

**PM₁₀-Efficient Street
Sweeper Evaluations**

Phase II Draft Final Report

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Principal Investigator
Dennis R. Fitz

Center for Environmental Research and Technology
College of Engineering
University of California
Riverside, CA 92521
(909) 781-5791
(909) 781-5790 fax

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1.0 Introduction

1.1 Background

State Implementation Plans (SIPs) are required to outline the Best Available Control Measures (BACM) for reducing ambient particulate matter in areas that do not comply with the National Ambient Air Quality Standards (NAAQS) for PM₁₀. PM₁₀ refers to particles less than 10 µm aerodynamic diameter, a size range that has been determined to be inhalable by humans. Receptor modeling studies have shown that fugitive dust generated from vehicles traveling on roadways can be a major source of PM₁₀ in the South Coast Air Basin (SoCAB) of California (Gaffney et al., 1995). Removing debris from streets has been suggested as a means of controlling emissions of PM₁₀ (US EPA, 1984), although this has not been experimentally established in practice (Chow et al., 1990; Fitz, 1998). Local governments routinely sweep streets, primarily for aesthetic and safety reasons. Recently, new street sweepers have been designed to collect typical street loadings and to reduce dust emissions for both aesthetic and regulatory reasons.

To reduce PM₁₀ emissions in the SoCAB, the South Coast Air Quality Management District (SCAQMD) has promulgated Rule 1186. This rule calls for procurement of “PM₁₀-efficient” street sweepers for equipment replacements made after January 1, 2000. Although manufacturers have claimed their new sweepers are PM₁₀-efficient, there has been a lack of test data because of the difficulty in making measurements of the fugitive PM₁₀ emissions from these machines. Recently a tunnel enclosure technique for measuring these emissions has been reported (Fitz and Bumiller, 1999). However, only a limited number of street sweepers were analyzed in this study. Based on the work of Fitz and Bumiller, the SCAQMD and the Society of Automotive Engineers (SAE) have recently developed a test protocol to quantify PM₁₀ emission rates and street sweeper collection efficiency. Although this test protocol may be used to certify sweepers as PM₁₀-efficient, this protocol has never been experimentally evaluated.

1.2 Objectives

The objectives of this project were to evaluate the Rule 1186 PM₁₀-efficient test protocol for a number of different street sweepers and, if possible, establish certification parameters. The test protocol addresses both PM₁₀ emission rate determination and sweeper collection efficiency. Certification of street sweepers will assure that local jurisdictions are able to purchase equipment that is PM₁₀-efficient for compliance with Rule 1186.

1.3 Project Approach

The approach is divided into two phases. In Phase 1, we selected a test site, evaluated the protocol by testing four types of sweepers, and reported the results of the evaluation. A number of recommendations were made for Phase 2 testing. This report describes the Phase 2 results. We identified a site for full-scale testing and tested 18 street sweepers using a revised testing protocol.

2.0 Technical Approach

Sweeper testing in Phase 1 was based on the Rule 1186 PM₁₀-efficient test protocol (South Coast Air Quality Management District, 1999). Modifications were made prior to the Phase 1 testing, and additional modifications were made for the Phase 2 testing based on the results from Phase 1. The SCAQMD management approved all of these changes. The following summarize the major changes from the original test protocol:

- TSP was not measured.
- Samples were not collected 30 minutes after draining the scrubber recovery tank.
- The solutions drained from the scrubbers were allowed to settle overnight before decanting.
- Recovered material was not sifted.

The following summarizes procedures not described in the original protocol:

- The material on the speed bump was swept off and the speed bump moved out of the way for scrubbing.
- The sweepers were staged in an area not upwind of the tunnel and brought to full power with sweeping mechanism directed to the tunnel while sweeping under full power. This eliminated the burst of PM₁₀ exhaust emissions that was often noticed during the Phase 1 testing.
- Meteorological and SO₂ data were collected with a one-minute averaging time while the DustLite data were recorded every two seconds.

2.1 Site Selection

The tunnel between the infield and parking lot of the California Speedway was again chosen for conducting the tests. The tunnel is 4.57 m wide, 4.42 m high and 73 m long and runs in a northeast direction. Figure 2-1 shows the location of the tunnel in relationship to the California Speedway facility. Figure 2-2 is a photograph of the entrance to the tunnel.

Arrangements were made with the Speedway to use the tunnel from May 11 to June 11, 1999. The easternmost of the three tunnels was selected since it allowed setting up data collection equipment next to the pedestrian tunnel (which is farther east). This arrangement also allowed the greatest personal safety from the traffic on the other two tunnels.

Generators were used to power sampling equipment. These were located downwind to the north of the tunnel. A ramp was made to elevate the floor scrubber so it could be drained of used wash water.

