Project Title:
Improvement of PM_{10} Emission Factors for Almond Harvesting

Annual Report F.Y. 2005-2006

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Executive Summary

This project aims to continually update and improve the PM_{10} emission factors for almond harvest operations. The focus for this year's work was the determination of the PM_{10} emission factor for conventional sweeping operations. This will replace the "professional judgment" estimate of sweeping operations emission factor based on percentage of harvest operation by providing actual field data. The study made use of representative harvest equipment and practices. Continued evaluation of the particle size distribution (PSD) of almond dust collected from the harvest operations was also conducted to be able to make an estimate of the true PM_{10} concentrations collected by FRM PM_{10} samplers.

Test sites for this year's study included orchards in the Bakersfield and Arbuckle areas. Equipment from two manufacturers was used during the conventional sweeping operations. These were designated as Equipment A (Model b, 1995, 8 ft head) and Equipment B (Model Year 2003, 8.5 ft head). These are typical equipment used for orchard sweeping operations. The Almond Board Environmental Committee was provided the codes for the equipment used for all the tests. PM_{10} emission factors were calculated based on the Vertical Profiling Method (VPM) and LIDAR being used by the U.C. Davis (UCD) group and the Dispersion Modeling used by both the UCD and Texas A&M University group (TAMU).

In the Bakersfield area (Site 1: Wasco area), PM_{10} for sweeping and windrowing of six complete rows were observed. The equipment made three sweeping passes with the blower on per tree row, followed by two passes to close out just using the sweeper. Both sweepers operated identically. In the Arbuckle area (Site 2), the sweeping required four passes per tree row including one blow pass. The sweeping included two inside sweeper passes, one with blower on and one off, and two closing sweeper passes, both with the blower off, for a total of four passes per tree row.

Soil moisture and percentages of sand, silt and clay components were also measured in each of the test sites. The table below shows the average value of these parameters at the two sites used for the tests.

Test Site	Soil Moisture (%)	% Sand	% Silt	% Clay
Site 1: Wasco Area	5.0	75	13.8	11.3
Site 2: Arbuckle Area	1.9	51.5	30.3	18.2

Summary of Results for this Year's Work

PM_{10} Concentrations, PSD and Over-sampling Bias

a. The average MMD and GSD from dust samples collected from TSP filters are 15.8 and 2.02, respectively. Following the lognormal distribution, the true PM_{10} was estimated to be about 25.77% of TSP. The average MMD and GSD for the past four years of data were about 18 and 2, respectively.
b. The ratio of FRM PM_{10} concentration measurements compared with TSP was found to be about 40%
c. Over-sampling bias calculations showed that the ratio of true PM_{10} from FRM PM_{10} sampler was found to be about 65%. There will be a 35% reduction in PM_{10} concentration when the bias is accounted for.
d. Regression analysis of true PM_{10} concentration from TSP showed that the ratio of true PM_{10} to TSP was about 28.6%. The data showed that the dust sample is very similar to other agricultural dust particularly feed yard dust with a true PM_{10} to TSP ratio of about 25%.

Dispersion Modeling Results

a. The overall average emission factor for the sweepers was 621 $\pm$ 587 kg/km^2.
b. When corrected for the true PM_{10} concentrations, the EF was recalculated and found to be an average of 321 $\pm$ 212 kg/km^2.
c. For this year's annual report, a value of 620 kg/km^2 is being recommended as the new and current emission factor for sweeping operations using conventional sweepers.

I. Project Overview

1.1 Background and Introduction

Concentrations of PM_{10}, particulate matter of 10 micrometers or less in aerodynamic diameter, at receptor areas in the San Joaquin Valley, have exceeded the national air quality standards for a number of years. Faced with a mandate to regulate PM_{10} sources to attain a 5% reduction in PM_{10} concentrations each year, the San Joaquin Valley Unified Air Pollution Control District (the District) will impose controls on all significant PM sources. The current PM_{10} emission inventory shows almond harvesting to be one of the largest agricultural sources of PM_{10}. The accuracy of this inventory depends on accurate estimates of emission rates from all sources. The PM_{10} emission factor currently used by the District for almond harvesting is based on measurements made on almond pick-up operations by the University of California, Davis (UCD). The measured emission factors for almond pick-up were used to estimate PM_{10} emission factors for the other two operations associated with almond harvesting: shaking and sweeping. Based on visual observation, a factor 10% of that for the pick-up was suggested for sweeping. Taken together, these three emission factors comprise the current almond harvest PM_{10} emission factor.

