Midwest Research Institute

Paved Road Modifications to AP-42

Background Documentation

For
Corn Refiners Association, Inc.

MRI Project No. 310842

July 18, 2008

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For
Corn Refiners Association, Inc.
1701 Pennsylvania Avenue, NW
Suite 950
Washington, DC 20006

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Preface

This report presents the results from a re-examination of tests of particulate emissions from paved roads. It provides background information for a proposed revision to the paved road section of the Environmental Protection Agency's *Compilation of Air Pollutant Emission Factors* (commonly referred to as "AP-42"). The work was sponsored by the Corn Refiners Association, Inc. with Mr. Steve Lomax as project manager. Dr. Gregory E. Muleski served as MRI's project leader and authored this report.

MIDWEST RESEARCH INSTITUTE

Gregory E. Muleski
Principal Environmental Engineer

Approved:

Gil Radolovich
Director
Special Programs Division

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Section 1. Introduction

This report provides background information for a proposed revision to the paved road section of the Environmental Protection Agency's *Compilation of Air Pollutant Emission Factors* [1], commonly referred to as "AP-42." This EPA handbook contains factors used to estimate the quantity of an atmospheric pollutant released as a result of a specific activity. Section 13.2.1 of AP-42 is entitled "Paved Roads."

Particulate emissions occur whenever vehicles travel over a paved surface, such as public and industrial roads and parking lots. These emissions may originate from material previously deposited on the travel surface, or resuspension of material from tires and undercarriages. In general, open emissions arise primarily from the loose surface material loading (measured as mass of material per unit area). Surface loading is in turn replenished by other sources (e.g., pavement wear, deposition of material from vehicles, deposition from other nearby sources, carryout from surrounding unpaved areas, and litter). Because of the importance of the surface loading, available control techniques either attempt to prevent material from being deposited on the surface or attempt to remove (from the travel lanes) any material that has been deposited.

Note that throughout this document the term "PM-x" refers to airborne particulate matter (PM) with an aerodynamic diameter equal to or less than x microns. PM-10 and PM-2.5 are of the greatest regulatory interest, although PM-30 is often used as a surrogate for total suspended particulate (TSP) which was the basis for former National Ambient Air Quality Standards. Also note that paved road emission factors are expressed in units such as grams per vehicle kilometer traveled (g/VKT), grams per vehicle mile traveled (g/VMT), and pounds per vehicle mile traveled (lb/VMT).

1.1 Background

Section 13.2.1 ("Paved Roads") contains the current paved road emission factor predictive equation:

$$E = k\,(sL/2)^{0.65}\,(W/3)^{1.5} - C \qquad \textbf{(1)}$$

where:

E	=	particulate emission factor (having the same units as "k")
K	=	particle size multiplier for particle size range and units of interest (see below)
sL	=	road surface silt loading (grams per square meter) (g/m^2)
W	=	average weight (tons) of the vehicles traveling the road

C = emission factor for 1980's vehicle fleet exhaust, brake wear, and tire wear

The road surface silt loading ("sL") represents the mass of material less than 200 mesh (74 microns in physical diameter) per unit area of the paved travel surface. The "k" and "C" factors are shown below:

Size range[a]	Particle size multiplier, k [b]			C, Emission factor for exhaust, brake wear, and tire wear [b]		
	g/VKT	g/VMT	lb/VMT	g/VKT	g/VMT	lb/VMT
PM-2.5	0.66	1.1	0.0024	0.1617	0.1005	0.00036
PM-10	2.6	7.3	0.016	0.2119	0.1317	0.00047
PM-15	5.5	9.0	0.020	0.2119	0.1317	0.00047
PM-30 [c]	24	38	0.082	0.2119	0.1317	0.00047

[a] Refers to airborne particulate matter (PM-x) with an aerodynamic diameter equal to or less than x microns.
[b] Units shown are grams per vehicle kilometer traveled (g/VKT), grams per vehicle mile traveled (g/VMT), and pounds per vehicle mile traveled (lb/VMT).
[c] PM-30 is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for total suspended particulate (TSP).

Equation 1 is based on a regression analysis of emission tests of public paved roads as well as controlled and uncontrolled industrial paved roads. Section 13.2.1 remarks that tests were of "freely flowing vehicles traveling at constant speed on relatively level roads" and that "[n]o tests of 'stop-and-go' traffic or vehicles under load were available for inclusion in the database."

The "C" term was added to the base emission factor in 2003 to avoid "double counting" of brake/tire wear and exhaust [2]. The development of the base emission factor (i.e., all but the C term in Equation 1) was described in the 1993 background document [3]. Before 1993, AP-42 contained two sections "Urban Paved Roads" and "Industrial Paved Roads." In the "urban" section, the PM-10 emission factor varied with sL raised to the 0.8 power. The "industrial" section contained two PM-10 factors: one which depended on sL raised to the 0.3 power and a second constant value for light-duty vehicles ($W < 4$ tons) traveling over heavily loaded ($sL > 15$ g/m^2) paved roads. The 1993 document included a figure similar to Figure 1 which shows the AP-42 PM-10 database and the three different PM-10 factors.

Thus, the emission factor depends on silt loading, but that dependence changes over the range of sL. In essence, as silt loading increases, it has a diminishing effect on emissions. At some point, the surface silt loading may become so high that emissions level remains constant.

For a clean (urban) road, the 0.8 power indicates that sL has a nearly linear effect on emissions. In other words, if sL doubles, then the emission factor nearly doubles. However, as sL continues to increase, the dependency becomes much less than linear. For an industrial road with higher silt loading, emissions vary with the 0.3 power. In that case, if sL doubles, then emissions would increase by only 20%. Finally, the single-valued factor indicated by the horizontal line in Figure 1 suggests that a road could become so heavily loaded that emissions remain constant.