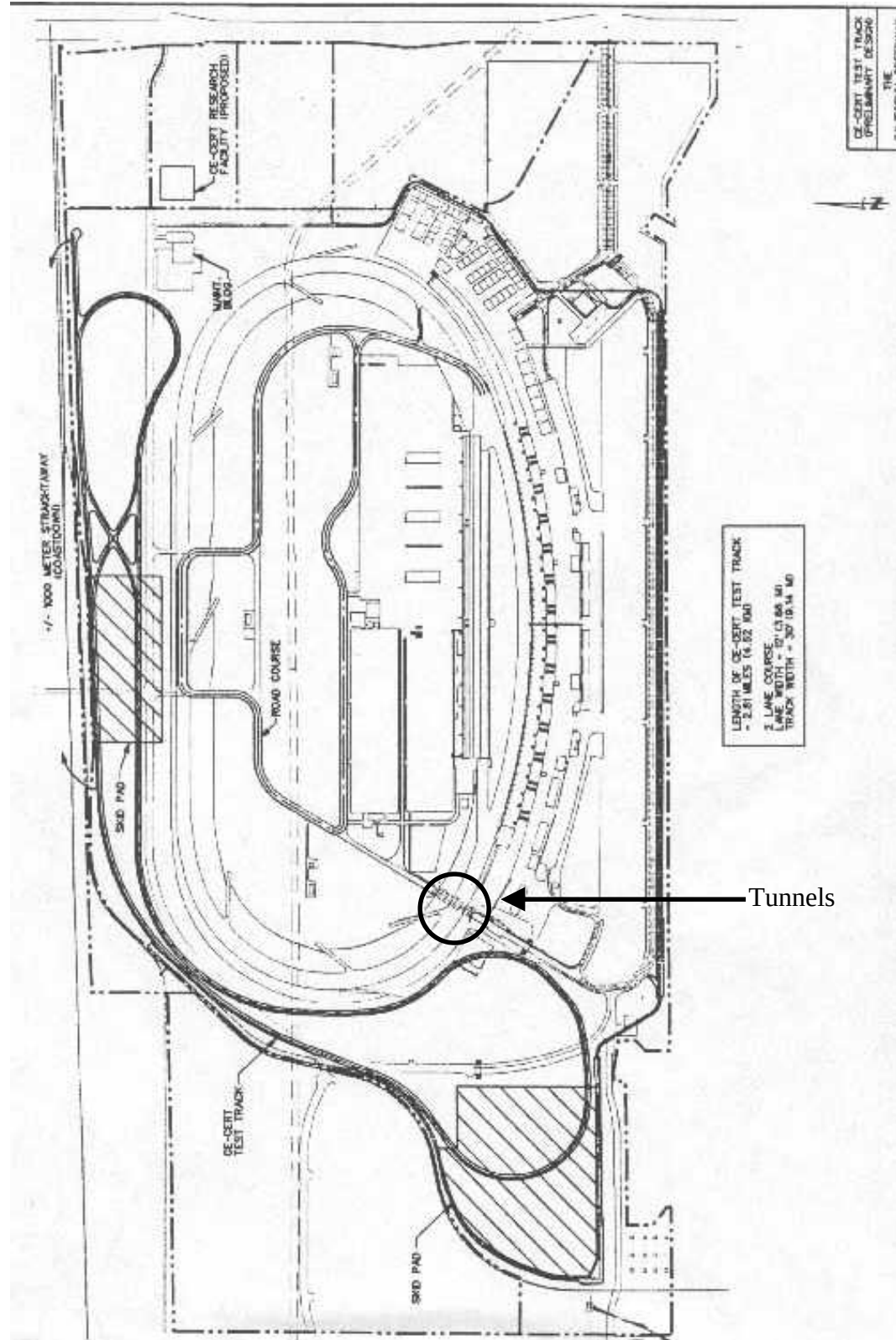
Figure 2-1. California Speedway Facility.

Figure 2-2. Tunnel Entrance.



2.2 Sweeper Procurement and Preparation

SCAQMD staff conducted sweeper procurement for the evaluations. Sweepers were identified only by a code name provided by SCAQMD staff. Sweepers for the evaluations were preconditioned by sweeping approximately 1 cubic yard of washed sand that was spread out in the parking lot, away from the tunnels. Sweeper operators were instructed by SCAQMD staff to operate their sweepers in a manner consistent with normal municipal sweeping requirements.

2.3 Track Surface Cleaning and Preparation

Since tests were performed daily and ended with the scrubbing of the test track, the track was assumed to be clean at the start of the day. Before testing a sweeper, the surface of the track was swept with the sweeper to be tested four times or until stabilization of the peak PM₁₀ concentrations were observed on the DustLite. The surrogate speed bump was installed prior to depositing the test material. This bump consisted of a 10-foot-long, 2-inch by 4-inch steel box tube welded to three flat steel plates, each two feet square and 3/8 inch thick. A 1-inch by 2-inch steel box tube was welded next to each side of the main tube to form a ramp with two one-inch steps.

17.2 kg of the test material was deposited as described in the Testing Protocol (SCAQMD, 1999) using two Scott's fertilizer spreaders. The exit of one spreader was blocked except for 6 inches, while the exit of the other was blocked except for 18 inches. The deposit started at the tunnel

entrance and ended 12 m from the outlet for a total length of 61 m. The release rate of the spreader and speed at which it was applied were adjusted so that at least two transverses were required to lay down the specified amount of test material. This assured that the deposit would be reasonably uniform along the length of the surface.

After sweeping, the bump was removed and the entire track cleaned with the floor scrubber.

2.4 Measurements

- **PM₁₀ Determination Using Automated PM₁₀ Monitor**

A Rupprecht and Patashnick model 3000 DustLite monitor was used to monitor PM₁₀ concentrations. This instrument has a two-second response time and a sensitivity of 1 µg/m³. A factory calibration based on Arizona road dust was used. The instrument was mounted 1.5 m above the ground, 2 m from the end of the tunnel.