Ongoing research addresses the difficulties and uncertainties in the measurements of PM_{10} emissions generated during almond harvesting operations. In addition, the work evaluates whether current measurement methods are sensitive enough to provide quantitative results from alternate almond harvesting management practices. This information will be necessary to determine the effectiveness of the District's PM_{10} control regulations.

Aerosol monitors developed by TAMU and UCD were used to measure PM_{10} in the vicinity, both upwind and downwind, of the ongoing almond harvest operations in the 2002, 2003, 2004 and 2005 seasons. Meteorological parameters were recorded simultaneously with aerosol collection and the LIDAR instrument was employed at some sites to detect and provide information about the vertical and horizontal extent of the plumes. Soil samples were collected for evaluation of moisture and soil texture.

The current EPA-approved model for source dispersion, the Industrial Source Complex Short Term (ISCST3), has been used and evaluated for the prediction of emission factors from almond harvesting. In 2006, the EPA will begin the transition from ISCST3 to AERMOD as the recommended model for use in modeling the downwind dispersion of PM. AERMOD was developed by the EPA and the American Meteorological Society to better describe the dispersion of pollutants in the planetary boundary layer.

Field work conducted in the 2005 almond harvest season was primarily focused on obtaining a measurement-based PM_{10} emission factor for almond sweeping operations to replace the estimate currently in use by the District. This measure of a base-line emission factor shall be as representative of standard industry practices as possible. Due to the diversity in harvest equipment, orchard conditions, and sweeping practices industry-wide, our approach was to measure PM_{10} emission factors for "typical" sweeping operations.

1.2 Goals and Objectives

The overall goal of the project is the continued improvement of the PM_{10} emission factor for almond harvesting operations. The specific objectives are as follows:

a. to provide a measurement-based PM_{10} emission factor for almond sweeping operations being most representative of standard industry practices;
b. to make use of dispersion modeling and vertical profiling to establish the emission factor; and
c. to provide continuous investigations on the sampling bias of FRM PM samplers including analysis of the particle size distribution of dust collected from ambient filters.

The current study was focused on replacing the "professional judgment" estimate of PM_{10} emission factor for sweeping operations while using representative equipment and practices. The study was supplemented by industry observers during the conduct of tests.

1.3 Test Sites

The two test sites identified for this year's study were the Wasco (Site 1) and the Arbuckle areas (Site 2). Our understanding is that the amount of energy required to effectively move the almonds in an orchard to windrows depends primarily on orchard conditions. Characteristics such as orchard floor conditions, presence of irrigation lines, and size of crop determine the number of sweeping passes that must be made with the blower on, the ground speed of those passes, and the volume and velocity of air needed. The number and intensity of sweeping (or raking) only passes (clean-up pass) are much more uniform within each category of equipment type. In order to capture the fullest range of "typical" sweeping practices, the following process variables were used:

- In the Wasco area (Site 1), the complete sweeping and windrowing of six complete rows, oriented in the North-South direction, were observed. The sweepers required 3 clean-up passes in "typical" conditions with the blower on per tree row followed by 2 blow passes to close out just using the sweeper.
- In the Arbuckle area (Site 2), the sweeping required four passes per tree row including one blow pass. The sweeping included two inside sweeper passes, one with blower on and one off and two closing sweeper passes, the latter with the blower off for a total of four passes per tree row. The rows are oriented in the East-West direction.

1.4 Experiment Summary

There were a total of 10 tests performed in 2005. The details are shown in the table below. TAMU personnel were present at Test Site 1 and their sampling equipment were left behind and used on Test Site 2 where UCD personnel followed the same protocol used in Test Site 1.

Summary of Soil Characteristics

Table 1 shows the average values for the soil characteristics in all the tests.

Table 1. Average of Soil Characteristics in the Test Sites

Test #	Site	Rows	Implement	Soil moisture (%)	Sand (%)	Silt (%)	Clay (%)
All	1	N-S	Equipment A/Equipment B, Model a	5.0	75.0	13.8	11.3
All	2	E-W	Equipment B, Model b	1.9	51.5	30.3	18.2

II. PM_{10} Concentration and PSD Analysis

2.1 Introduction

FRM PM_{10} and TSP samplers were collocated upwind and downwind from the almond orchard while conventional sweeping operations were in progress. The most common sweepers were used (Labeled Equipment A and Equipment B). For the TAMU group, there were a total of five locations for the samplers, one upwind and four downwind along the edge of the orchard. GPS locations of the samplers were encoded to aid in accurate placement for the dispersion modeling runs. The UCD group installed similar FRM PM samplers on several towers coupled with the aid of LIDAR for plume height characterization.