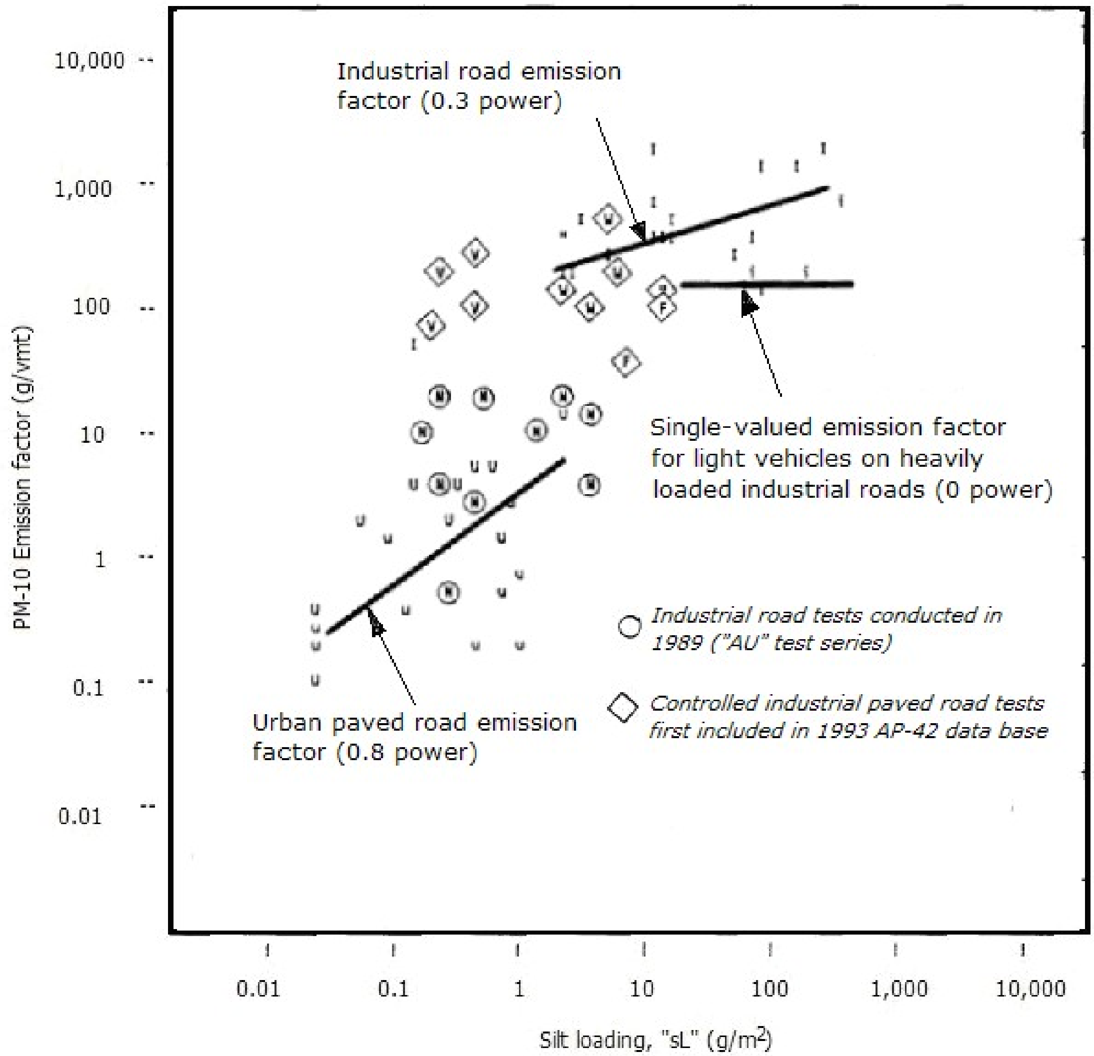

Figure 1. Figure Based on Figure 4-1 of the 1993 Background Document

The background document also discussed practical issues raised by AP-42 users prior to 1993:

- **AP-42 users noted difficulty in selecting the appropriate emission factor model.** Because of control programs undertaken during the 1980s, silt loadings measured at industrial facilities were often substantially lower than those in the "industrial" database. Users had reported numerous instances when, because the emission factor was used outside the range of applicability, estimated PM-10 emission factors were greater than those for TSP.

- **Furthermore, many users were interested in temporary increases in public road silt loadings.** Similarly, the urban road factor was being applied outside its range of applicability. Problems occurred when the equilibrium between deposition and removal processes was upset. The upset situation could occur for various reasons, including (a) application of abrasives as snow and ice controls, (b) mud/dirt trackout from construction activities in the area, and (c) wind and/or water erosion from surrounding unstabilized roadside areas.
- **In summary, the distinction between "urban" and "industrial" paved roads had become blurred**. The 1993 document described a gradual realization that emission levels did not depend on ownership as much as surface silt loading and traffic characteristics.

The 1993 AP-42 revision attempted to correct as many of the shortcomings as possible by assembling the database without regard to the labels of "urban/industrial" or "controlled/uncontrolled." Figure 1 shows the database, with the origin of each data point indicated by a key letter:

I	Data point used to develop the industrial paved road equation
i	Data point used in developing the single-valued factor for light-duty vehicles on heavily loaded roads
U	Data point used to develop the urban paved road emission factor equation
u	Data point excluded during development of the urban paved road
V, W, F	Controlled industrial paved road emission test, omitted during development of the industrial paved road equation (corresponding to vacuum swept, water flushed, or flushed/broom swept, respectively)
N	New (in 1993) test data

The 1993 background document remarked that new data (shown in diamonds or circles in Figure 1) functioned like "glue" to combine the old industrial and urban data sets.

1.2 Newer Emission Tests

Between 2001 and 2003, member companies of the Corn Refiners Association (CRA) carried out four PM-10 paved road emission testing programs. Testing was motivated by recognition that Equation 1 was being applied to situations far outside the limits of the AP-42 database. For example, the AP-42 emission factor applies to "freely flowing traffic moving at fairly constant speeds." Traffic into and out of the CRA member company plants often required frequent starts and stops. Plants also had speed limits well below what was typical in the database. Finally, the corn haul roads had far lower sL values than the industrial roads in the AP-42 database.

Figure 2 adds the CRA-member company tests to Figure 1. Just as new data in 1993 provided the "glue" between the old urban and industrial road data sets, the CRA data serve much the same purpose. In other words, the CRA tests could be used to extend the range of AP-42's applicability to different source conditions (i.e., heavy vehicles traveling slowly over lightly loaded surfaces).

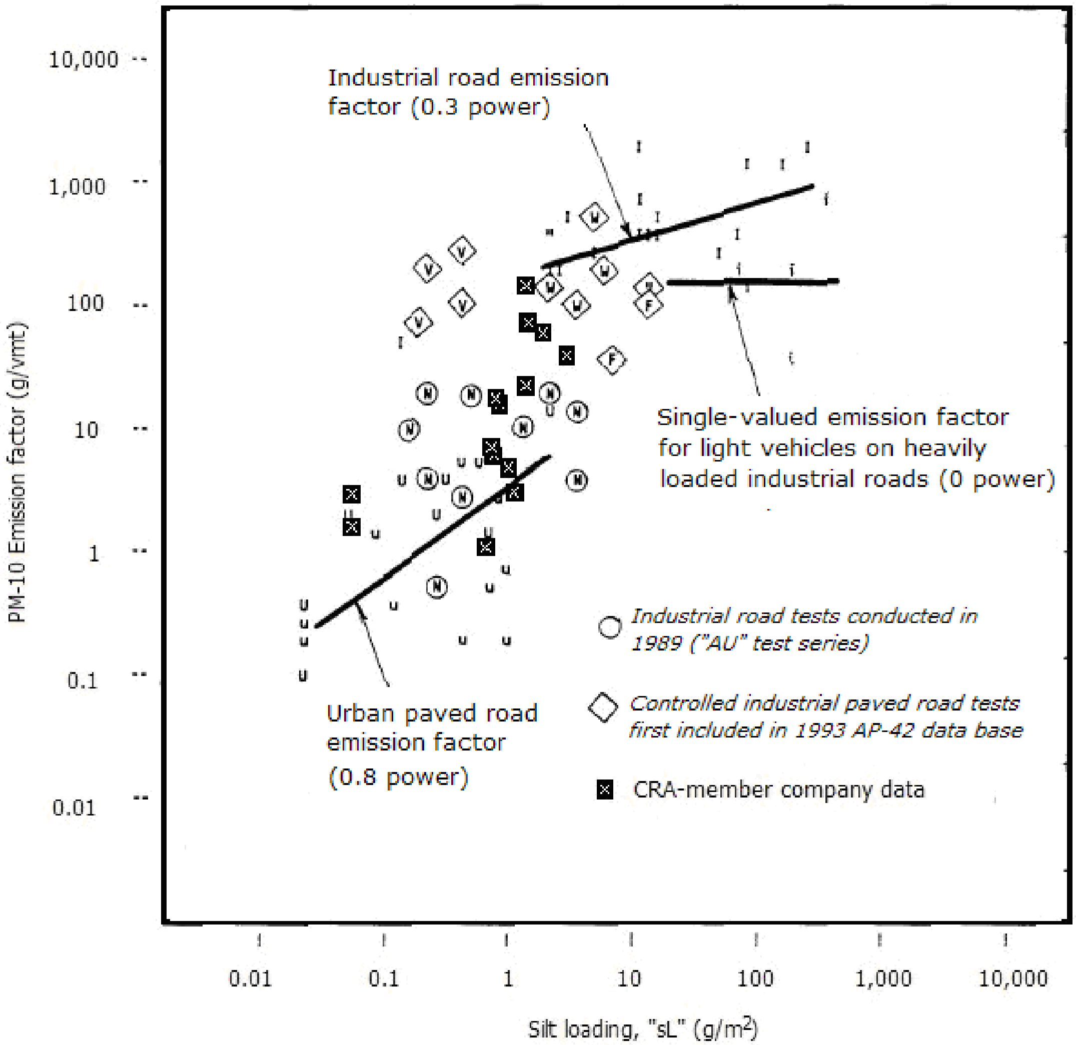

Figure 2. CRA Member Company Data Added to AP-42 Database

In February 2008, CRA and EPA representatives met in Research Triangle Park, NC to discuss how to incorporate the newer data into AP-42. During the meeting, the parties discussed how the CRA data could be incorporated into AP-42. In particular, the participants discussed the merits of the three following approaches:

1. Regression of the CRA data to produce a separate predictive emission factor equation for slowly moving vehicles on lightly loaded paved roads.
2. Simple averaging of the CRA data to produce a single-valued emission factor for heavy vehicles on clean roads (i.e., the opposite condition considered in the single-valued factor that existed prior to the 1993 AP-42 update).
3. Re-regression of an expanded AP-42 database to extend the factor's applicability to slower speeds and stop-and-go situations.