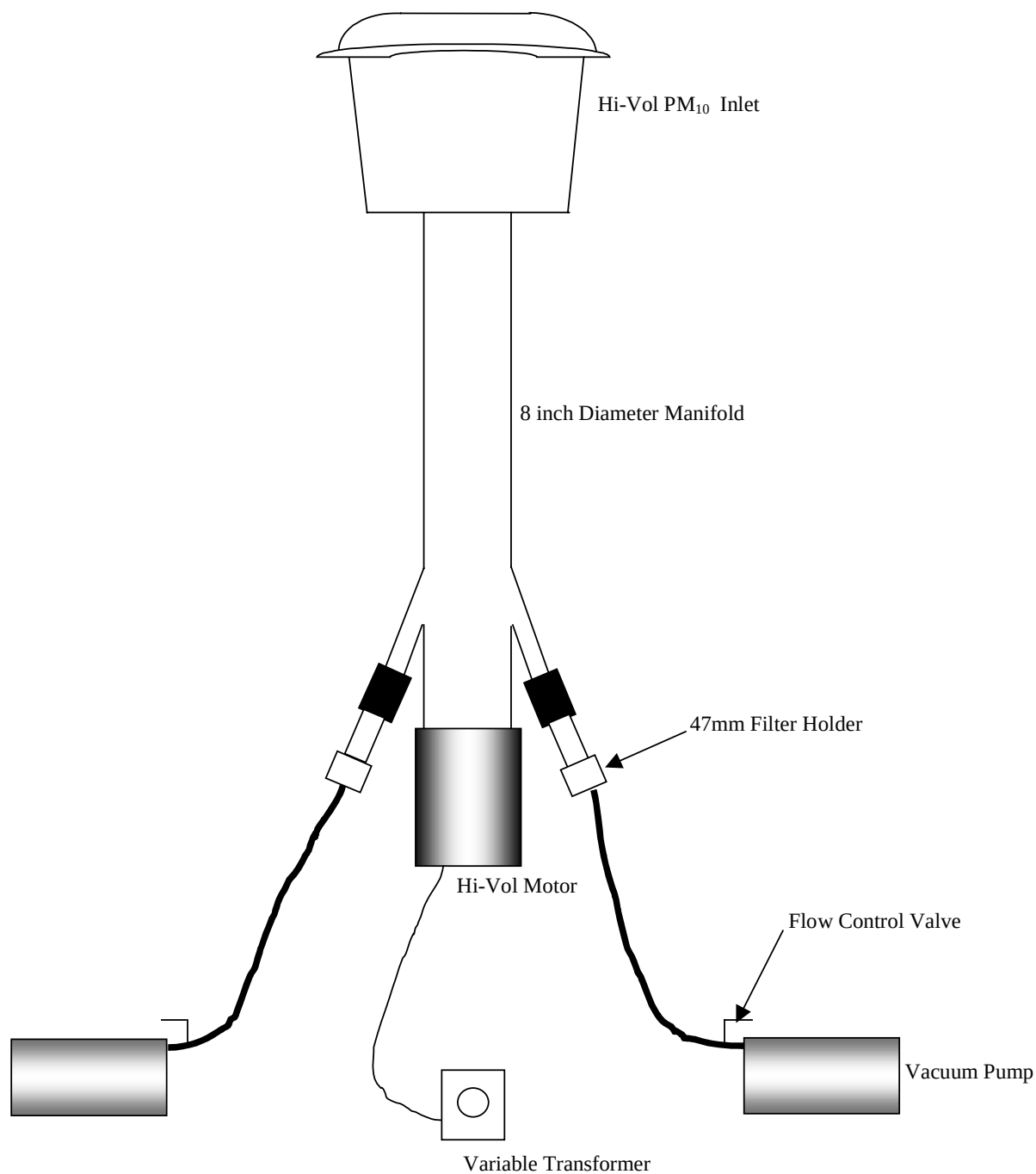
- **PM₁₀ Determination Using Filter Collection**

Filter samples were collected using 47 mm Teflo filters held in Savillex open-face filter holders at a nominal flow rate of 120 L/min. The holders were inserted into a PM₁₀ inlet assembly as shown in Figure 2-3. A commercial high-volume PM₁₀ inlet was used remove particles greater than 10 µm aerodynamic diameter. A hi-vol motor was used to provide make-up flow. A pair of collocated PM₁₀ samples were collected at the exit of the tunnel, while a single background sample was collected. Filter holders were installed just before the first test and removed just after the last test.

The sampling was started for a two-minute duration when the sweeper entered the tunnel. Filters were equilibrated at 20°C and 40% RH prior to weighing. Filters were weighed using a Cahn model 34 microbalance. The balance was zeroed every ten weighings and calibrated with a class M weight before and after any weighing period. Each filter was weighed a minimum of two times before and after sampling. If the weighings disagreed by more than 3 µg, the filter was reweighed until consecutive weighings were within this criterion.

- **Flow Rate Determination Using a Tracer Gas**

The tracer gas used was pure sulfur dioxide (SO₂). The gas was metered through a capillary to maintain a constant flow rate. The gas flow was checked before or after each test run with an automated bubble flow meter. The gas was initially released 6 m from the inlet of the tunnel and sampled 6 m from the end of the tunnel. After Sweeper B6 was tested, the release point was moved to a position 10 m from the entrance of the tunnel and sampled 13 m from the end of the tunnel. The tracer gas concentration was determined with a flame photometric sulfur detector. The background concentrations were determined before or after sweeper tests by turning off the SO₂ flow.

Figure 2-3. PM₁₀ Sampling System.

- **Flow Rate Determination Using an Anemometer**

A vane anemometer was mounted 12 m from the outlet of the tunnel at a height of 4 m. Temperature and relative humidity sensing equipment was also located at this point.

- **Sweep Time**

The sweep time was determined with a stopwatch by a CE-CERT technician positioned at the end of the tunnel. The start time was when the sweeper entered the tunnel (at which time the driver turned on the lights of the sweeper) and the stop time was at the end of the tunnel. Time was recorded to the nearest tenth of a second.

- **Sweeper Collection Efficiency**

After each sweeper test run, the remaining test material was removed using a floor scrubber. The used water tank was drained into a 15 gallon tub and the floor scrubber's tank rinsed thoroughly until the effluent was clear. The tub was allowed to stand overnight and decanted. The remaining material in the tub was transferred to a 2-gallon or 5-gallon bucket. After allowing several days for settling, the clear liquid in the 2-gallon bucket was poured off and the remainder was transferred to a tared pan for drying in an oven at 200°C. The sample was dried until the material no longer showed a weight loss within the precision of the balance ($\pm 0.001\text{kg}$).

