TEOM-BASED MEASUREMENT OF INDUSTRIAL UNPAVED ROAD PM_{10}, $PM_{2.5}$, AND $PM_{10-2.5}$ EMISSION FACTORS

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ABSTRACT

The National Stone, Sand and Gravel ("NSSGA") sponsored an emission factor test program to evaluate PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$ emission factors from industrial unpaved roads at two Aggregates Industry plants (sand & gravel plants) in California. Tapered electrode oscillating microbalance ("TEOM") instruments were mounted in vertical arrays on each side of the road section tested. These instruments were used to provide a continuous, real time measurement of PM_{10} and $PM_{2.5}$ concentrations. $PM_{10-2.5}$ concentrations were determined by the difference between the PM_{10} and $PM_{2.5}$ concentrations. The TEOM data were used in conjunction with wind speed data and road traffic information to determine the PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$ emission factors. The authors believe that the use of TEOMs is a significant advance over the filter-based techniques available previously for unpaved and paved road emission factor tests.

The results of the test program indicate that the PM_{10} emission factors at the two plants studied ranged from 0.08 to 0.18 pounds per vehicle mile traveled ("VMT"). This is slightly below the 0.25 to 0.35 lbs per VMT values tested previously by NSSGA and Air Control Techniques, P.C. at two Aggregates Industry plants (crushed stone plants) in Georgia. These differences appear to be due to differences in vehicle weights, traffic frequency, and topographically dependent airflow effects. When major variables such as moisture content, silt content, and average vehicle weights are taken into account, the data sets from Georgia and California are consistent and comparable.

The emission factors determined in this study are below those predicted by EPA's industrial unpaved road equation and adjusted by the moisture ratio. There is general consistency only if a control efficiency in the range of 90% to 98% is applied to EPA's uncontrolled emission factor.

The $PM_{2.5}$/ PM_{10} ratios measured in this study indicate that $PM_{2.5}$ emissions from Aggregate Industry unpaved roads are equal to approximately 15% of the PM_{10} emissions. This value is very similar to ratios measured by Air Control Techniques, P.C. in NSSGA sponsored studies of quarry haul roads in North Carolina and to the ratio published by EPA in AP42 Section 13.2.2. Based on this $PM_{2.5}$/ PM_{10} ratio, the $PM_{10-2.5}$ emissions can be estimated as 85% of the PM_{10} emissions.

BACKGROUND

The primary objective of this test program was to accurately measure PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$ emission factors for controlled (wet suppression only) haul roads at plants representative of the Aggregates Industry throughout the U.S. The test results will considerably increase the emission factor data available for $PM_{2.5}$ and $PM_{10-2.5}$. These tests in California will also increase the geographical range of test sites used by NSSGA to evaluate industrial unpaved road emissions. Previous haul road tests were sponsored by NSSGA in North Carolina and Georgia.

The tests were conducted in accordance with a detailed testing protocol reviewed by NSSGA, Granite Construction, and the California Air Resources Board ("CARB") more than thirty days prior to the start of the test program. Based on comments from CARB, Air Control Techniques, P.C. revised the testing protocol with respect to the $PM_{2.5}$ monitoring approach. CARB representatives observed portions of the test programs at both the Tracy and Bradshaw plants.

INDUSTRIAL UNPAVED ROAD TESTING PROCEDURES

Unwind-Downwind Concentration Profile Test Procedures

Air Control Techniques, P.C. used a conventional upwind downwind profiling technique to measure PM_{10} emissions from the haul road section. This technique has been used in essentially all EPA and NSSGA sponsored emission factor tests on unpaved roads at various types of industrial sources.

The PM_{10} concentrations on the downwind side of the unpaved road were measured using a set of four tapered electrode oscillating microbalance ("TEOM") monitors that measure particulate matter on a continuous basis. The monitors were arranged in a vertical structure as shown in Figure 1 to provide multi-point measurement of the fugitive dust plume exiting the road. The heights of the TEOM sample intakes ranged from approximately 4 feet to 24 feet above the ground. The PM_{10} concentrations of the upwind side of the unpaved road were measured by a TEOM located approximately 10 feet above the ground.

The TEOMs were mounted on a set of open scaffolds that did not block wind flow through the sampling area. The mass flux of particulate matter through the vertical section was integrated vertically and multiplied by the average wind speed through the vertical section.

The differences between the upwind and downwind PM_{10} concentrations were used as a measure of the fugitive dust emissions from the vehicles. The emissions from the entire road section were divided by the vehicle traffic measured in units of vehicle miles per test hour.

Five TEOM monitors were used to measure PM_{10} concentrations during the unpaved road tests. These instruments had a PM_{10} sampling head and were operated at a flow rate of 16.67 liters per minute. The instruments were calibrated in accordance with Section 12.1 of Method IO-1.3.