The parties agreed that the CRA data shared basic similarity with the existing AP-42 data base. Furthermore, the inclusion of the CRA tests would extend the applicability of an emission factor equation based on the expanded data set. First, inclusion of the CRA tests would reduce the lowest travel speeds in the AP-42 database to about 5 mph from 10 mph. Inclusion would also extend the applicability of the resulting equation to stop-and-go traffic which the present version of AP-42 expressly excludes. Furthermore, even though the ranges for sL and vehicle weight for the CRA tests lie within the ranges in the current database (0.03 to 400 g/m^2 and 2 to 42 tons), the expanded data set would better "cover" possible combinations of source conditions. The parties decided to prepare background documentation for stepwise multiple linear regression of the expanded database using the same procedures as in 1993.

This report uses the 1993 document as a template and is structured as follows. Following this introduction, Section 2 first reviews specific tests to assemble a final database; thereafter, Section 2 develops and validates a revised emission factor equation. (Note that the development and validation processes mirror those described in the 1993 background document.) Section 3 describes the proposed revisions to AP-42 Section 13.2.1, while Section 4 presents the references.

Note that large sections of the 1993 background document are unaffected in this process. In particular, the reader is referred to Section 3 ("General Data Review and Analysis") of the 1993 report background document for a discussion of emission data/factor rating schemes and a general description of emission measurement techniques.

Section 2.
AP-42 Section Development

2.1 Revisions to Section Narrative

The draft AP-42 presented later in this background document is intended to update and expand the applicability of Section 13.2.1, “Paved Roads.” The update follows the same procedures used in 1993 to develop and validate the basic form of Equation 1.

2.2 Pollutant Emission Factor Development

The following general approach was taken:

1. Use new test data for paved roads to supplement the current AP-42 database to extend the range of source conditions (e.g., heavy trucks traveling slowly over lightly loaded road surfaces).
2. Conduct stepwise multiple linear regression analysis of the revised data base to develop an emission factor model using the following as potential correction parameters:
    a. silt loading
    b. mean vehicle weight
    c. mean travel speeds
3. Conduct an appropriate validation of the reformulated model.

2.2.1 Review of Specific Data Sets

CRA member companies carried out four paved road PM-10 test programs (Table 1) because site conditions did not match source conditions underlying the AP-42 emission factor equation. The sites enforce speed limits of 5 or 15 mph. In addition, plants experience traffic queues (i.e., stop-and-go traffic) during periods with high corn receipts. The combination of heavy trucks (delivering corn to the facilities) and fairly low silt loading (sL) values on the plant roads was not typical of the AP-42 database. Given these differences, the member companies undertook testing to develop more representative emission factors.

All four testing programs employed the same exposure profiling method used to develop the test data underlying Equation 1.[1] In each program, a test plan was submitted

[1] See Section 3 of the 1993 background document for a thorough discussion of open dust source measurement techniques.

to the state agency for comment and review prior to the start of testing. The final test reports and supporting information were also submitted to state agencies.

Table 1. Test Reports Reviewed

Test Report 1	Midwest Research Institute, "Emission Tests of Paved Road Traffic at Minnesota Corn Processors Marshall, Minnesota Facility," report prepared for McVehil-Monnett Associates, Project No. 310212.1.001. July 6, 2001.
Test Report 2	Midwest Research Institute, "Emission Tests of Paved Road Traffic at Minnesota Corn Processors Columbus, Nebraska Facility," report prepared for McVehil-Monnett Associates, Project No. 310212.1.002. July 13, 2001.
Test Report 3	Midwest Research Institute, "Emission Tests of Paved Road Traffic at Cargill Sweeteners North America Blair, Nebraska Facility," report prepared for McVehil-Monnett Associates, Project No. 310395.1.001. November 27, 2002.
Test Report 4	Midwest Research Institute, "Emission Tests of Paved Road Traffic at ADM's Marshall, Minnesota Facility," report prepared for McVehil-Monnett Associates, Project No. 310479.1.001. December 5, 2003.

Because low emission levels were expected (due to low sL and slow speeds), several precautions were taken to assure reliable quantification. First, long sampling durations were employed. Samplers were operated up to 5 hours to collect adequate sample mass.[2] Second, to ensure adequate traffic during test periods, the facilities provided "drone" passes by corn semi-trailers. Drone traffic mimicked the actual traffic except those trucks returned to staging areas without emptying corn. In addition, testing applied "lessons learned" throughout the programs. For example, when it became apparent how difficult it could be to separate net PM-10 concentrations (i.e., due to traffic on the road) from background (upwind) concentrations, changes were made in equipment deployment. The use of identical upwind and downwind vertical sampling arrays permitted better definition of the net contribution of roadway emissions. In the tables that follow, those test results from simultaneous upwind and downwind exposure profiling are shown in **bold.**

In addition to PM-10 concentrations, each sampling program samples included the following:

- Average wind speeds at two heights and wind direction at one height for 5-minute intervals throughout the test period.
- Traffic counts by vehicle type were recorded manually. The host facilities provided information on vehicle weights and corn receipts.
- Vacuums with disposable paper bags were used to collect the loose material from the road surface. The material collected within the bag was sieved to determine the surface silt loading. Sampling and analysis procedures followed those given in Appendices C.1 and C.2 of AP-42.

Individual tests reports are discussed below.

[2] Minimally detectable PM-10 concentrations ranged from 5.7 to 14 $\mu g/m^3$.

Test Report 1. Truck traffic flow at the Minnesota Corn Processor's (MCP's) Marshall, Minnesota facility is characterized as either slowly moving (5 mph enforced speed limit) or stop-and-go in nature. In this testing program, data was collected over 5 days during April of 2001. During this period, three stop-and-go traffic situations and six slowly moving traffic instances were examined. Truck traffic progressing through the test site was held to two lanes for queued traffic. Silt content (sL, measured by MCP), truck weight, and number of passes, along with other pertinent data was recorded for each run. For all runs, a vertical network of samplers was operated downwind. The last test period used a vertical array of samplers upwind to better characterize upwind concentrations and to provide a more accurate calculation of the net PM-10 emission factor.

The results of this testing program are summarized in Table 2. The test report remarked that the emission factors obtained were far below the value (0.453 lb/VMT) used in the plant emission inventory. Use of test-specific silt loading and vehicle weight did not significantly improve the predictive accuracy of the AP-42 factor. The tests found no discernable relationship between emission levels and either silt loading or vehicle weight. Finally, the shape of the exposure profile was more likely due to diesel exhaust than re-entrained road dust.

Table 2. Summary of Emissions Data from MCP's Marshall, Minnesota Facility (Test Report 1)

Run	Test condition	Traffic rate (veh/hr)	Traffic speed (mph)[a]	Mean vehicle weight, W (tons)	Surface silt loading, sL (g/m^2)	Measured PM-10 emission factor (lb/VMT)	AP-42 predicted PM-10 emission factor (lb/VMT)
CE-1	Stop-and-go	38	NA	36	1.16	0.059	0.47
CE-2	Stop-and-go	32	NA	36	0.86	0.14	0.38
CE-11	Slowly moving	35	5	12	1.34	0.34	0.10
CE-3	Stop-and-go	47	NA	39	0.86	0.10	0.43
CE-13	Slowly moving	48	5	13	1.34	0.051	0.11
CE-15	Slowly moving	30	5	40	1.91	0.14	0.76
CE-16	Slowly moving	28	5	40	1.41	0.17	0.62
CE-17	Slowly moving	29	5	40	2.93	0.091	1.0
CE-19	**Slowly moving**	**61**	**5**	**38**	**0.76**	**0.041**	**0.39**

[a] Vehicle speed was maintained at the plant limit of 5 mph. NA = Not applicable.
Bold entries indicate that identical vertical sampling arrays were used to better isolate the source contribution.