- **Data Collection**

Data from the DustLite were stored in an internal memory and downloaded to a laptop PC at the end of each day. The result was a spreadsheet with two-second resolution. The wind speed, temperature, RH, and SO₂ values were stored as one-minute averages and also downloaded to the PC daily.

3. Results

Table 3-1 summarizes the run conditions. The target sweep time was 33 seconds to achieve an average 5 mph speed through the tunnel. With two exceptions all runs were completed in a single day. For the exceptions, the third run was completed the following day. Three runs were completed for all sweepers with the exception of B15, for which two runs were completed during the last day available for testing.

Sweepers B6 and B8 swept a clean track while samples were collected for carbon analysis. These data will be used to determine the contribution of the sweepers' exhaust to the PM₁₀ emission rates. All other tests were as described in the Testing Protocol and the modifications described in this report.

Sweep time was measured with a stopwatch as previously described. The DustLite integration time was determined as the time between the beginning of instrument response and the return to background concentrations. This instrument showed a fast response time, and the sweep time could be determined easily for sweepers with significant PM₁₀ emissions. Figure 3-1 is a typical time series plot of the DustLite data, which is updated every two seconds.

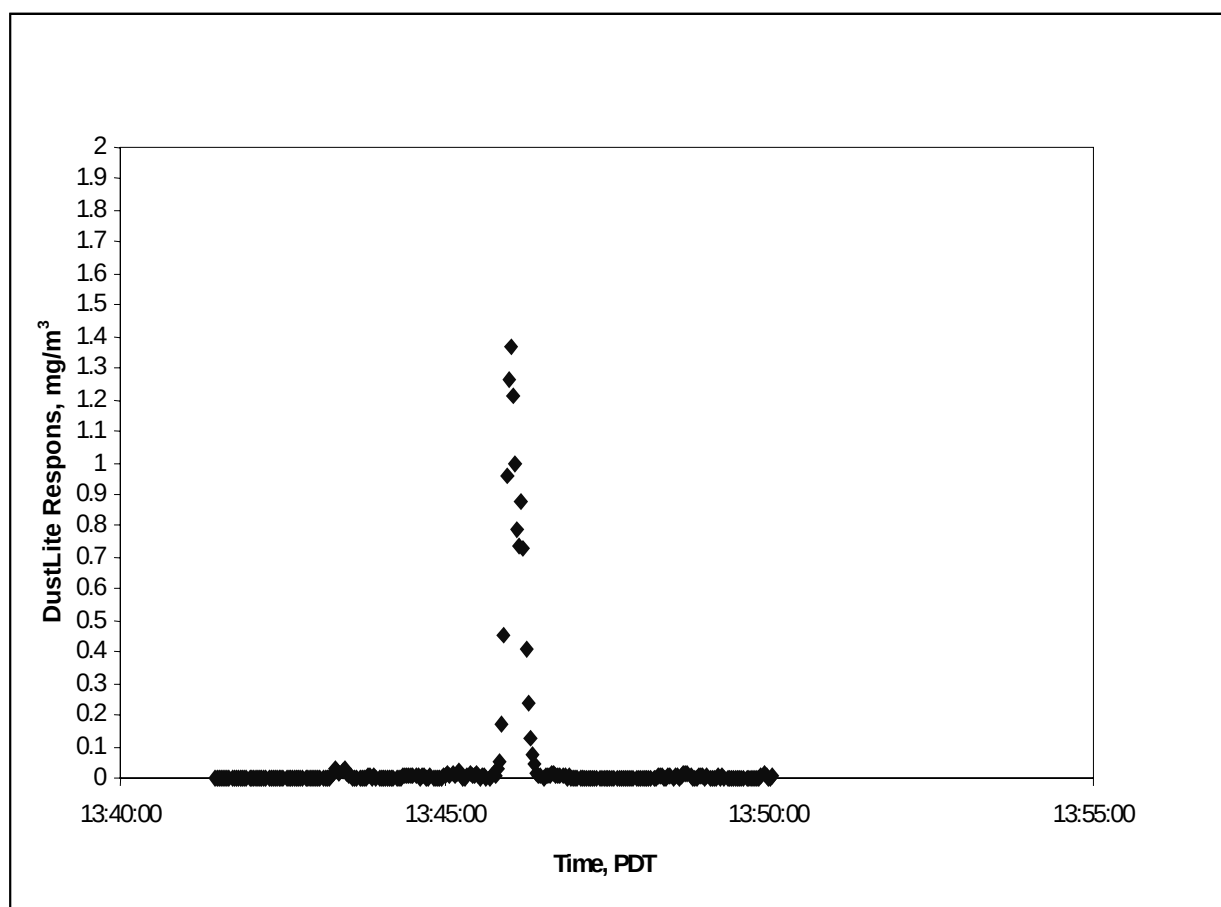
Table 3-1. Street Sweeper Test Conditions.