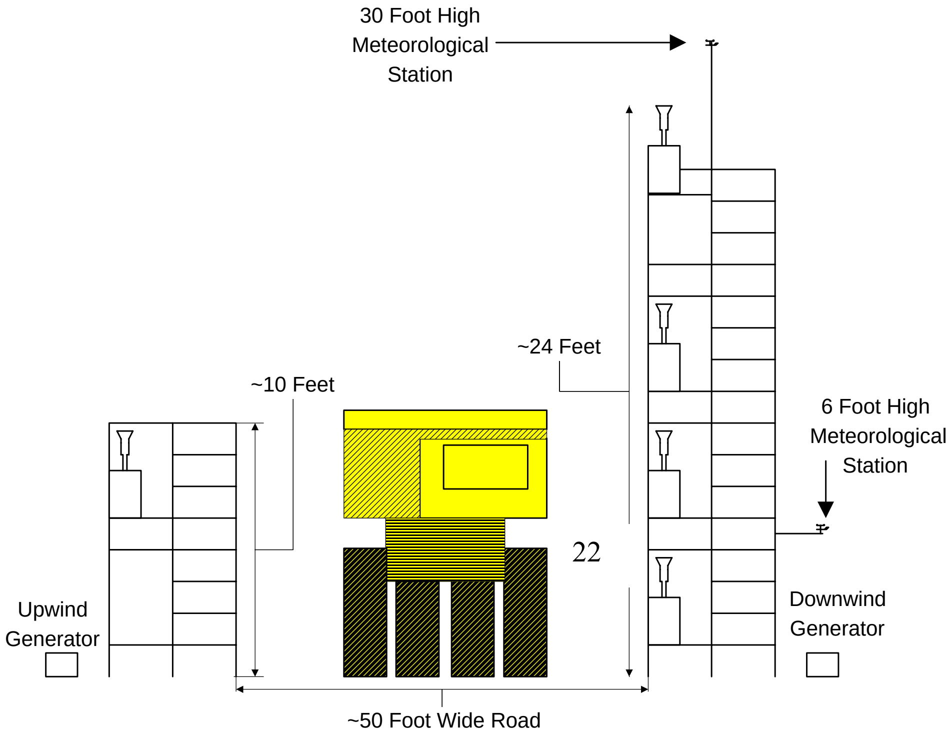

Figure 1. Upwind Downwind Profile Sampling System

The instruments were mounted on a secure base in the vertical arrays to minimize vibration. The instruments were equilibrated prior to the start of the first test run each test day.

Leak checks were performed at the test sites according to the Rupprecht & Patashnick Co, Inc. (R&P) performance audit procedures. The leak checks were conducted prior to sampling and immediately following the final day of sampling at each plant. R&P also completed a calibration of the sample flow rates prior to shipment to Air Control Techniques, P.C. These calibrations were conducted using an NIST traceable flow rate standard that is accurate to ±2%. Single point verifications of the sample flow rate were conducted by Air Control Techniques, P.C. upon receipt of the monitor, prior to testing, and following testing.

The temperature and pressure calibration checks were documented in the full test report. The temperature checks were conducted with a K-type thermocouple and electronic hand-held readouts.

The extensive quality assurance protocol built into the TEOM instrument stops sampling if any required operation parameters are out of the specified range. The PM_{10} monitor operating data were scanned for any problems that could potentially affect the adequacy of the observed PM_{10} concentrations.

Two $PM_{2.5}$ TEOMs were operated during the test program to directly measure the $PM_{2.5}/PM_{10}$ ratios. One of the $PM_{2.5}$ TEOMs was collocated with the upwind PM_{10} TEOM. The other $PM_{2.5}$ TEOM was collocated with a PM_{10} TEOM at the second elevation of the downwind monitoring location. The ratios between $PM_{2.5}$ and PM_{10} at these two locations were used in calculating a factor for converting the PM_{10} emissions to $PM_{2.5}$ and $PM_{10-2.5}$ emissions.

NSSGA and Air Control Techniques, P.C. selected Granite Construction, Inc. plants in Sacramento and Tracy, California as test sites because (1) sections of unpaved haul roads at these plants were amenable for testing, and (2) wind conditions (direction and speed) were reasonably predictable. Both plants use conventional wet suppression for unpaved road fugitive dust control until the middle of summer when ambient temperatures are very high.

Meteorological data were monitored on a continuous basis on the downwind side of the unpaved road at two levels. The monitoring stations were located at ~2 meters and ~10 meters to determine if there were any differences in wind speed caused by the passing of the vehicles or the topography of the test area. Air Control Techniques, P.C. installed Davis Weather Wizard III monitoring stations. These instrument systems monitored wind speed, wind direction, and temperature. The meteorological data were recorded continuously and were reduced to 1-minute average values in a data acquisition system.

During the test runs, Air Control Techniques, P.C. compiled the following data and information concerning the unpaved road conditions.

- Road surface moisture level
- Road silt content
- Number of truck passes along the haul road
- Average and peak wind speed
- Average wind direction
- Average vehicle speed
- Truck load (loaded and unloaded)

Four of these variables were used as criteria to determine if a test should be accepted. Table 1 outlines the required test condition variables that were used as test-no test criteria.

Table 1. Test-No Test Criteria

Variable	Required Conditions
Frequency of truck passage	Minimum 20 trips / hour
Road moisture content	>0.5% and ≤ 10%
Wind speed	≥ 1 mph average winds and ≤ 20 mph gusts
Wind direction	Predominantly toward the sampling structure (90 degree sector)

Test Location – Bradshaw Plant

Sand and gravel products are shipped via 15 to 20 ton haul trucks. The upwind and downwind monitoring locations on the section of haul road tested are shown in Figure 2 and Figure 3. These monitoring sites were located on a 100-foot section of the entry road that was traveled by trucks approaching and leaving both the sand and gravel operation and the ready mixed concrete location.