2.2 PM_{10} and TSP Concentration Measurements

The PM_{10} concentration of dust collected downwind when the two different machines were in operation as described above are summarized in Table 1. These concentrations were calculated from the low volume FRM PM_{10} samplers used during the tests. There were a total of 27 PM_{10} filters from 6 tests. The overall average PM_{10} concentrations measured downwind when the sweepers were in operation was found to be 701 $\pm$ 533 μg/m^3. The average TSP concentration was found to be 1591 $\pm$ 1310 μg/m^3. The ratio of PM_{10} to TSP was about 44% based on the overall average concentrations for both samplers.

2.3 PSD Analysis

Particle size distribution analyses were performed on all TSP filters. The average mass median diameter (MMD) and geometric standard deviation (GSD) of the dust collected from the filters when the sweepers were in operation are shown in Table 2.2. The overall MMD and GSD were 15.8 and 2.02 respectively. Table 2.3 shows the summary of PSD analysis over the four almond harvesting seasons. The average MMD and GSD over four years was about 18 and 2, respectively. Following a log normal distribution, the fraction of “true” PM_{10} from these MMD and GSD data were found to be about 19.8%. This value is significantly lower than the fraction of PM_{10} concentrations derived from the FRM PM_{10} samplers as discussed above (i.e. 44%). This shows over sampling of the FRM PM_{10} samplers.

2.4 Over-sampling Calculations

Over several years, over-sampling bias was observed on the FRM PM_{10} samplers when compared with TSP samplers. Regression analysis was performed on FRM PM_{10} and TSP sampler measurements. This is shown in Figure 2.1. Good linear correlation was observed although the regression coefficient (R^2 = 0.702) was lower than the previous year’s data. The FRM PM_{10} concentrations were about 40.4% of the TSP concentration measurements. There were many instances where the PM_{10} concentration readings were much greater than the TSP readings on collocated samplers (upper left most points in the graph). This value compares well with the ratio of the overall FRM PM_{10} concentrations to that of the TSP concentrations.

Shown in Figure 2.2 is the regression analysis between true PM_{10} and FRM PM_{10} sampler concentration readings. The regression coefficient was higher ($R^2 = 0.753$) and about 65% of FRM PM_{10} concentration readings were considered “true” PM_{10}. There should be a 35% reduction in the FRM PM_{10} concentration readings if over sampling bias is accounted for.

Figure 2.3 shows the correlation between true PM_{10} and TSP sampler concentration readings. This gave the highest correlation coefficient ($R^2 = 0.93$) and also showed that about 28.9% of the TSP concentrations were considered true PM_{10}. These numbers were consistent with the previous year’s data. Following the lognormal distribution, the true PM_{10} was estimated to be about 25.77% of TSP.

2.5 Summary:

a. The average MMD and GSD from dust samples collected from TSP filters were15.8 and 2.02, respectively. Following the lognormal distribution, the true PM_{10} was estimated to be about 25.77% of TSP. Over four years the MMD and GSD values were converging to about 18 and 2, respectively.
b. The ratio of FRM PM_{10} concentration measurements compared with TSP was about 40%
c. Over-sampling bias calculations showed that the ratio of true PM_{10} from FRM PM_{10} sampler was about 65%. There will be a 35% reduction in the PM_{10} concentration when the bias is accounted for.
d. Regression analysis of true PM_{10} concentration from TSP showed that the ratio of true PM_{10} to TSP was about 28.6%.

Table 2.1 Summary of PM_{10} and TSP concentration measurements for sweeping operation using representative conventional equipment.

Test #	Location	PM_{10} (ug/m^3)	TSP(ug/m^3)	Average PM_{10}(ug/m^3)
05-041	D1	1,306	672	327 $\pm$ 232
	D3	661	219	
	D4	48	171	
	Levy	80	245	
05-042	D1	883	2916	1900 $\pm$ 835
	D2	889	2221	
	D3	1,003	1406	
	Levy	387	1055	
05-043	D1	601	1686	3624 $\pm$ 1522
	D2	1,420	3239	
	D3	1,989	5890	
	D4	2,154	3986	
	Levy	1,253	3319	
05-044	D1	446	1146	1177 $\pm$ 272
	D2	525	1119	
	D3	587	1443	
	D4	542	1409	
	Levy	268	767	
05-045	D1	251	664	1032 $\pm$ 373
	D2	388	1236	
	D3	644	1465	
	D4	391	1177	
	Levy	300	617	
05-046	D2	756	1990	1225 $\pm$ 792
	D3	696	1809	
	D4	221	704	
	Levy	234	398	
All		701 $\pm$533	1591 $\pm$ 1310	

Table 2.2 Summary of PSD analysis of dust collected downwind during sweeping operation.