Sweeper	Run #	Sweep Time, sec	Integration Time, sec	SO ₂ Flow ml/min	Temp °C	RH %	Wind Speed, m/s
A1A	1	32	32	118	27	28	1.8
A1A	2	32	32	118	27	32	5.1
A1A	3	32	32	118	26	35	5.1
A2B	1	37	44	118	22	48	2.5
A2B	2	45	32	118	23	44	4.2
A2B	3	40	32	118	23	45	4
A3C	1	38	40	118	20	54	3.3
A3C	2	37	44	118	21	50	4.2
A3C	3	31	44	118	22	49	4.8
B1	1	28	36	118	17	61	1.4
B1	2	28	36	118	17	60	1.6
B1	0	31	24	113	17	67	2.4
B2	1	35	26	125	21	52	2.8
B2	2	35	26	122	21	53	1.8
B2	3	31	18	129	19	60	2.6
B3	1	40	50	119	22	45	2.9
B3	2	31	44	126	22	50	2.9
B3	3	44	44	123	22	52	1.7
B4	1	39	22	118	25	47	3.8
B4	2	37	42	114	25	44	2.8
B4	3	40	46	118	26	41	3.3
B5	1	35	34	118	28	39	3.7
B5	2	41	36	121	27	40	5
B5	3	38	26	122	27	41	4.6
B6	1	41	44	117	27	37	2.4
B6	2	32	46	116	28	37	4.1
B6	3	33	38	118	27	39	4.4
B7	1	41	38	119	25	48	4.5
B7	2	34	44	122	27	44	4.8
B7	3	31	34	124	26	41	4.2
B8	1	28	24	119	21	39	3.7
B8	2	30	28	0	21	41	3.3
B8	3	30	26	119	21	37	3.6
B9	1	29	12	120	17	50	4.6
B9	2	31	14	114	16	49	3.7
B9	3	31	14	113	15	48	5.1
B10	1	33	32	114	16	58	2.4
B10	2	38	26	114	16	53	1.2
B10	3	37	36	110	15	53	2.1
B11	1	40	28	115	24	39	3.1
B11	2	38	36	115	23	46	3.3
B11	3	34	34	159	22	47	2.7
B12	1	33	26	155	26	37	4.1
B12	2	35	36	155	26	39	3.7
B12	3	33	ND	152	26	39	4

Continued next page

Table 3-1, continued

Sweeper	Run #	Sweep Time, sec	Integration Time, sec	SO ₂ Flow ml/min	Temp °C	RH %	Wind Speed, m/s
B13	1	31	32	144	22	43	3.4
B13	2	32	36	144	22	50	1.1
B13	3	34	28	144	22	46	4.2
B14	1	48	28	145	22	44	3.4
B14	2	33	24	144	22	47	4.3
B14	3	35	14	142	21	50	4
B15	1	31	36	156	22	48	3.4
B15	2	32	42	148	22	48	2.6

Figure 3-1. Typical Response of the DustLite Monitor.

3.1 PM₁₀ Emission Rates

The PM₁₀ emission rates were calculated from the filter sampling using the equation in the Testing Protocol:

$$M_{PM10} = \frac{S \times U \times \int_0^{T_s} (C_{PM10, test} - C_{PM10,0}) \times dt}{L \times T_{test}}$$

Where,

M_{PM10} = mass of PM₁₀ entrained per length per unit of time [$\mu\text{g}/(\text{m}\cdot\text{s})$]

$C_{PM10, test}$ = PM₁₀ concentration ($\mu\text{g}/\text{m}^3$) measured during the test

$C_{PM10,0}$ = Baseline PM₁₀ concentration ($\mu\text{g}/\text{m}^3$) measured at the start and finish of the test (continuous sampler) or background PM₁₀ concentration ($\mu\text{g}/\text{m}^3$) (filter-based sampler)

S = cross sectional area of the tunnel (m^2)

U = Linear speed of airflow in tunnel (m/sec)

L = length of the tunnel deposit (m)

T_s = Time of sampling (for continuous samplers the time response is above the background)

T_{test} = Time for sweeper to complete test track

Since an integrated sample was collected on the filter, integrations were not performed when calculations were made using filter-based data. The difference between the sample and background PM₁₀ concentrations ($C_{PM10, test}$ and $C_{PM10,0}$) were multiplied by the total sampling time (usually 360 seconds). The mean flow rate ($S \times U$) was used in the equation and L and T_{test} were derived by summing over the number of tests.

The emission rate was also calculated using the DustLite data. In this case the integral was determined numerically by multiplying each DustLite value (after subtracting the background) during the interval in which the values were above the background by the 2-second update time and adding the values together. The background was determined by averaging the values 22 seconds before and after the response rose or fell to the baseline. The value of T_s for integration was the period in which the PM₁₀ concentrations were above the background.

Table 3-2 summarizes the emission rates for the runs performed on a clean track without any deposited test material. Four such runs were conducted unless the peak DustLite values continued to drop. These emission rates represent PM₁₀ primarily from the vehicle's exhaust

although there is some contribution from the sweeping motion. The sweeping motion was turned on in order to fully load the engine(s) of the sweepers in the same manner as when actual sweeping tests were performed. No filters were collected; the rates were based on the DustLite response. For sweeper B1 there was no detectable response during any of the four tests. At the bottom of the table all the values for a run number are averaged. Overall the rates decreased somewhat during the first three runs, and they stabilized by the fourth test run.

Table 3-2. PM₁₀ Emission Rates for Test Sweeping Runs Conducted on a Clean Track (no test material deposited).

Sweeper ID	Run #1 Emission Rate μg/m*sec	Run#2 Emission Rate μg/m*sec	Run #3 Emission Rate μg/m*sec	Run #4 Emission Rate μg/m*sec	Run #5 Emission Rate μg/m*sec
A1A	116	71	126	46	
A2B	95	124	Wind Reversal		
A3C	38	43	61	101	
B1	Below Detection All Runs				
B2	43	35	28	30	
B3	233	243	140	91	81
B4	79	87	112	65	
B5	102	57	42	56	
B6	36	54	36	23	
B7	63	69	58	67	49
B8	57	82	68	21	
B9	7	31	25	2	9
B10	30	52	34	58	
B11	122	110	78	126	
B12	44	36	29	50	61
B13	44	28	19	36	
B14	12	21	3	6	
B15	252	136	137	125	44
Average	81	75	62	56	49

Table 3-3 summarizes the PM₁₀ data collected during the test runs. The background PM₁₀ concentrations were between 23 and 300 μg/m³, which indicates a range in ambient pollutant levels from low to high. The precision of the filter measurements was determined by calculating the relative difference between the concentrations of the collocated pairs. The mean difference was less than 2%, indicating little bias between the samplers. The standard deviation of the relative differences was 14%, which represents the overall uncertainty of the PM₁₀ measurements (but not the overall uncertainty of the emission rate measurements). The overall precision of the DustLite emission rate measurements was determined by calculating the relative standard deviation of each set of three test runs for a sweeper and calculating the average standard deviation for all sweepers. The result was an uncertainty of 41%.