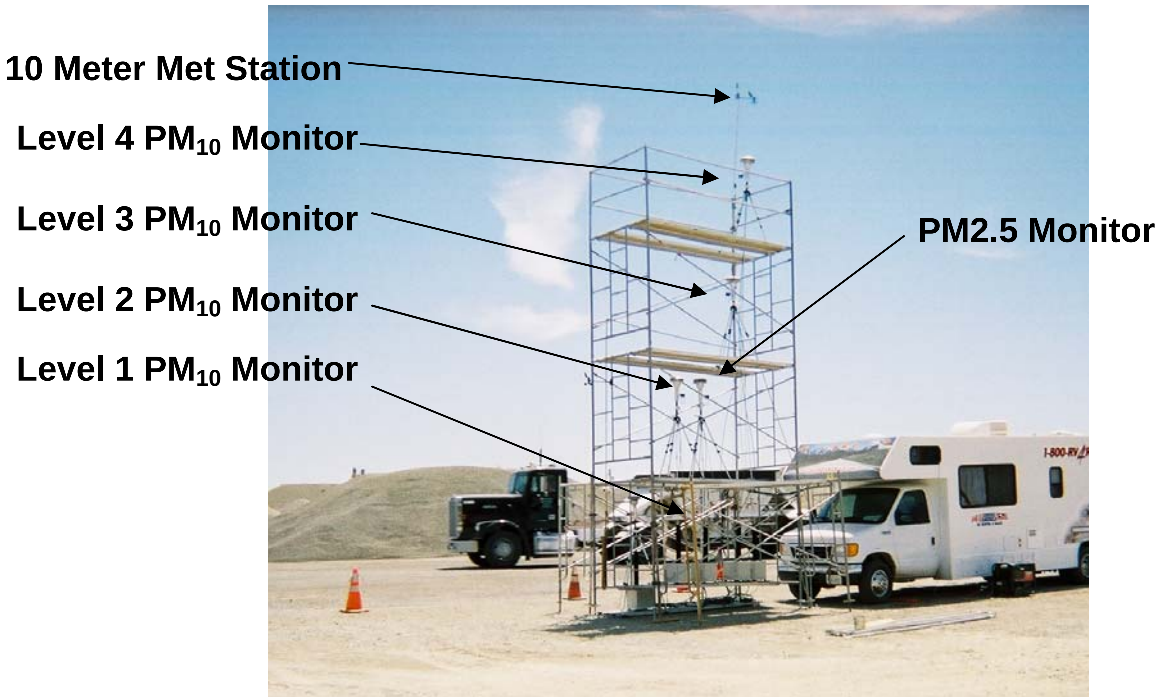

Figure 2. Downwind Monitoring Location, Bradshaw Plant

Figure 3. Upwind Monitoring Location, Bradshaw Plant

Truck frequency on the test site was at or above the expected volume of 20 to 50 vehicles per hour. The plant used conventional wet suppression techniques (Figure 4) for the section of unpaved road tested. The peak daytime temperatures during the test period were in the range of 85 to 95ºF. The relative humidities remained below 40% throughout the test period.

Figure 4. Water Truck at the Bradshaw Plant
(Downwind monitoring site shown on left)

Test Location - Tracy Plant

The Tracy, California plant includes sand and gravel production systems and an asphalt plant. A 100-foot section of road on the long entrance road to the plant was tested. This is the entry road that is traveled by trucks approaching and leaving both the sand and gravel operation and the asphalt plant.

The unpaved entry road is oriented in a direction that is perpendicular to the prevailing wind pattern, which is channeled by nearby mountains. There are moderate depressions on both the upwind and downwind sides of the roads; therefore, the wind flow across the road is typical of the complex flow patterns that are common in quarries and aggregate plants in general. There was adequate space on both sides of the unpaved roads to set up the test equipment without restricting traffic flow or speed.

Truck frequency on the test site was at or above the expected frequency of 40 to 60 vehicles per hour, especially during the morning test periods. The plant used conventional wet suppression techniques through the study period. During the tests, the weather was unusually cool for central California. The upwind and downwind monitoring sites are shown in Figures 5, 6, and 7.