Test No.		
	Average for All	
PSD ->	MMD	GSD
05-041	18.05	2.18
05-042	16.63	2.04
05-043	14.08	1.89
05-044	16.04	2.07
05-045	16.11	2.36
05-046	16.11	2.49
Average	15.80	2.02

Table 2.3 Summary of PSD analysis over the four almond harvesting seasons.

2002		2003		2004		2005	
MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD
19.0	2.0	18.8	2.1	17.6	2.1	15.8	2.02
ρ_d	2.7565	ρ_d	2.5621	ρ_d	2.3855	ρ_d	2.568

ρ_d = particle density, g/cc

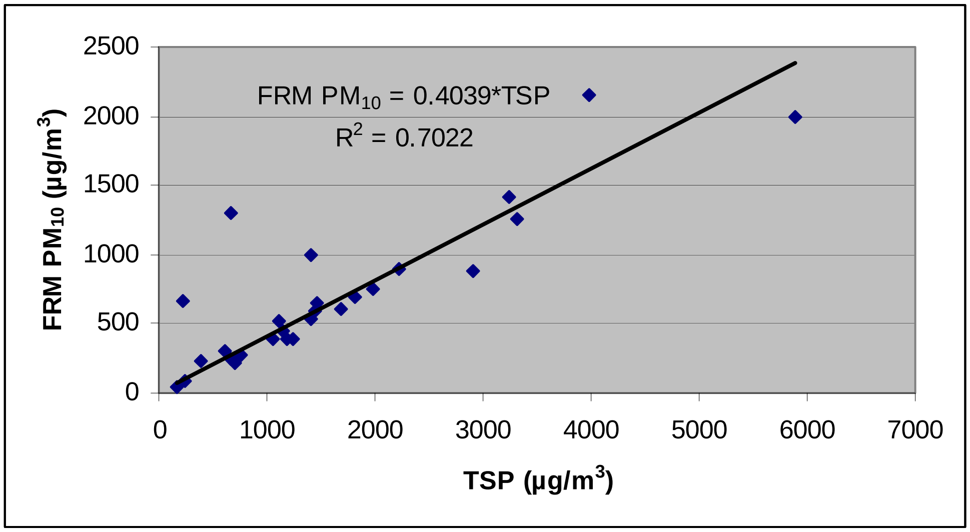

Figure 1. Regression analysis between FRM PM_{10} and TSP Concentrations.

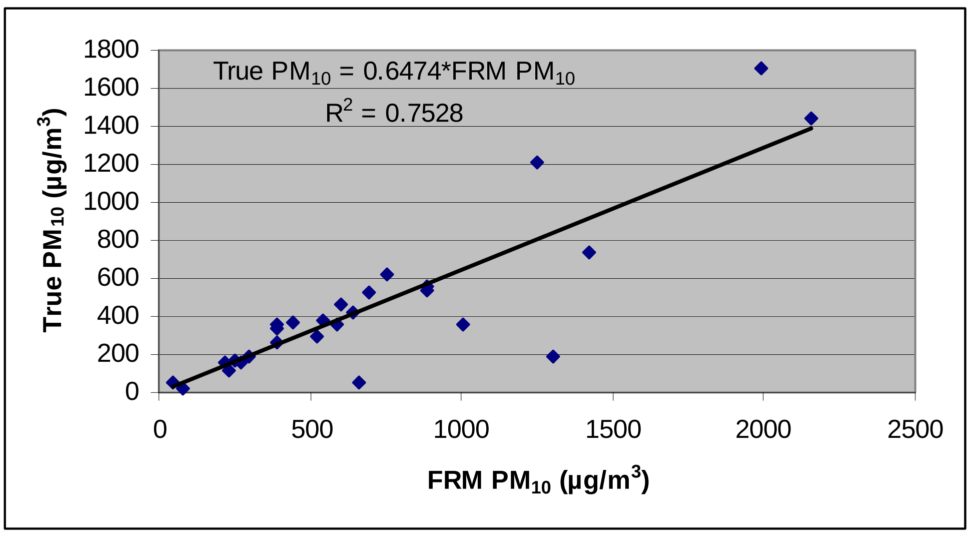

Figure 2. Over- sampling bias for FRM PM_{10} sampler.