Table 3-3 Summary of Street Sweeper PM₁₀ Concentrations and Emission Rates.

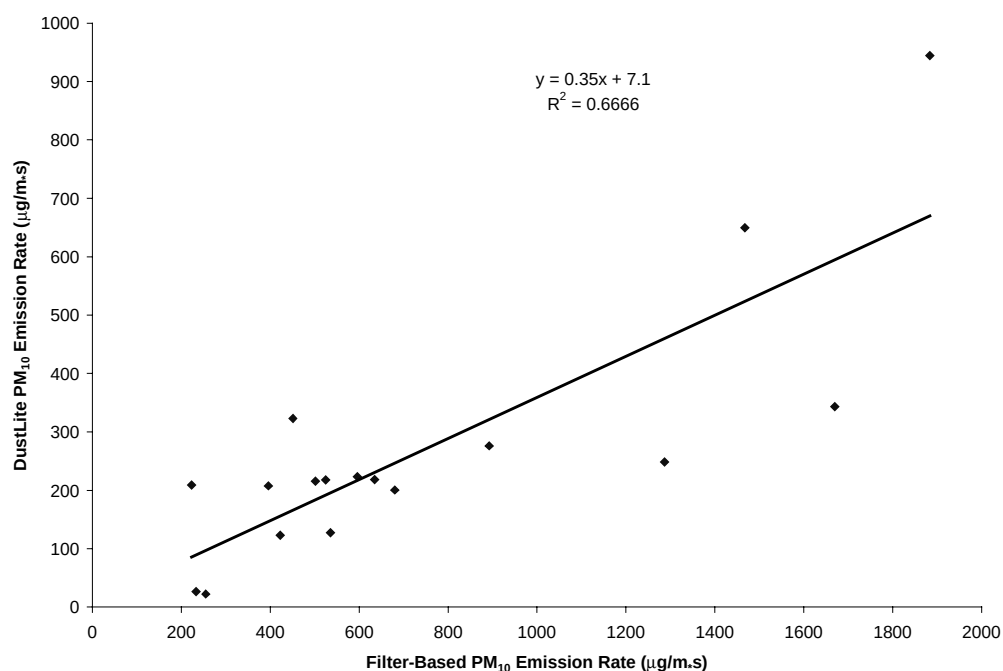
Sweeper ID	Background Filter-Based Concentration PM ₁₀ µg/m ³	Test Filter-Based Concentration PM ₁₀ #1 µg/m ³	Test Filter-Based Concentration PM ₁₀ #2 µg/m ³	Filter-Based Emission Rate Average µg/m*s	Filter-Based Emission Rate Average mg/m	DustLite Emission Rate Average µg/m*s	Clean Run DustLite Emission Rate Average µg/m*s
A1A	114	465	481	596	114	223	90
A2B	151	570	592	502	122	216	110
A3C	148	424	386	396	84	208	61
B1	110	661	650	451	78	323	
B2	23	702	681	635	128	218	34
B3	146	909	950	680	156	201	157
B4	90	348	226	223	52	209	85
B5	124	451	488	536	122	127	65
B6	253	1,599	1,659	1883	399	944	37
B7	98	955	971	1468	311	649	61
B8	62	393	386	525	92	218	57
B9	54	146	201	233	43	27	15
B10	89	2,512	2,421	1670	361	343	43
B11	126	1,363	1,269	1287	288	248	109
B12	83	661	653	892	180	276	44
B13	96	481	420	423	82	123	32
B14	105	294	295	255	59	22	10
B15	317	18,298	18,182	33585	2147	3392	139

The emission rates are expressed in $\mu\text{g}/\text{m}\cdot\text{sec}$ as described in the Protocol. This normalizes the rate to both the distance and time swept. For the filter-based method we also show the emission rate normalized only to the distance swept. Since the nominal cumulative sweep time for three runs was about 100 seconds, these values are about 100 time higher and are expressed in units of milligrams/m (mg/m). This method of expressing the emission rate does not penalize sweepers that went faster in which case their sweep time would be shorter and the emission rate higher.

The column that is second from the right shows the emission rate determined from the DustLite and averaged over the number of test runs. In all cases the DustLite emission rates were significantly less than the emission rate determined by the filter sampling. This is consistent with the results obtained in Phase 1. This bias is likely due a lower scattering efficiency of the test material dust compared with the dust on which the factory calibration was based. This could be due to differences in size distribution between the two types of dust (i.e., washed sand mixed with paint pigment compared to Arizona road dust). Figure 3-2 is a plot of this data with a least squares regression line shown. The correlation coefficient squared (0.67) indicates a moderate correlation between the emission rates based on the two types of measurements.

The far right column is the averaged emission rate for the clean runs as determined by the DustLite. This represents primarily the sweeper's exhaust PM₁₀ emissions. These emission account for between 5 and 50% of the emissions when the sweepers were sweeping test material. These are most likely upper limits as the DustLite probably underestimates PM₁₀ emissions from the test material (which are expected to generally be greater than 1 μm aerodynamic diameter) compared to diesel emissions (which are expected to be generally less than 1 μm aerodynamic diameter).

Figure 3-2. Comparison of Filter-based and DustLite-based Emission Rates.