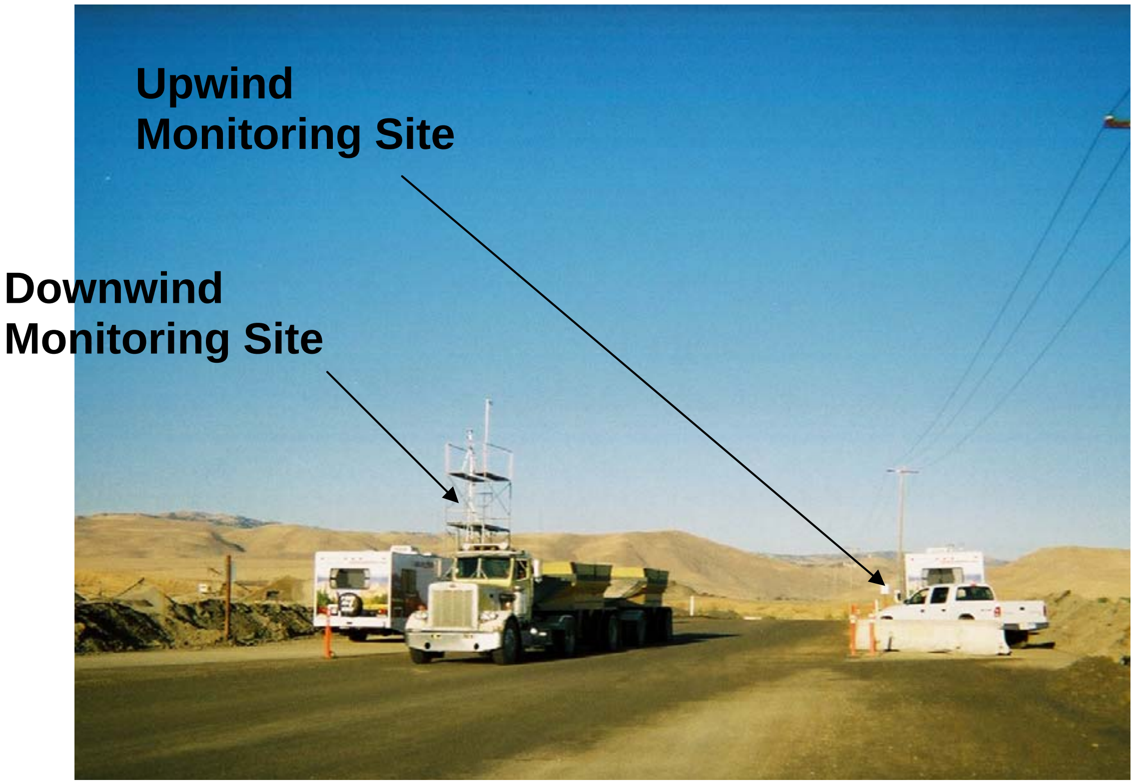

Figure 5. Upwind and Downwind Monitoring Sites, Tracy

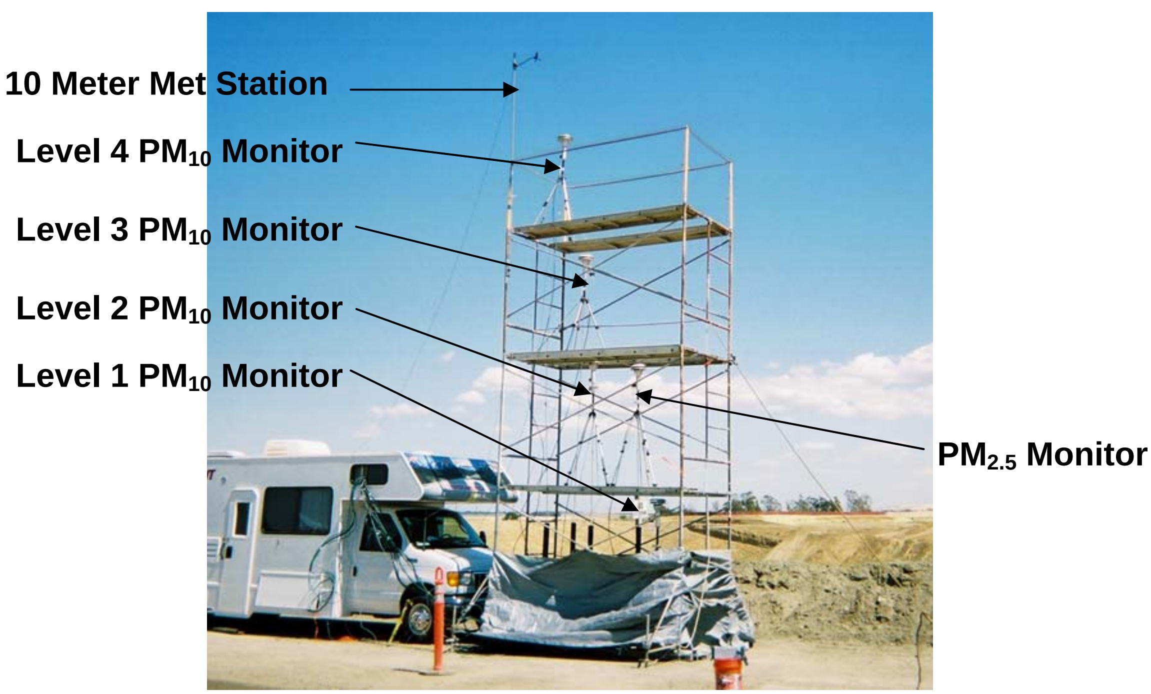

Figure 6. Downwind Monitoring Site, Tracy

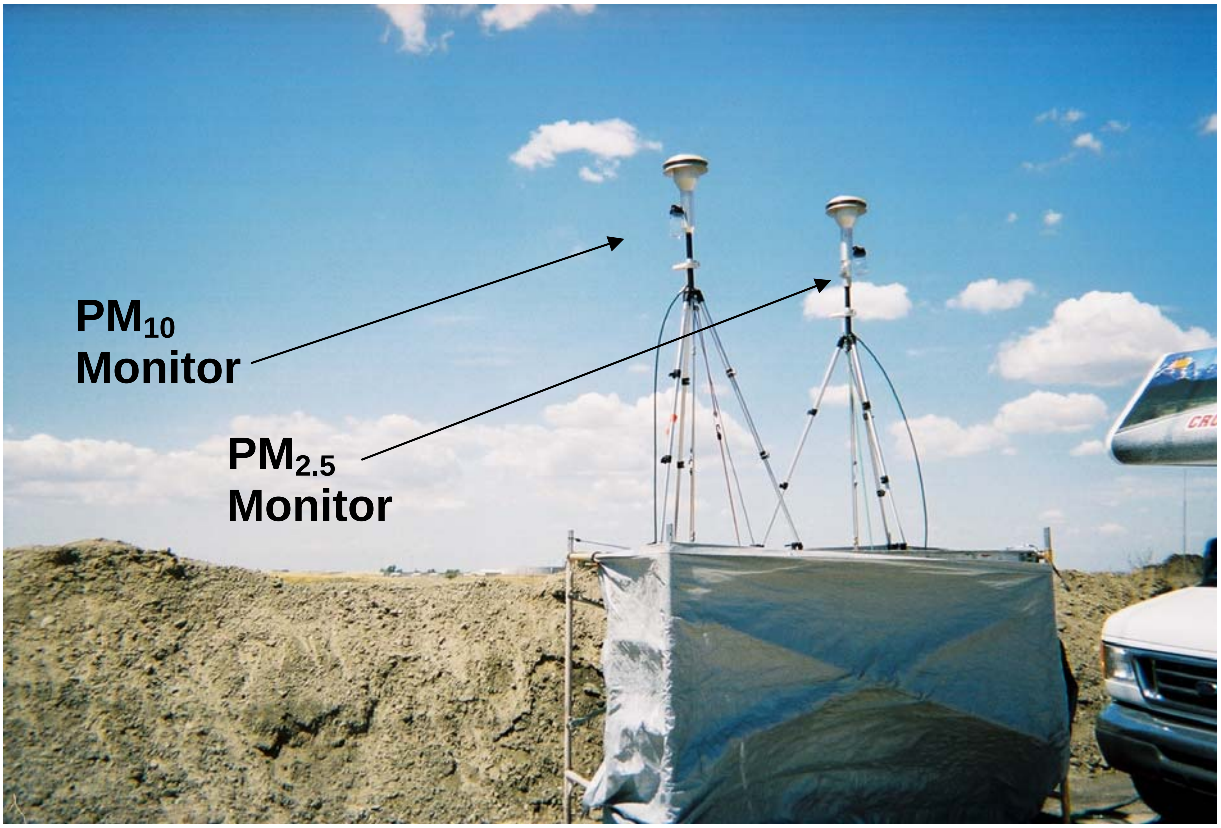

Figure 7. Upwind Monitoring Site, Tracy

EMISSION FACTOR TEST RESULTS

Forty-four one-half hour test runs were conducted from June 6 through June 16, 2004. Of these, twenty of the test runs were conducted during conditions that satisfied all test no-test criteria. The data used to determine the adequacy of the test run conditions are summarized in the following sections for the Tracy and Bradshaw plants.

Test Conditions - Tracy Plant

Samples of the road material were taken once per hour using techniques specified in AP42, Section C. Due to the heavy traffic volume on the road, it was necessary to take the samples when there was a break in traffic flow. The silt content was determined on-site using a set of ASTM screens and a Ro-Tap. The moisture content was determined on-site by drying at 250ºF for a period of two hours.

The silt content varied from a low of 0.31% by weight to a high of 4.26% by weight. These silt levels are below those measured in previous haul road tests conducted by Air Control Techniques, P.C. in North Carolina and Georgia. The reduced levels are believed to be due to (1) heavy traffic volumes on the unpaved roads, (2) exposure to high ambient temperatures, and (3) exposure to ambient winds.

The moisture content of the silt fraction of the road surface ranged from a low of 0.25% by weight to a maximum of 5.29% by weight. The road surface moisture content varied moderately during each test run. Immediately after application of water, the road surface content increased to the range of 4% to 5% by weight. The road dried between applications of water. Because the road surface sampling could not be conducted at a prescribed interval between water applications, some of the variation in run-to-run moisture levels was due to the time elapsed since the last water application rather than actual run-to-run variations in moisture. As stated earlier, road material sampling could only be conducted during short breaks in traffic flow when it was safe to sweep a one-foot section across the road.

Air Control Techniques, P.C. recorded the time of passage, speed, and weight (estimated) of each vehicle passing through the 100-foot test section. The average speed was 13.6 mph. This indicates that drivers were complying with the posted speed limit of 14 mph on this section of road. The maximum speed was 24.5 mph. Essentially, all of the vehicles passing at greater than 20 mph were light duty vehicles such as pick-up trucks and delivery trucks. All of the loaded and returning haul trucks maintained speeds less than 20 mph. A few trucks slowed to less than 10 mph due to apparent curiosity concerning the large monitoring sites on both shoulders of the road.

The number of vehicle miles traveled in the 100-foot test section of the road averaged 40.3 for each half-hour test run. This traffic volume is considerably higher than that observed in previous tests conducted by Air Control Techniques, P.C. and by EPA. The number of vehicle miles traveled and the total weight of vehicles passing through the test sections were compiled on a run-by-run basis and used in the analyses of the particulate matter emissions data.