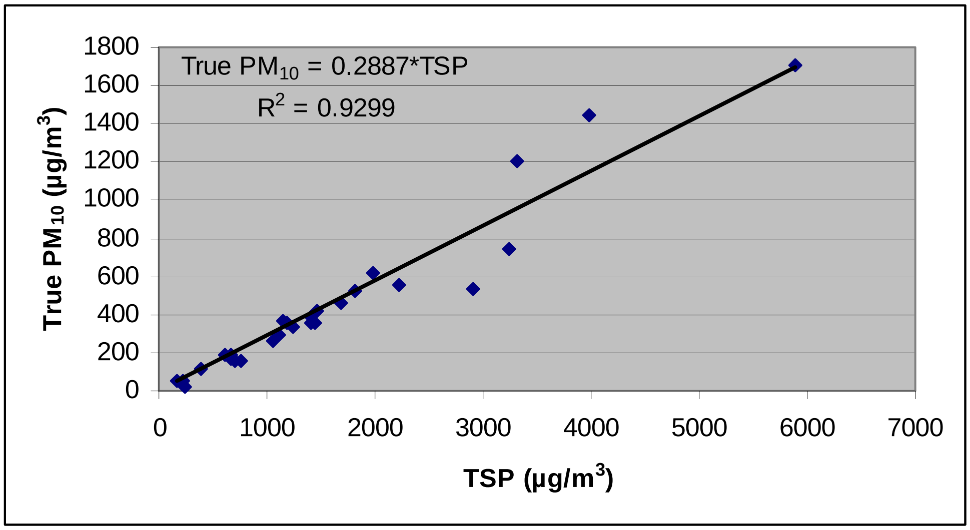

Figure 3. Regression analysis between true PM_{10} and TSP concentrations.

III. Dispersion Modeling and Vertical Profiling Method

3.1 Introduction

One primary goal for this year is to make full use of EPA-approved dispersion modeling tools to establish the emission factor for almond harvest operations. Evaluations of the PM_{10} measurements and modeling method presented in previous years have noted the EPA-approved ISCST3 model as the preferred method for computing PM_{10} emission factors. The downwind PM_{10} concentrations from all samplers were inputted into the model and the PM_{10} emissions from the source was back-calculated. The model considers all pertinent meteorological data gathered during each run. Applying this dispersion model to the wide range of data collected was based on the experience that the average emission factor for a test was found to be relatively insensitive to the choice of measured concentration used to predict emission rates. However, the sampler locations should be within a given wind-vector coverage (i.e. within 45^o from the source). In addition, the project has developed a way to make full use of all downwind sampler data to establish the emission factor by way of normalizing all sampler data. Thus, the only reasons for eliminating raw data were filters that were known to be contaminated and samples collected when wind direction was 180^o different from ideal. Runs were also made to establish the emission factor based on downwind PM_{10} and TSP concentrations. The latter was used to predict the "true" PM_{10} concentrations and therefore a corrected PM_{10} emission factor considering sampler biases.

The only limitation of this dispersion modeling as a tool to establish the emission factor is that, the back-calculated emission rates from the source (i.e. the harvester or the sweeper) cannot be compared with a measured gravimetric PM_{10} concentration data. This will be the goal for this year's sampling.

3.2 ISCST3 Results from 1 meter Sampler PM_{10} Concentrations Data

Shown in Table 3.1 is the summary of the dispersion modeling runs using downwind sampler PM_{10} measured concentrations data collected with TAMU samplers (at 1 meter height). The overall average emission factors for the sweepers were found to be about 647 $\pm$ 749 kg/km^2. This emission factor was estimated from a total of 27 PM_{10} sample filters used during 6 tests. Actual meteorological data collected during the field sampling events were used to run the dispersion modeling.

3.3 ISCST3 Results from "True" PM_{10} Concentrations Data

Table 3.2 shows the sweeping emission factors calculated from the results of using the TSP concentrations followed by calculating the "true" PM_{10} concentrations. The overall average emission factors for the sweepers were found to be about 321 $\pm$ 212 kg/km^2. There was a reduction of about half from the uncorrected emission factor (about 650 versus 320 kg/km^2). These results were consistent with the estimated ratio of "true" PM_{10} concentrations to the FRM PM_{10} concentrations and largely due to the over sampling bias of the FRM PM_{10} sampler. The emission factors derived from the FRM PM_{10} concentrations is still a very conservative emission factor to use for regulatory purposes.