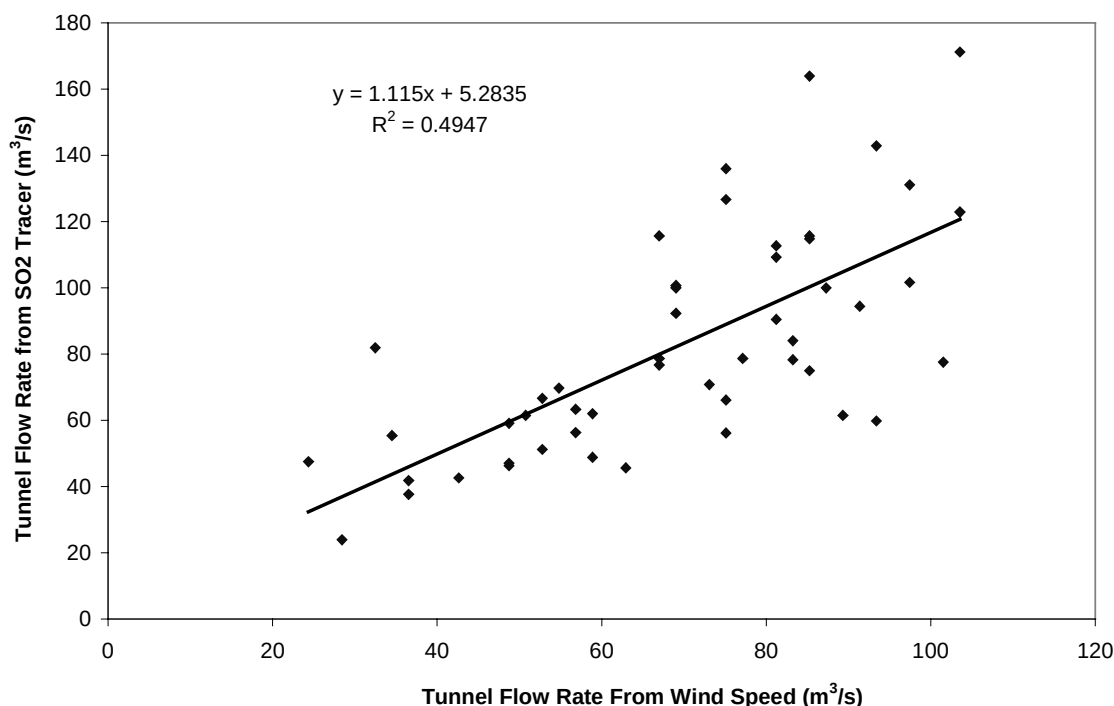


The flow rate through the tunnel was calculated by both the measured wind speeds multiplied by the cross-sectional area of the tunnel as specified in the protocol and by the dilution ratio of the tracer gas. The latter is calculated by the following expression:

$$F(\text{m}^3/\text{s}) = \text{SO}_2 \text{ Flow Rate (ml/sec)}/\text{SO}_2 \text{ net concentration (ppm)}$$

Figure 3-3 shows a comparison of the flow rate derived by the two methods. While there is a general agreement, a large amount of scatter is indicated. These results are similar to those we previously obtained (Fitz, 1995) and during Phase 1. For the wind speed approach to be accurate, the measured flow must represent the mean flow rate through the tunnel. Since the velocity profile is non-linear, with zero flow at the walls, it is unlikely that this is true. The degree to which the measured speed represents the mean speed is also expected to depend on the flow rate through the tunnel. Although we believe that the tracer method is more accurate, the wind speed approach does yield values that are similar since the slope is near unity. Since the wind speed approach is specified in the protocol, the approach was used in the emission rate calculations.

Figure 3-3. Tunnel Flow Rates Derived from Wind Speed Compared with Those Derived from SO₂ Tracer.



3.2 Determination of Particulate Carbon

Following the four cleans runs for sweepers for sweepers B6 and B8, four additional clean runs were made while sampling with quartz filters. The objective was to determine the fraction of diesel exhaust contributing to the PM₁₀ emission rate assuming that the emissions under these conditions are primarily from the engine(s). Based on the total carbon measurements, the rates were 5 and 23 µg/m*s for sweepers B6 and B8, respectively. These may be compared with the much higher filter-based PM₁₀ emission rates of 1883 and 525 µg/m*s when these sweepers swept test material.

For these carbon-sampling clean runs the averaged PM₁₀ emission rates from the DustLite data were 27 µg/m*s for B6 and 44 µg/m*s for B8. These are similar to the carbon emission rate and may be compared with the average DustLite-derived emission rates of 944 and 218 µg/m*s when these sweepers swept test material.

3.3 Pick-up Efficiency

Pick-up efficiency was calculated by assuming that the amount of particulate matter lost by transport by air out of the tunnel and the amount of residue in the decanted solutions were negligible. This was shown to be the case in the Phase 1 testing. The efficiency was therefore calculated as follows:

$$N_{\text{pick-up}} = \frac{W_{\text{base}} - W_{\text{test}}}{W_{\text{base}}} \times 100$$

Where:

$N_{\text{pick-up}}$ = pick-up efficiency (%)

W_{base} = weight of the test material spread over the track before the test (kg)

W_{test} = weight of the test material recovered by scrubbing the track and drying the residue

Table 3-4 summarizes the results of the pickup efficiency calculations. The overall precision of the pick-up measurements was determined by calculating the relative standard deviation of each set of three test runs for a sweeper and taking the average for all sweepers. The result was an uncertainty of 11%. This may be used as a measure of overall uncertainty for pick-up measurements.

We also performed two quality control tests for the pick-up efficiency. The first involved scrubbing the track a second time to determine how much material might be left on the track after the first scrubbing. The amount was 0.22 kg, which was nearly ten times less than the smallest amount picked up after a sweeper run. We also deposited 3.6 kg (this amount was typical of that recovered from sweeper tests) on the test track and scrubbed it without running a sweeper. We were able to recover 84% of that material. This is most likely a lower limit for recovery as some material was observed to be transported out of the tunnel during application. We conclude that

the scrubber was a highly effective method to determine the amount of test material that the sweeper did not remove.