The Tracy plant was selected as a test site, in part, because of the anticipated favorable meteorological conditions. During the June test period, previously compiled weather data indicated that the winds were predominantly from the west, and the daytime air temperatures exceeded 90ºF. As further confirmation of the dominant wind directions, the Tracy Airport adjacent to the Tracy plant has a runway oriented west-to-east. Accordingly, the downwind monitoring site was located on the east side of the road.

The wind direction was measured using Davis Weatherwizard wind vanes mounted at 2-meter and 10-meter elevations on the downwind monitoring site. It became apparent that only the 10-meter instrument provided accurate information. The wind vane at the 2-meter location was subject to rapid short term variations in wind direction apparently due to recirculating air caused by either the berm or the depression immediately to the east of the downwind monitoring station. The 2-meter wind vane was not consistent with observed movement of winds across the road surface and with "flags" mounted on the scaffolds supporting the TEOMs.

The wind directions as measured at the 10-meter location were not favorable during the early part of the study. During the early afternoon on June 9th, the winds shifted to the appropriate direction, and it was possible to conduct several runs. During these periods, the wind speed ranged from 3.4 to 12.8 mph. During most of the June 10th and the early morning hours of June 11th, the winds were from the west, northwest, or west-northwest. Tests conducted during these periods satisfied the test criteria. The wind speeds during these periods ranged from 3.6 to 14.7 mph. There were frequent gusts exceeding 15 mph during the test periods on June 10th. The complete wind speed, wind direction, and ambient temperature data are summarized in the full test report.

Test Conditions - Bradshaw Plant

The monitoring sites were set-up at the Bradshaw Plant on June 14, 2004; however, no data were compiled throughout June 14th and 15th due to unfavorable wind directions. Due to a stalled cold front off the coast of California, the winds did not return to the normal (and necessary) direction at the Bradshaw plant until approximately 2 pm on June 16th.

Twenty eight test runs were conducted on June 16th. Of these, twelve of the test runs were conducted during conditions that satisfied all test-no-test criteria.

Samples of the road material were taken once per hour using techniques specified in AP42, Section C. Due to the heavy traffic volume on the road, it was necessary to take the samples when there was a break in traffic flow. The silt content was determined on-site using a set of ASTM screens and a Ro-Tap. The moisture content was determined on-site by drying at 250ºF for a period of two hours. The silt content varied from a low of 1.23% by weight to a maximum of 3.03%. This variation is believed to be due primarily to the specific portion of the road sampled rather than any routine variations in the silt content on the road surface.