Test Report 2. Similar to the Marshall site, truck traffic flow at MCP's Columbus, Nebraska facility is also either slowly moving (5 mph enforced speed limit) or stop-and-go in nature. Between June 12 and 15, 2001, four tests each of stop-and-go and slowly moving traffic were performed. Trucks entered by the north gate and traveled past a vertical sampling array en route to a staggered queue at which a second vertical sampling array was positioned. In this way, testing evaluated both source conditions (stop-and-go and slowing moving) at once. Building on experience from the Marshall facility, the last two runs, CF-4 and CF-5, used identical upwind and downwind vertical sampling arrays to better characterize background concentrations. In that case, only one condition could be evaluated during a test.

The results are summarized in Table 3. All measured emission factors are far below AP-42 equation estimates. On average, the measured emission factors were eight times lower than the value applied in the plant's emission inventory.

Table 3. Summary of Emissions Data from MCP's Columbus, Nebraska Facility (Test Report 2)

Run[a]	Test condition	Traffic rate (veh/hr)	Traffic speed (mph)[b]	Mean vehicle weight, W (tons)	Surface silt loading, sL (g/m^2)	Measured PM-10 emission factor (lb/VMT)	AP-42 Predicted PM-10 emission factor (lb/VMT)
CF-1/N	Low Speed	47	5.0	40	0.97	0.011	0.49
CF-1/S	Stop-and-go	47	NA	40	0.97	0.043	0.49
CF-2/N	Slowly moving	66	5.3	41	0.81	0.036	0.44
CF-2/S	Stop-and-go	66	NA	41	0.81	0.14	0.44
CF-3/N	Slowly moving	54	5.1	41	0.63	0.0024	0.38
CF-3/S	Stop-and-go	54	NA	41	0.63	0.051	0.38
CF-4/N	**Slowly moving**	**86**	**4.7**	**41**	**1.1**	**0.0068**	**0.53**
CF-5/N	**Stop-and-go**	**52**	**NA**	**41**	**1.4**	**0.036**	**0.64**

[a] Suffix indicates whether tests was conducted on the North or South portion of the corn haul road. Trucks were held in a queue toward the south; trucks entering the north gate traveled passed the north sampling array to reach the queue.
[b] Speed of moving trucks determined by accumulating time required to travel a measured distance. NA = not applicable.
Bold entries indicate that identical vertical sampling arrays were used to better isolate the source contribution.

Test Report 3. This report describes a testing program conducted at Cargill's Blair, Nebraska facility during August 2002. The plant used a regular sweeping program to reduce surface loadings on paved roads. Testing relied on regular corn truck traffic at the site, although the plant provided a limited amount of "drone" traffic.

Eight PM-10 emission tests were attempted. The test report describes difficulty encountered in isolating net PM-10 mass due to traffic on the test road. During test plan review, the Nebraska Department of Environmental Quality requested a change in test site to allow two trucks to pass by at the same time. The original site would have permitted upwind monitoring in the immediate vicinity of the tests road, but this was not possible at the second location. Furthermore, steeply sloping ground on the upwind side of the test road prevented use of a vertical background sampling array (as used at the two MCP plants) to better isolate the source contribution.

The results are summarized in Table 4. Only two tests (CI-7 and CI-8) had net mass attributed to the source. In the remaining instances, the measured downwind PM-10 concentrations were lower than upwind values. Again, this is believed to be an undesired result from moving the test source. Runs CI-7 and CI-8 showed the measured emission factor to be much lower than that predicted by the AP-42 equation. Exposure profiles showed a maximum more likely due to diesel exhaust than from re-entrained surface road dust.

Table 4. Summary of Emissions Data from Cargill's Blair, Nebraska Facility (Test Report 3)

Run	Test condition	Traffic rate (veh/hr)	Traffic speed (mph) [a]	Mean vehicle weight, W (tons)	Surface silt loading, sL (g/m^2) [b]	Measured PM-10 emission factor (lb/VMT) [c]	AP-42 predicted PM-10 emission factor (lb/VMT)
CI-1	Low Speed	45	13.4 / 16.8	26	0.06	–	0.042
CI-2	Low Speed	45	12.8 / 16.9	26	0.06	–	0.042
CI-3	Slowly moving	60[d]	13.6 / 12.7	27	0.06	–	0.044
CI-4	Low Speed	60[d]	13.5 / 15.5	27	0.06	–	0.044
CI-7	Slowly moving	47	15.2 / 16.2	27	0.05	0.0036	0.039
CI-8	Low Speed	47	13.6 / 16.1	27	0.05	0.0066	0.039
CI-11	Low Speed	56	13.5 / 12.7	27	0.025	–	0.025
CI-12	Low Speed	56		27	0.25	–	0.11

[a] Vehicle speed for inbound (loaded) /outbound (empty) trucks determined by accumulating time required to travel a measured distance.
[b] Surface silt loading sample information provided by Cargill.
[c] "-" indicates that no net mass was attributed to the test road traffic.
[d] Twenty of 238 total passes were by "drone" trucks.

Test Report 4. This program represented a continuation of the testing begun in Test Report 1. By September 2003, the Marshall facility had implemented a road-sweeping program. Three tests of PM-10 emissions were conducted, one from stop-and-go traffic and two from slowly moving traffic. Because of experience gained from the April 2001 tests, identical vertical networks of samplers were operated downwind and upwind during each test.

The results of this testing program are summarized in Table 5. Measured emission factors were all significantly lower than that predicted by the AP-42 equation. The test report also remarked that the measured emission rates were independent of traffic rate, while the AP-42 factor implies a linear dependency between the emission and traffic rates.

Table 5. Summary of Emissions Data from ADM's Marshall, Minnesota Facility (Test Report 4)

Run	Test Condition	Traffic rate (veh/hr)	Traffic speed (mph)[a]	Mean vehicle weight, W (tons)	Surface silt loading, sL (g/m^2)	Measured PM-10 emission factor (lb/VMT)	AP-42 predicted PM-10 emission factor (lb/VMT)
CM-1	**Slowly moving**	**154**	**NA**	**40**	**0.72**	**0.014**	**0.40**
CM-2	**Stop-and-go**	**42**	**NA**	**40**	**0.72**	**0.14**	**0.40**
CM-4	**Slowly moving**	**156**	**5**	**40**	**0.70**	**0.016**	**0.39**

[a] Vehicles speeds maintained at plant limit of 5 mph. NA = not applicable.
Bold entries indicate that identical vertical sampling arrays were used to better isolate the source contribution.

Summary of the CRA Member Company Test Data. The four test programs produced 14 and 8 PM-10 emission factor values for slowly moving and stop-and-go traffic, respectively. In all but one of the 22 cases, the AP-42 emission factor overestimated the measured value.

For the simultaneous "slowly moving" and "stop-and-go" tests (CF-1, -2, and -3 in Table 3), the "stop-and-go" value was substantially greater than the "slowly moving" factor[3] (presumably because of the diesel exhaust as trucks moved from a dead stop). However, there is no significant difference between "slowly moving" and "stop-and-go" results on average.

Furthermore, Tables 2, 3, and 5 used bold font to indicate those tests that used identical upwind and downwind vertical sampling arrays. Those tests provided better definition of net PM-10 mass thus producing more accurate emission factors. Although these test results tended to be lower than the other emission factors, the two sets on average did not differ significantly.

In summary, the CRA data provide emission measurements for combinations of source conditions (heavy vehicles traveling slowly over fairly clean roads) outside those currently in the AP-42 database. Because no significant differences were found between different groupings of CRA results, all 22 tests were used to expand the AP-42's "coverage" of source conditions.

2.2.2 Compilation of Final Data Base

Results from Test Reports 1 through 4 supplemented the existing AP-42 database (i.e., the emission tests used to develop Equation 1). Earlier, in Section 1, Figure 2 showed one view of how the new data compare to the current database. That plot (of emission factor versus silt loading) emphasized that the two data sets are comparable. Figure 3, on the other hand, plots all six pairwise combinations[4] of emission factor, silt loading, average vehicle weight, and average vehicle speed. (In other words, the six plots consider each possible pairing of two different variables.) The pairwise plots emphasize the differences in source conditions; the CRA-member company data clearly reflect heavier (than average) vehicles moving slower (than average) over cleaner (than average) paved road surfaces. The CRA results provide the "tests of 'stop-and-go' traffic or vehicles under load" mentioned on AP-42 page 13.2.1-5.