3.4 ISCST3 Results from Tower PM_{10} Concentrations Data

Shown in Table 3.3 is the summary of the dispersion modeling runs using downwind sampler PM_{10} measured concentrations data collected with UCD samplers at 1, 3, and 5 meter heights The overall average emission factors for the sweepers were found to be about 592 $\pm$ 336 kg/km^2. The meteorological data used to arrive at this emission factor is the same as those used for the TAMU tests. Only the locations of the samplers have changed as well as the sampler heights. The difference in the means is only about 50 kg/km^2. Thus, the dispersion modeling runs proved to be quite consistent regardless of sampler location or the differences in sampler elevation.

3.5 Overall Summary

Results of dispersion modeling suggest that the sweeping emission factor based on FRM PM_{10} sampler was about 621 $\pm$ 587 kg/km^2 when considering all samples collected using both TAMU and UCD samplers. When corrected for the true PM_{10} concentrations, the PM_{10} emission factor was found to be about 321 $\pm$ 212 kg/km^2. The corrected PM_{10} emission factor showed no significant difference between the two sweepers used in the tests. For this year's report, a value of 620 kg/km^2 is being recommended as the new and current emission factor for sweeping operations using conventional sweepers.

Table 3.1 Summary of ISCST3 dispersion modeling runs for sweeping operations

Test #	Location	PM_{10} (ug/m^3)	EF (kg/km^2)	Average EF (kg/km^2)
05-041	D1	1,306	4,157	1,535
	D3	661	2,028	
	D4	48	228	
	Levy	80	235	
05-042	D1	883	997	520
	D2	889	633	
	D3	1,003	664	
	Levy	387	399	
05-043	D1	601	1043	755
	D2	1,420	1174	
	D3	1,989	1209	
	D4	2,154	1104	
	Levy	1,253	1012	
05-044	D1	446	3355	665
	D2	525	1980	
	D3	587	1573	
	D4	542	1137	
	Levy	268	2024	
05-045	D1	251	277	266
	D2	388	307	
	D3	644	450	
	D4	391	263	
	Levy	300	351	
05-046	D2	756	323	203
	D3	696	620	
	D4	221	3310	
	Levy	234	1145	
			Overall Mean	647
			Overall Standard Deviation	749

Table 3.2 Summary of ISCST3 dispersion modeling runs for sweeping operations

Test #	Location	True PM_{10} (ug/m^3)	EF (kg/km^2)	Average EF (kg/km^2)
05-041	D1	185	543	229
	D3	55	161	
	D4	53	156	
	Levy	19	56	
05-042	D1	544	356	279
	D2	564	369	
	D3	341	226	
	Levy	251	166	
05-043	D1	467	236	566
	D2	741	375	
	D3	1703	865	
	D4	1459	748	
	Levy	1195	608	
05-044	D1	368	519	441
	D2	301	423	
	D3	361	506	
	D4	383	536	
	Levy	158	222	
05-045	D1	166	112	196
	D2	333	225	
	D3	412	278	
	D4	359	241	
	Levy	186	125	
05-046	D2	616	263	151
	D3	524	224	
	D4	157	67	
	Levy	117	49	
			Overall Mean	321
			Overall Standard Deviation	212

Table 3.3 Summary of ISCST3 dispersion modeling runs for sweeping operations

Test #	Location	PM_{10} (ug/m^3)	EF (kg/km^2)	Average EF (kg/km^2)
05-041	1 m	571	613	720
	3 m	562	720	
	5 m	492	827	
05-042	1 m	329	258	417
	3 m	589	625	
	5 m	468	367	
05-043	1 m	670	204	275
	3 m	730	334	
	5 m	452	288	
05-044	1 m	345	392	291
	3 m	259	312	
	5 m	127	168	
05-045	1 m	1221	858	717
	3 m	664	630	
	5 m	462	662	
	9 m	260	1107	
05-046	1 m	2392	596	708
	3 m	1551	788	
	5 m	686	740	
05-047	1 m	621	596	1013
	3 m	355	625	
	5 m	593	1818	
05-049	1 m	390	342	594
	3 m	425	645	
	5 m	308	795	
			Overall Mean	592
			Standard Deviation	336