The moisture levels on the unpaved road varied from 0.46% by weight to 2.03% by weight. There were routine variations in road moisture content between applications. Due to high ambient temperatures, the moisture on the road surface evaporated quickly.

The winds did not shift to the proper direction until mid-afternoon on June 16th. Due to reduced sales rates in the afternoon, the traffic volume decreased substantially. Air Control Techniques, P.C. requested that Granite provide a driver and a loaded truck to generate sufficient traffic volume during the available test period. Most of the vehicle traffic through the test section at Bradshaw after 3 pm was due to the truck provided by Granite. The vehicle speeds averaged approximately 10 mph and ranged from 5 to 17 mph. There was an average of approximately 35 vehicle passes per test run. This traffic frequency was higher than previous haul road tests.

The wind speeds ranged from 4.3 to 9.6 mph after the winds shifted to a westerly direction after 2 pm. All accepted test runs were from 2 pm to 8 pm.

Confirmation of the Sampling Technique

The vertical profiling technique used in this emission factor test program is consistent with procedures used in a variety of NSSGA and EPA sponsored studies of unpaved roads. The validity of this approach is dependent on (1) adequate capture of the plume within the height of the downwind monitoring tower and (2) representative measurements of the emissions passing through the vertical profile being measured. The first requirement is demonstrated by upwind concentrations that are approximately equal to those at the tallest point in the monitoring tower. This is illustrated by the relationships between the upwind and downwind monitors shown in Figure 8 (data applicable to 16:15 pm June 16, 2004 at the Bradshaw plant). The second requirement was demonstrated at both the Tracy and Bradshaw plants with Nephelometer measurements indicating that the first monitoring elevation was at or near the point of maximum concentration as illustrated in Figure 8.

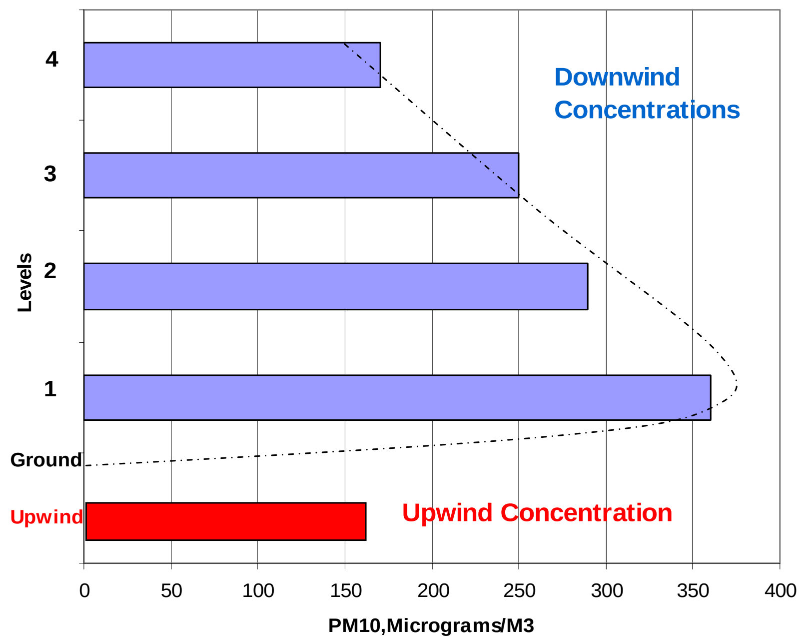

Figure 8. Vertical Profile PM_{10} Concentration Measurements
(specific data applies to Bradshaw, June 16th, 16:15 pm)

The relationships between the four TEOM monitors in the vertical tower also provided a direct and continuous indication of the proper operation of the PM_{10} concentration measurement system. As indicated in Figure 9, there was a high degree of correlation between the concentrations measured at the first and second elevations. This correlation weakened

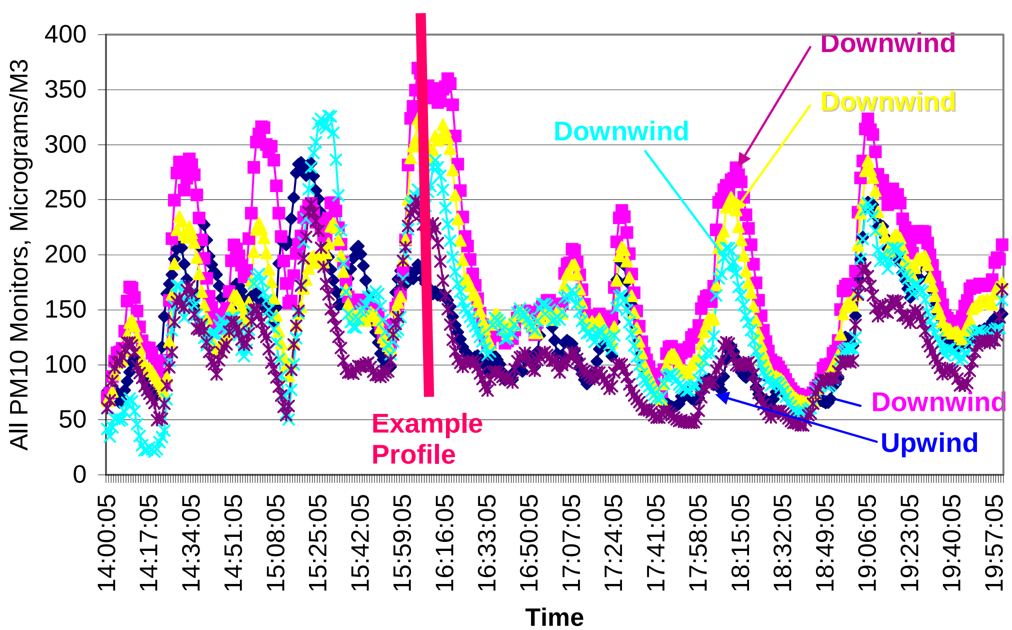

Figure 9. Vertical Concentration Profiles, Sacramento

considerably, as expected, in comparisons between the third and fourth monitoring elevations. Figure 10 shows the correlation between TEOM levels 1 and 2 at Bradshaw, and Figure 11 shows the correlation between TEOM levels 1 and 3 at Bradshaw. TEOM level 4 concentrations were related to level 1 concentrations only to the extent that the background concentrations as measured by the upwind monitor varied. The TEOM data strongly support the validity of the conventional testing approach. This type of confirmation cannot be easily obtained using the filter-based monitoring techniques used in previous studies conducted by EPA and NSSGA.