[3] This is also the case for the tests CM-1 and CM-2 in Table 5. The first was conducted during the morning and the second during the afternoon of the same day.

[4] In other words, the six plots consider each possible pairing of two different variables:

- Silt loading versus emission factor
- Silt loading versus weight
- Silt loading versus speed
- Speed versus emission factor
- Speed versus weight
- Weight versus emission factor

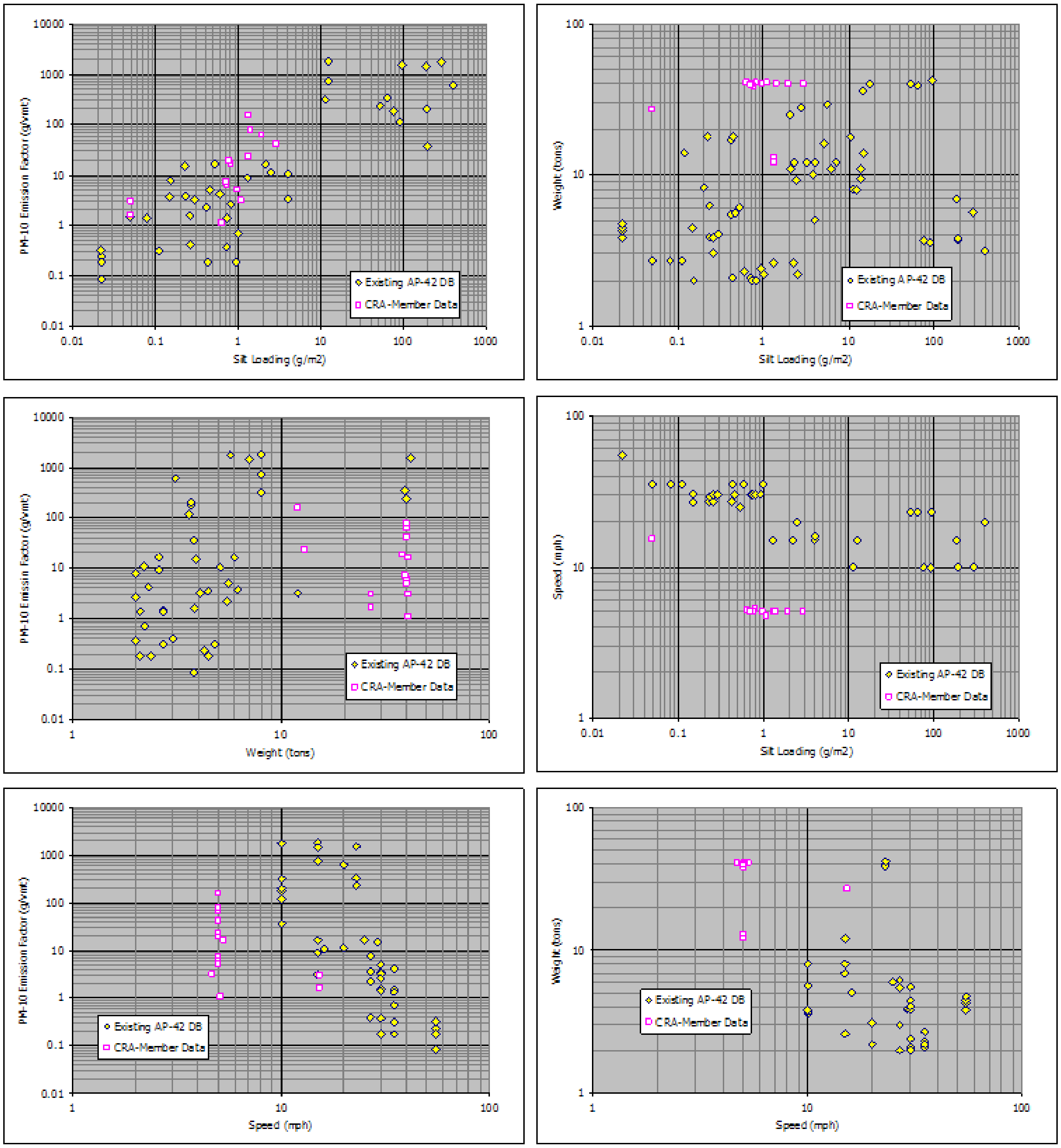

Figure 3. Pairwise Combinations Within the Expanded Database

2.2.3 PM-10 Emission Factor Development

Stepwise multiple linear regression [4] was used to develop a PM-10 predictive model. The potential correction factors included:[5]

[5] The 1993 update also considered "number of wheels, w" as a potential correction factor. However, those data were only available for about 20% of the tests. Furthermore, in those tests, "w" was highly correlated with mean vehicle weight ("W") and could not have provided any additional predictive accuracy. For those reasons, the number of wheels was excluded from consideration during this update.

- silt loading, sL
- mean vehicle weight, W
- mean vehicle speed, S

All variables were log-transformed in order to obtain a multiplicative model as in the past. The final data set is included as Appendix A to this report. Several points should be noted:

- Because 22 of the original AP-42 tests did not include a speed value, this feature carried over into the expanded database. See the discussion in connection with Table 6 below.
- Stop-and-go tests were associated with nominal speed of 1 mph so that the log-transformation was possible.
- An attempt was made to "back out" the exhaust portion (estimated to be roughly 0.5 g/VMT [0.001 lb/VMT]) from the CRA emission factors. However, because the test reports did not contain the traffic information[6] necessary to characterize vehicle types, the conservative decision was made to not subtract any exhaust component from the CRA emission factors.

Table 6 presents the correlations between the log-transformed independent and dependent variables

Table 6. Correlation Matrix for the Expanded PM-10 Data Base

Listwise[a]					Pairwise[b]				
	PM-10 EF	Weight	Speed	sL		PM-10 EF	Weight	Speed	sL
PM-10 EF	1	0.362	–0.418	0.803	PM-10 EF	1	0.423	–0.418	0.737
Weight	0.362	1	–0.747	0.083	Weight	0.423	1	–0.747	0.120
Speed	–0.418	–0.747	1	–0.190	Speed	–0.418	–0.747	1	–0.190
sL	0.803	0.083	–0.190	1	sL	0.737	0.120	–0.190	1

EF = emission factor, sL = silt loading.
[a] "Listwise" indicates that, if the speed value was missing for a specific test, the entire test was excluded in calculating the correlation coefficient. In other words, the correlations are for the 64 tests with complete data.
[b] "Pairwise" indicates that, if the speed value was missing for a specific test, then correlations are based on all possible pairings. In other words, the correlations not involving speed are based on 86 tests and those that involve speed are based on the 64 tests with complete data.

The left-hand correlation matrix is based on the 64 tests (42 in the old AP-42 data set and the 22 CRA member company tests) for which emission factor, speed, weight, and silt loading are all available. The right-hand matrix calculates correlations on a pairwise basis and so is based on all 86 tests.

Note the following about the correlation matrices:

- Silt loading and the emission factor are highly correlated.
- Silt loading and vehicle weight are essentially independent of one another.
- There is a strong inverse correlation between vehicle weight and speed.

[6] Most vehicles were 1990s-model year diesels. However, very old farm trucks ("smokers") were encountered.