Table 3-4 Sweeper Pick-up Efficiency.

Sweeper	Run #	Residue Run, kg	Pick-up Efficiency %	Sweeper	Run #	Residue Run, kg	Pick-up Efficiency , %
A1A	1	5.664	67%	B7	1	1.888	89%
A1A	2	12.648	26%	B7	2	1.936	89%
A1A	3	8.545	50%	B7	3	4.397	74%
A2B	1	9.329	46%	B8	1	9.944	42%
A2B	2	12.462	28%	B8	2	6.733	61%
A2B	3	6.036	65%	B8	3	9.954	42%
A3C	1	6.859	60%	B9	1	2.623	85%
A3C	2	4.163	76%	B9	2	2.137	88%
A3C	3	6.280	63%	B9	3	2.354	86%
B1	1	6.134	64%	B10	1	2.723	84%
B1	2	2.348	86%	B10	2	1.536	91%
B1	3	1.618	91%	B10	3	1.815	89%
B2	1	1.672	90%	B11	1	2.783	84%
B2	2	2.186	87%	B11	2	2.040	88%
B2	3	3.315	81%	B11	3	1.857	89%
B3	1	2.785	84%	B12	1	1.645	90%
B3	2	3.361	80%	B12	2	1.181	93%
B3	3	2.750	84%	B12	3	1.151	93%
B4	1	8.191	52%	B13	1	4.986	71%
B4	2	7.032	59%	B13	2	4.868	72%
B4	3	7.586	56%	B13	3	6.730	61%
B5	1	1.800	90%	B14	1	2.323	86%
B5	2	1.408	92%	B14	2	2.984	83%
B5	3	1.828	89%	B14	3	2.447	86%
B6	1	1.106	94%	B15	1	2.165	87%
B6	2	1.039	94%	B15	2	1.904	89%
B6	3	2.145	88%				

4.0 Conclusions and Recommendations

PM₁₀ emission rates were determined for street sweepers by measuring concentrations when the sweepers negotiated a test track set up within a tunnel. Measurements were made using continuous sampler based on light scattering and by collecting a filter sample for three consecutive test runs. The emission factors determined by two measurement methods were moderately correlated and the factors from the continuous analyzer were biased low by approximately a factor of three compared with the filter-based PM₁₀ emission measurements. The precision of the PM₁₀ filter samplers was calculated to be 14%. We believe that the filter samples

should be the reference due to their quantifiably good precision and their ability to directly determine mass (the continuous analyzers measure particle scattering, which is particle-size dependent). We do not see any reason for using continuous analyzers for sweeper testing as those currently available do not respond directly to mass or have insufficient time resolution.

Several changes were made in the original test protocol to streamline the operation. These included not collecting TSP samples and not taking a sample of the supernate of the scrubber recovery solution, but rather waiting overnight for the solids to settle. The sweepers were also staged in an area that was not upwind of the test track and brought to the track under full power. This procedure eliminated the continuous analyzer's double peak often observed during the Phase 1 testing in which the first peak was ascribed to emissions from the diesel engine as it was brought up to full power.

The use of a floor scrubber to determine sweeper pick-up efficiency was shown to be accurate and precise. The overall precision for the pick-up efficiency was found to be 11% including the variability due to the sweepers. The precision of the scrubber approach alone was therefore even better. The scrubber was shown to recover over 80% of material deposited.

The T_{test} in the algorithms for defining the PM₁₀ emission rates also needs further definition in the Test Protocol. The T_{test} in the denominator should simply be the time required for the sweeper to negotiate the test track and not include the clear time since the objective is to normalize the data to the amount of time sweeping. When integrating to T_{test} , this should represent the time until the response of the analyzer has returned to background.

We have shown for our conditions that, although there is significant scatter, the tunnel flow rates determined by wind speed and by tracer measurements were similar although there was not a strong correlation between the two. Part of this poor correlation may be due to the variability of the wind speed and that the SO₂ and wind speed being offset in time by the time required for the SO₂ to travel the length of the tunnel. We could not make this adjustment since the travel time was typically 30 seconds and we recorded one-minute averages. A higher rate of data capture such as one data point per second would allow this adjustment and the two flow measurements would most likely a higher degree of correlation. We recommend that for any test setup that flow measurements based on wind speed verified by a tracer approach.

One aspect of the test protocol that was almost universally disliked by operators was the speed bump. This bump usually required the operator to slow down, thus making runs of a consistent time difficult to achieve. A bump of less height or a smoother one should be considered for future test protocols, and its dimensions should be exactly specified. Allowing the sweeper to operate at a higher speed than 5mph also should be considered as an option for manufacturers. Several were confident that they could maintain the PM₁₀ control and sweeper efficiency at higher speeds.

Based on our observations we recommend several other minor changes in the Test Protocol that we feel would improve the accuracy and precision. One would be to lay down test material starting 20 or more feet past the tunnel entrance to lower the amount of backwash (dust blown outside the tunnel that subsequently went around the tunnel). A shorter length of test material to sweep or a longer tunnel would also allow greater mixing of the PM₁₀ and present a more

homogeneous mixture to the PM₁₀ sampler. The device used to deposit the test material should be designed to minimize suspension of the test material during the depositing. This may involve lowering the drop height and/or shrouding the release area. Another concern is maintaining a more consistent wind speed. The direction and variability of the prevailing wind at our test location resulted in a wide degree of wind speeds. Since there may be some second order effects of wind speed on emission measurements, an effort should be made to achieve more consistent flow rates. This may involve mounting partial doors on the tunnel, aligning the tunnel directly with the prevailing wind direction, or choosing a location with more favorable prevailing winds. A final recommendation is that the track surface more closely resemble a street surface. Our test track was roughly broomed concrete with grooves perpendicular to the direction of travel.

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