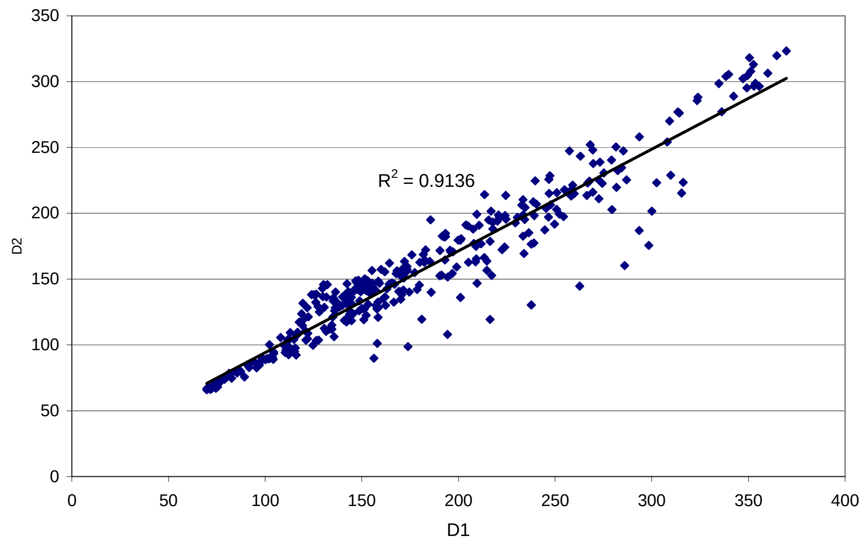

Figure 10. Correlation Between the Lowest Downwind Monitor and the Second Level Monitor at Bradshaw, TEOM PM_{10} concentrations.

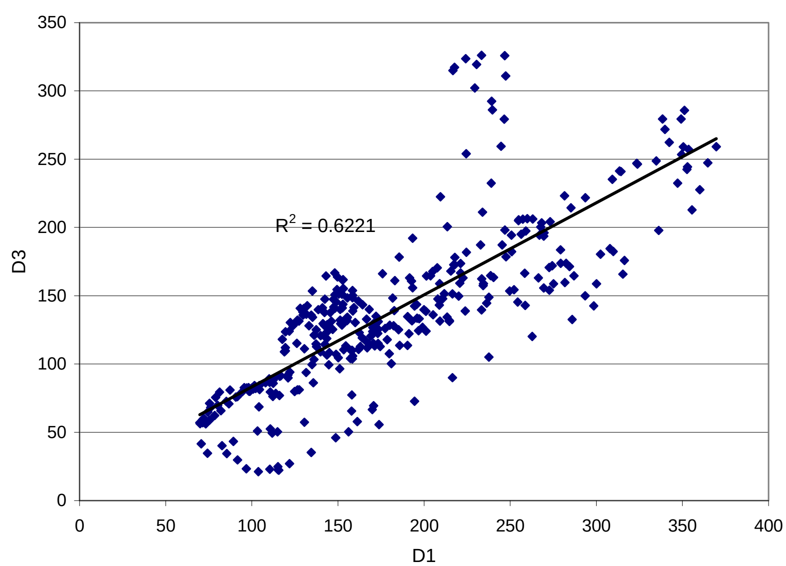

Figure 11. Correlation Between the Lowest Downwind Monitor and the Third Level Monitor at Bradshaw, TEOM PM_{10} concentrations.

PM_{10} Emission Factor Test Results

The haul road particulate matter emission factors were calculated based on the difference between the upwind and downwind PM_{10} monitor concentrations. The measured concentrations from the four downwind monitors at different elevations were averaged in order to calculate an average particulate matter concentration for each test run.

This average concentration was then multiplied by the average wind speed to calculate the mass flux through a vertical surface 22 feet high and 100 feet long. The average wind speed was calculated based solely on the wind speed at the 10-meter elevation. The 2-meter wind vane was subject to mixing conditions and was not consistent with other indicators of wind direction and speed (i.e. wind pennants).

The total vehicular miles traveled through the 100 foot long test section during each test run were then calculated by multiplying the total number of truck passes by the length of the haul road. The particulate matter emission rate was then divided by the total number of vehicular miles traveled to yield an emission factor in pounds per vehicular mile traveled.

The PM_{10} emission factors measured during the tests are summarized in Tables 2 and 3 for Tracy and Bradshaw respectively. The average emission rate at the Tracy plant was 0.079 pounds of PM_{10} per vehicle mile traveled. The average emission rate at the Bradshaw plant was 0.186 pounds of PM_{10} per vehicle mile. The road conditions during each of the test runs are summarized in these tables.