- Unlike the case during 1993, silt loading and mean vehicle speed are not significantly correlated.[7]

Taken together, these observations indicate that (a) silt loading and vehicle weight may be used as independent variables and that (b) inclusion of speed would add very little to the predictive capability of a model. In stepwise multiple linear regression of the (log-transformed) data set, silt loading entered on the first step and vehicle weight on the second. The resulting model output is shown below:

```
DEP VAR:   LGVMT      N:      86   MULTIPLE R:  .811  SQUARED MULTIPLE R:  .657
ADJUSTED SQUARED MULTIPLE R:  .649     STANDARD ERROR OF ESTIMATE:        1.489

VARIABLE    COEFFICIENT    STD ERROR     STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT       0.897        0.390        0.000      .        2.299    0.024
sL             0.769        0.071        0.697     0.985   10.758    0.000
Weight         0.803        0.153        0.339     0.985    5.241    0.000

ANALYSIS OF VARIANCE
SOURCE    SUM-OF-SQUARES    DF  MEAN-SQUARE     F-RATIO       P
REGRESSION      352.684     2      176.342      79.548       0.000
RESIDUAL        183.994    83        2.217
```

This leads to a PM-10 emission factor of the form

$$E = 2.45\ (sL)^{0.77}\ (W)^{0.80} \qquad \textbf{(2)}$$

where E is emission factor in g/vehicle-mile traveled (g/VMT), sL is silt loading in g/m^2, and W is mean vehicle weight in tons. Inclusion of the "stop-and-go" tests had a negligible effect on the emission factor.[8] Plots of the residuals (i.e., the error between individual predicted and measured observed emission factors) versus individual PM-10 emission factor, silt loading, mean vehicle weight, and mean vehicle speed are presented in Figures 4 through 7, respectively. The only significant relationship was observed in Figure 4 in which it is seen that Equation 2 tends to overpredict the lowest and underpredict the highest measured factors. In other words, the PM-10 emission factor equation has a systematic bias at the extremes of the parent database. This tendency is

[7] A correlation coefficient of –0.837 (significant at the 0.1% level) was found between silt loading and mean vehicle speed during the 1993 revision.

[8] Had the eight stop-and-go tests not been included, stepwise multiple linear regression would have produced the following output:

```
DEP VAR:   LGVMT      N:      78   MULTIPLE R:  .814  SQUARED MULTIPLE R:  .662
 ADJUSTED SQUARED MULTIPLE R:  .653     STANDARD ERROR OF ESTIMATE:        1.549

   VARIABLE    COEFFICIENT    STD ERROR     STD COEF TOLERANCE    T    P(2 TAIL)

 CONSTANT           0.850        0.420        0.000      .        2.025    0.046
       sL           0.766        0.075        0.694     0.972   10.194    0.000
   Weight           0.834        0.176        0.324     0.972    4.752    0.000

                              ANALYSIS OF VARIANCE

    SOURCE   SUM-OF-SQUARES    DF  MEAN-SQUARE     F-RATIO       P

  REGRESSION        352.660     2      176.330      73.451       0.000
    RESIDUAL        180.049    75        2.401
```

In this case, Equation 2 would have been only slightly different:

$$E = 2.34\ (sL)^{0.77}\ (W)^{0.83}$$

typical of any linear regression model. In the three other figures, residuals are scattered fairly evenly about the x-axis (i.e., residual = 0) over the range of the independent variable thus indicating no systematic bias.

SYSTAT INFLUENCE PLOT N = 86 R= .585

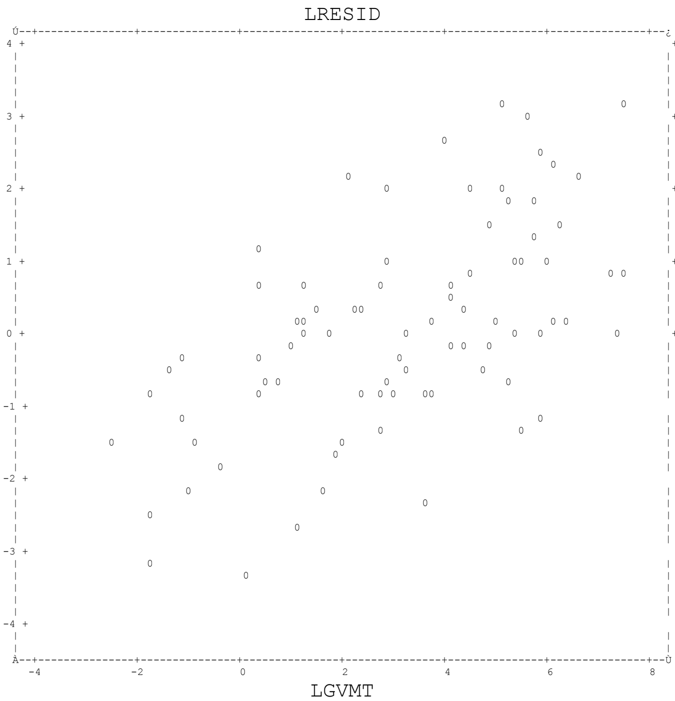

Figure 4. PM-10 Residuals (natural log) versus Measured Emission Factor (natural log)

SYSTAT INFLUENCE PLOT N = 86 R= -.001

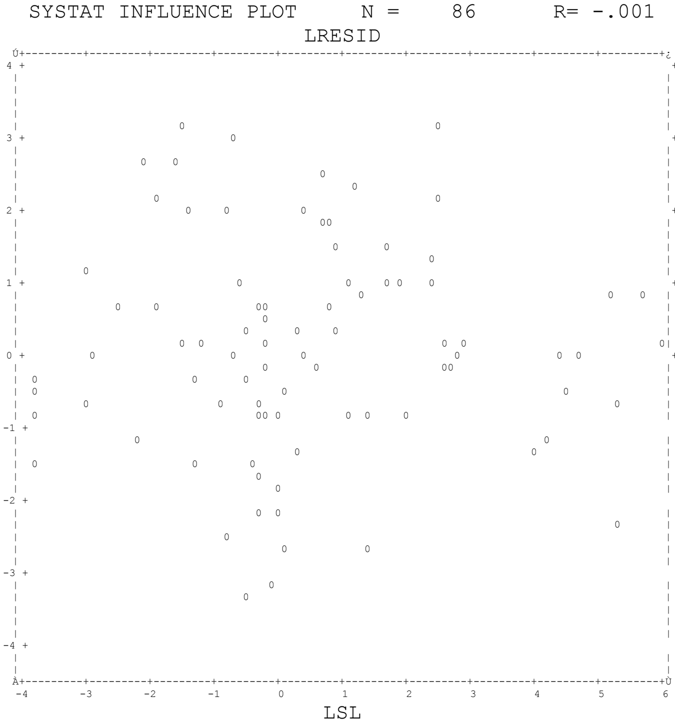

Figure 5. PM-10 Residuals (natural log) versus Silt Loading (natural log)

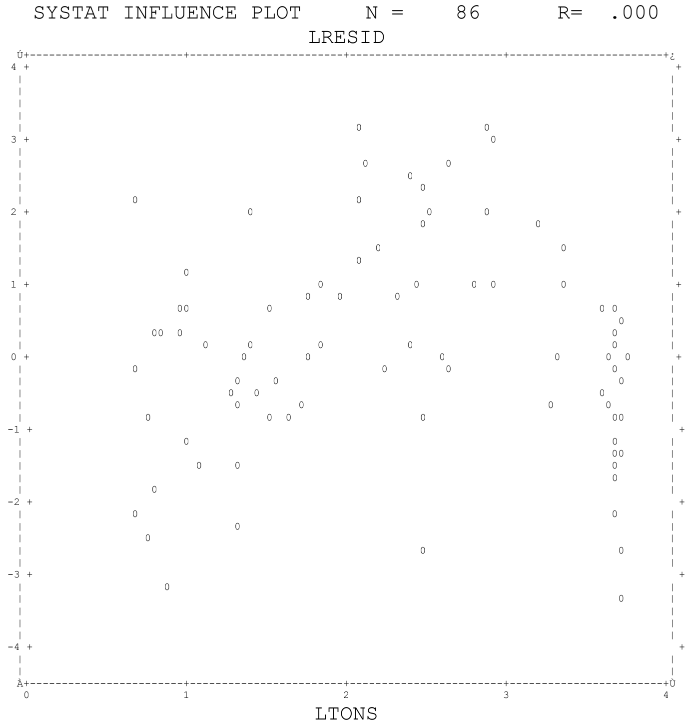

Figure 6. PM-10 Residuals (natural log) versus Mean Vehicle Weight (natural log)

