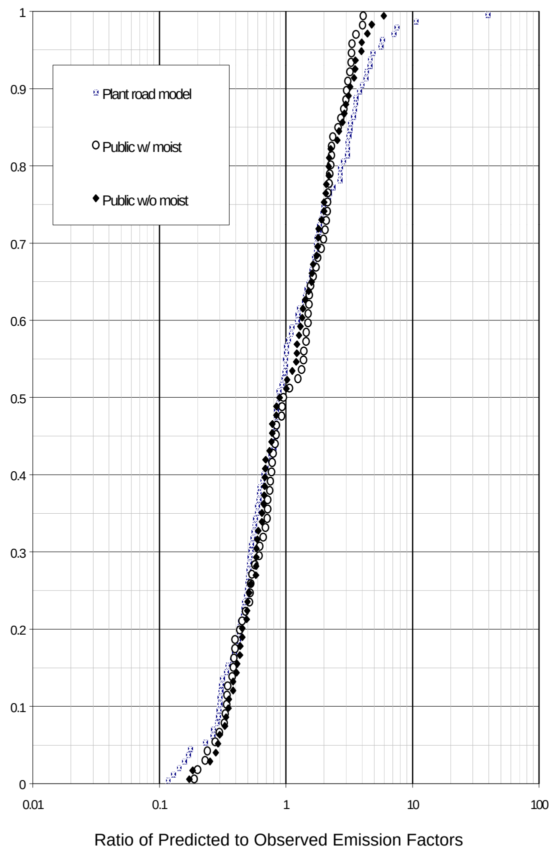
Figure 2. Cumulative Frequency Distribution for Predicted-to-Observed



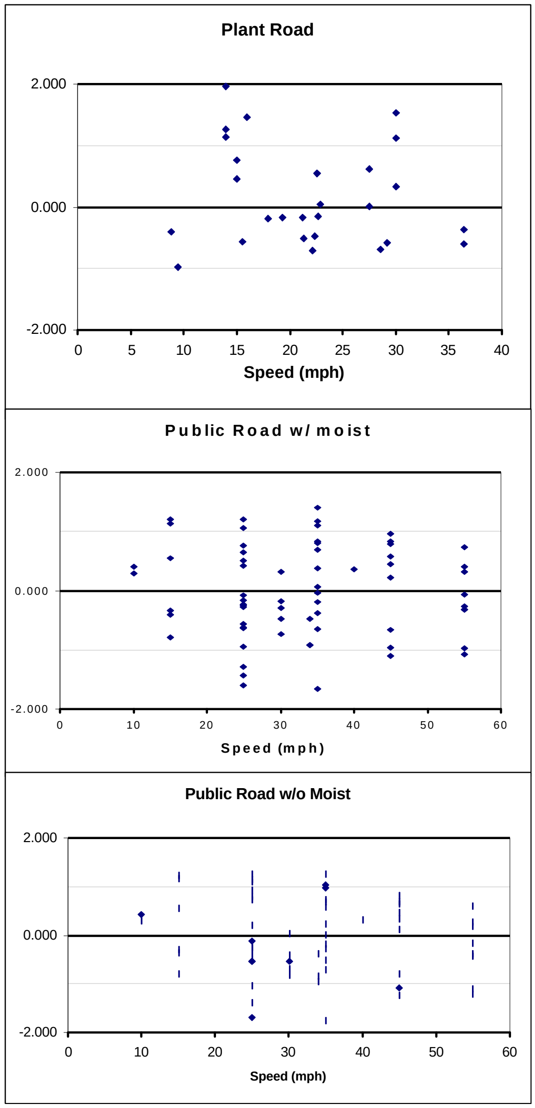


Figure 3. Residuals versus mean vehicle speed.

Keywords

Unpaved road
PM-10
PM-2.5
Fugitive dust
Emission factor