Table 2. PM_{10} Emission Factor Test Results, Tracy

Run	Winds	Silt	Moisture	Avg. Truck Wt	PM_{10} Measured	EPA Uncontrolled	% Difference
7a	8.7	3.27	4.2	20.0	0.052	1.09	95.26
7b	10.9	3.27	4.2	20.0	0.122	1.09	88.84
8a	11.6	0.31	3.4	19.2	0.018	0.13	86.34
9a	12.8	2.37	5.3	12.0	0.125	0.65	80.79
10a	5.7	4.26	5.2	21.6	0.015	1.44	98.98
14a	3.6	2.63	2.5	21.0	0.004	0.92	99.56
14b	8.4	2.63	2.5	21.0	0.026	0.92	97.13
15a	10.3	1.99	2.4	23.0	0.064	0.74	91.40
15b	11.7	1.99	2.4	23.0	0.048	0.74	93.51
16a	13.1	1.75	0.6	22.7	0.076	0.66	88.44
16b	11.9	1.75	0.6	22.7	0.050	0.66	92.43
17a	13.5	1.71	0.4	22.0	0.054	0.64	91.56
17b	14.7	1.71	0.4	22.0	0.248	0.64	60.99
18a	10.7	2.92	4.2	19.7	0.167	0.98	82.93
18b	11.8	2.92	4.2	19.7	0.145	0.98	85.17
19a	11.8	1.98	3.4	17.2	0.206	0.65	68.30
19b	12.0	1.98	3.4	17.2	0.068	0.65	89.59
21b	2.0	2.42	0.9	22.4	0.000	0.88	99.94
22a	1.5	2.43	0.9	22.1	0.012	0.88	98.63
Average	9.8	2.3	2.7	20.4	0.079	0.81	88.94

Table 3. PM_{10} Emission Factor Test Results, Bradshaw							
Run	Winds	Silt	Moisture	Avg. Truck Wt	PM_{10} Measured	EPA Uncontrolled	% Difference
11a	8.7	2.92	1.2	33.6	0.563	1.25	54.86
11b	8.6	2.92	1.2	33.6	0.129	1.25	89.66
12a	8.5	1.71	0.8	36.0	0.147	0.79	81.54
12b	9.6	1.71	0.8	36.0	0.040	0.79	94.93
13a	9.4	1.72	1.3	35.9	0.503	0.80	36.93
13b	9.9	1.72	1.3	35.9	0.052	0.80	93.42
14a	9.7	1.94	0.7	36.0	0.030	0.89	96.63
14b	9.7	1.94	0.7	36.0	0.023	0.89	97.45
Average	9.3	2.07	1.0	35.4	0.186	0.93	80.68

$PM_{10-2.5}$ and $PM_{2.5}$ Emission Factor Test Results

The $PM_{10-2.5}$ and $PM_{2.5}$ emission factors were estimated based on the $PM_{2.5}$/ PM_{10} ratios observed at the downwind monitoring sites at the Tracy and Bradshaw Plants. These ratios were calculated for the same time periods as the runs accepted for PM_{10} emission factors. No attempt has been made to estimate run-by-run emission factors. The $PM_{2.5}$ TEOMs are subject to intermittent excursions to negative concentration values due to the initial capture and then evaporation of water spray from the water truck and diesel emissions from vehicles on the road. Due to this evaporation effect, the $PM_{2.5}$data cannot be evaluated on a short term averaging basis. Instead, the ratios have been calculated for sets of test runs lasting for more than 3 hours. These data are summarized in Table 4.

Table 4. $PM_{2.5}$ Ratios					
Plant	Monitoring Location	Run Group	PM_{10}, $\mu g/M^3$	$PM_{2.5}$ $\mu g/M^3$	Ratio $PM_{2.5}/PM_{10}$ %
Tracy	Down	10-19	38.19	10.52	27.54
	Up	10-19	25.18	7.05	28.02
Tracy	Down	20-22	73.16	6.49	8.88
	Up	20-22	77.04	6.05	7.86
Bradshaw	Down	11-14	158.42	13.83	8.73
	Up	11-14	135.24	34.81	25.74
Average, Upwind and Downwind Sites					17.8
Average, Downwind Sites Only					15.0

$PM_{2.5}$ ratios observed in this study are consistent with values measured by Air Control Techniques, P.C. in NSSGA studies conducted in North Carolina. The $PM_{2.5}$ ratios observed in the California tests are also similar to ratio published by EPA in Section 13.2.2 of AP42. In EPA's equation, a constant of 1.5 is used for PM_{10} estimation, and a value of 0.25 is used for $PM_{2.5}$ estimation. The ratio of these EPA constants is 16.7%. Based on the similarities of ratios observed in various EPA and NSSGA studies, the value of 15% appears to be an appropriate adjustment factor for estimating $PM_{2.5}$emissions from PM_{10} emissions from Aggregate Industry unpaved roads.

SUMMARY

NSSGA and Air Control Techniques, P.C. used a set of PM_{10} and $PM_{2.5}$ TEOMs to measure PM_{10}, $PM_{2.5}$, and $PM_{10\text{-}2.5}$ emission factors for industrial unpaved roads at two sand & gravel plants in California. The TEOMs provide particulate matter concentration data that are superior to data provided by filter-based monitors in that it is possible to compare the concentrations at the monitors in the vertical array on a continuous basis. It is also possible to identify unusual ambient airflow patterns caused by local topography.

The results of the test program indicate that the PM_{10} emission factors at the two plants studied ranged from 0.08 to 0.18 pounds per vehicle mile traveled ("VMT"). This is slightly below the 0.25 to 0.35 lbs per VMT values measured previously by NSSGA and Air Control Techniques, P.C. at two Aggregates Industry plants (crushed stone plants) in Georgia. These differences appear to be due to differences in vehicle weights, traffic frequency, and topographically dependent airflow effects. When major variables such as moisture content, silt content, and average vehicle weights are taken into account, the data sets from Georgia and California are consistent and comparable.

Acknowledgements

The authors would like to thank Granite Construction, Inc. for hosting the studies at the Tracy and Bradshaw plants. We would also like to thank CARB personnel for reviewing the pre-test protocol, providing valuable comments concerning the test procedures, and observing portions of both test programs.