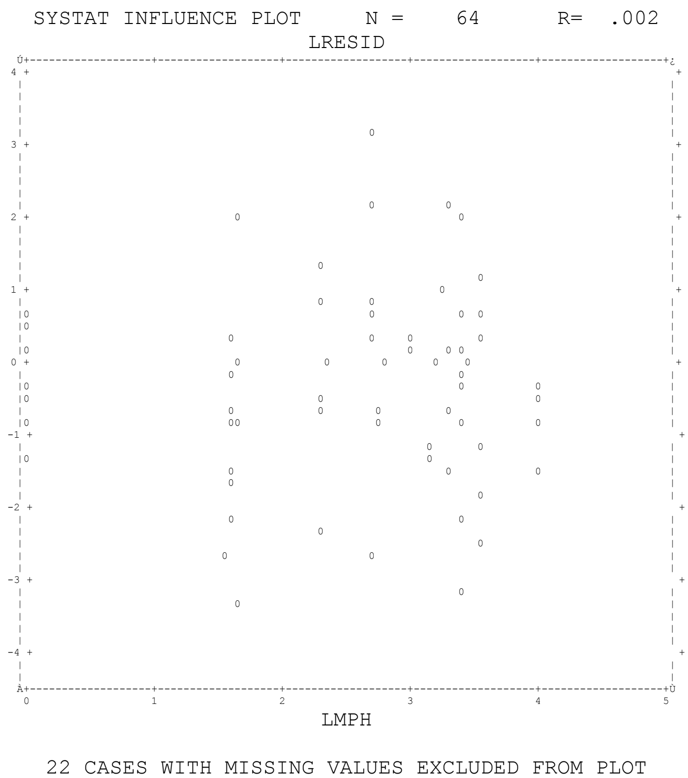

Figure 7. PM-10 Residuals (natural log) versus Mean Vehicle Speed (natural log)

2.2.4 Validation Studies

A cross-validation (CV) was undertaken to assess the predictive capability of the revised paved road emission model for PM-10. Using this technique [5], each point in the underlying database is excluded one at a time, and the equation generated from the reduced database is used to estimate the missing value.

By using a CV technique, "n" quasi-independent estimates are obtained from a database of "n" tests, and the overall validity of using stepwise regression to obtain a model of the form

$$E = k\,(sL)^a\,(W)^b$$

is evaluated. Summary information is shown in Table 7.

Table 7. Results of Cross-Validation Study

	Variable	Minimum	Maximum	Mean	Std. Deviation
a	Exponent of sL	0.754	0.799	0.769	0.0066
b	Exponent of W	0.752	0.857	0.803	0.017
k	Leading term (PM-10)	0.786	1.057	0.897	0.042
	Ratio of quasi-independent estimate to measured emission factor	Minimum	Maximum	Geo. Mean	Geo. Std. Deviation
	Original AP-42 data set (n=64)	**0.043**	**30**	**0.79**	**4.65**
	AP-42 with speed given (n=42)	0.050	26	1.36	4.26
	AP-42 with speed missing (n=22)	0.043	2.4	0.30	3.28
	CRA tests (n=22)	**0.143**	**35**	**2.03**	**3.47**
	CRA slowly moving tests (n=14)	0.146	31	2.71	4.10
	CRA stop-and-go tests (n=8)	0.56	4.1	1.22	2.08
	Overall (n=86)	**0.043**	**35**	**1.01**	**4.56**
	1993 Results [a] (n=64)	*0.050*	*30*	*1.00*	*4.23*

[a] The 1993 cross-validation study results are included in the last line for comparison purposes.

Figure 8 presents the cumulative frequency distribution of the ratio of the quasi-independent estimate to the measured emission factor. Approximately 60% of the estimates are within a factor of 3 and approximately 70% are within a factor of 5. By comparison, the 1993 revision found a little over half and 70% are within a factor of 3 and 5, respectively.

In summary, the emission factor developed from the expanded database appears to be very comparable in terms of predictive accuracy to the current AP-42 factor. However, Equation 2 encompasses a broader range of source conditions than does Equation 1 and so is recommended for inclusion in a revised AP-42 Section 13.2.1. Using the "normalization factors" of 2 g/m^2 and 3 tons for silt loading and mean vehicle weight,[9] the following emission is recommended in the next section:

$$E = 10.3\,(sL/2)^{0.8}\,(W/3)^{0.8} \qquad (3)$$

where E represents the PM-10 emission factor and sL and W are as defined before.

[9] These are the same normalization factors used in 1993. The constant term in Equation 3 is the result when sL =2g/m^2 and W = 3 tons are substituted in Equation 2. Normalization also involves rounding exponents to one decimal place.

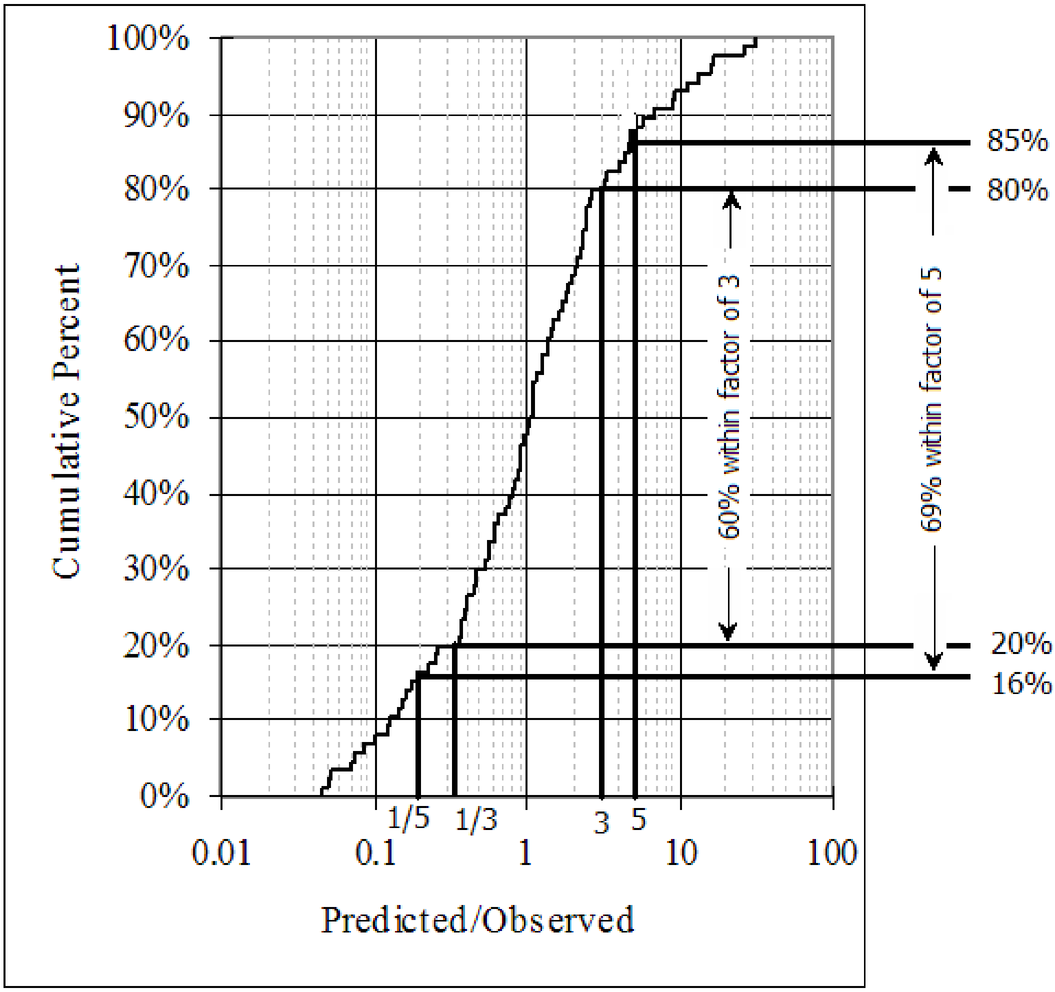

Figure 8. Cumulative Frequency Distribution From Cross-Validation Study

Section 3. Proposed Revisions to AP-42 Section

This section presents proposed revisions to AP-42 Section 13.2.1, "Paved Roads." The proposed revision has been submitted separately as a Word document (with changes tracked).

3.1 Changes to Section Narrative

Only minor changes are proposed to the narrative. The most significant change would involve the description on page 13.2.1-5 shown below with strikethroughs and **bold** indicting insertions:

> Equation 1 is based on a regression analysis of ~~numerous emission tests, including 65~~ **86** tests for PM-10.[10,**29**] Sources tested include public paved roads, as well as controlled and uncontrolled industrial paved roads. ~~All sources tested~~ **The majority of tests** were of freely flowing vehicles traveling at constant speed on relatively level roads. ~~No~~ **However, 8** tests of "stop-and-go" traffic or vehicles under load were available for inclusion in the data base.[**29**]

This change was made to indicate that some stop-and-go tests are included in the database underlying the emission factor developed and validated in the previous section.

A line entitled "Corn Wet Mills" has been added to Table 13.2.1-4 to incorporate the silt loading values from Test Reports 1 through 4.

Although no change been made in the proposed revision, it is recommended that EPA consider removing the column entitled "Total Loading" in Table 13.2.1-4. The entries refer to the "L" term in the old Section 11.2.6 "Industrial Paved Roads" TSP emission factor, which was removed during the 1993 revision.

3.2 Emission Factor Revisions

The base forms in AP-42 Section 13.2.1 Equations 1, 2, and 3 were revised to reflect the PM-10 emission factor developed and validated in the previous section. The change to Equation 1 is indicated below

$$E = k\ (sL/2)^{\cancel{0.65}\mathbf{0.8}} \times (W/3)^{\cancel{1.5}\mathbf{0.8}} - C$$

Similarly, the particle size multipliers in AP-42 Table 13.2.1-1.1 are changed as shown below:

Size range[a]	Particle size multiplier k[b]		
	g/VKT	g/VMT	lb/VMT
PM-2.5[c]	**0.93** ~~0.66~~	**1.6** ~~1.1~~	**0.0034** ~~0.0024~~
PM-10	**6.5** ~~4.6~~	**10** ~~7.3~~	**0.023** ~~0.016~~
PM-15	**7.8** ~~5.5~~	**13** ~~9.0~~	**0.028** ~~0.020~~
PM-30[d]	**34** ~~24~~	**54** ~~38~~	**0.12** ~~0.082~~

These values were scaled from the PM-10 emission factor given as Equation 3 in Section 2 of this report.[10]

It is recommended that EPA consider dropping the PM-15 particle size multiplier in Table 13.2.1-1.1. This size range was removed from the discussion in AP-42 Section 13.2.2, "Unpaved Roads," during the 1997 revision because it has no history as the basis for a particulate standard.

[10] The new "k" values were obtained by multiplying the old values by the ratio of the new and old PM-10 factors. Since the "new" PM-10 value in Equation 3 is 10.3 g/VMT and the "old" value from Equation 1 is 7.3 g/VMT, the scaling ratio was (10.3/7.3) = 1.4. For example, the old PM-2.5 k value of 1.1 g/VMT was multiplied by (10.3/7.3) to obtain the value of 1.6 g/VMT given in the table.

Section 4.
References

1. USEPA, Compilation of Air Pollutant Emission Factors. AP-42. Fifth Edition, Office of Air Quality Planning and Standards, Research Triangle Park, NC. January 1995.
2. E. H. Pechan & Associates, Inc. "Recommendations for Emission Factor Equations in AP-42 Paved Roads Section: Technical Memorandum," Prepared for USEPA Office of Air Quality Planning and Standards, Research Triangle Park, NC. August 21, 2003. Available as http://www.epa.gov/ttn/chief/ap42/ch13/related/pavedroadstechmemo_082103.pdf
3. USEPA, *Procedures for Preparing Emission Factor Document.* EPA-454/R95-015. November 1997. Available as http://www.epa.gov/ttn/chief/efdocs/procedur.pdf.
4. Draper, N. and H. Smith, *Applied Regression Analysis*. Second Edition, John Wiley & Sons, Inc. New York. 1980.
5. Martens H.A. and P. Dardenne. "Validation and Verification of Regression in Small Data Sets," *Chemometrics and Intelligent Laboratory Systems*, Volume 44, Number 1, 14 December 1998 , pp. 99-121(23)

Appendix A

Combined Data Set

This appendix contains the data set used to develop the PM-10 emission factor given in Equation 2 of the report. Note that a nominal speed of 1 mph is used to indicate the "stop-and-go" tests.

Run ID	Silt loading (g/m^2)	Speed (mph)	Weight (tons)	PM-10 Emission factor (g/vmt)
AUC8	0.15	27	2	7.88
M-17	0.809	30	2	2.64
M-18	0.731	30	2	0.37
M-6	0.716	30	2.1	1.38
M-4	0.432	35	2.1	0.177
M-8	2.48	20	2.2	11.2
M-5	1.01	35	2.2	0.692
M-7	0.59	35	2.3	4.22
M-19	0.929	30	2.4	0.177
AUE3	2.2	15	2.6	16.1
AUE4	1.3	15	2.6	9.01
M-15	0.049	35	2.7	1.47
M-14	0.079	35	2.7	1.37
M-13	0.11	35	2.7	0.306
AUC7	0.26	27	3	0.402
AC6	399	20	3.1	613
Y1	90.7	10	3.6	117
Y2	76.1	10	3.7	182
Y4	193	10	3.7	200
M-2	0.26	30	3.8	1.55
Y3	193	10	3.8	36.3
M-12	0.022	55	3.8	0.084
AUC5	0.23	29	3.9	15.3
M-9	0.293	30	4.1	3.24
M-16	0.022	55	4.3	0.241
M-3	0.147	30	4.5	3.54
M-10	0.022	55	4.5	0.177
M-11	0.022	55	4.8	0.322
AUE2	4.0	16	5.1	10.6
AUC3	0.42	27	5.5	2.25
M-1	0.46	30	5.6	4.99
AC4	287	10	5.7	1750
AUC4	0.52	25	6	16.1
AUC6	0.23	27	6.2	3.7
AC5	188	15	7	1420
Z3	12.4	15	8	1820
Z2	12.4	15	8	740
Z1	11.3	10	8	317
F36	0.201	NR	8.3	54.7
B56	2.4	NR	9.2	126
B50	13.6	NR	9.4	82.1
B54	3.77	NR	10	93.3
B59	2.06	NR	11	348
B55	6.3	NR	11	183
B51	13.6	NR	11	140
B60	3.19	NR	12	439
B57	2.32	NR	12	195
B52	7.19	NR	12	35.4
AUE1	4.0	15	12	3.22
F32	0.117	NR	14	53.1
F27	14.8	NR	14	130
F45	5.11	NR	16	212
F37	0.417	NR	17	77.2
F38	0.218	NR	18	167
F39	0.441	NR	18	253
B58	10.4	NR	18	368
F35	2.03	NR	25	298

Run ID	Silt loading (g/m^2)	Speed (mph)	Weight (tons)	PM-10 Emission factor (g/vmt)
F34	2.78	NR	28	188
F74	5.59	NR	29	545
F62	14.4	NR	36	317
AD2	63.6	23	39	342
F61	17.9	NR	40	463
AD3	52.9	23	40	233
AD1	94.8	23	42	1480
CI-7	0.05	15.3	27	1.63
CI-8	0.05	15.3	27	2.99
CF-1N	0.97	5	40	4.99
CF-2N	0.81	5.3	41	16.3
CF-3N	0.63	5.1	41	1.09
CF-4N	1.1	4.7	41	3.08
CE-11	1.34	5	12	154
CE-12	1.34	5	13	23.1
CE-15	1.91	5	40	63.5
CE-16	1.41	5	40	77.1
CE-17	2.93	5	40	41.3
CE-19	0.76	5	38	18.6
CM-1	0.72	5	39.8	6.35
CM-4	0.70	5	39.5	7.26
CE-1	1.16	1	36	27
CE-2	0.86	1	36	64
CE-3	0.86	1	39	45
CF-1/South	0.97	1	40	20
CF-2/South	0.81	1	41	64
CF-3/South	0.63	1	41	23
CF-5	1.4	1	41	16
CM-2	0.72	1	39.6	64