Chapter 3
Test Site Results

This section presents and discusses the results from the two-part field testing program. The watering tests of scraper transit conducted at NCKTC are discussed first, and the DFS mud/dirt carryout tests are discussed second. In spite of weather-related delays (from rain and variable winds), the number of tests performed at both sites exceeded the targets set in the Site-Specific Test Plan.

Watering Control of Scraper Transit Emissions

A total of 19 mass flux profiling tests were conducted at NCKTC during September 1999. Table 3-1 presents the test site parameters associated with each run. Note that the 19 tests are distributed over two uncontrolled test "series" (201, 601) and five controlled test "series" (301, 401, 501, 701, 1001)." The tests in the uncontrolled series were conducted simultaneously. Controlled tests were staggered in time after watering to track the decay in control efficiency as the scraper travel surface dried. Table 3-1 also shows the vehicle passes by the type of scraper in use during the test. NCKTC operates three basic models of Caterpillar scrapers:

Model	Type	Nominal Capacity	Empty Weight
613	Elevating ("paddle")	11 yd^3	16 ton
621	Pan	20 yd^3 (heaped)	33 ton
623	Elevating ("paddle")	22 yd^3	36 ton

All tests, whether controlled or uncontrolled, were conducted on the same stretch of the return route at the approximate mid-point. Note that, because of the orientation of the operation with respect to the prevailing wind direction, all scrapers were empty when they passed the sampling array (see Figure 2-1). The overall mean travel speed measured during the tests was 11 mph. No significant differences in travel speed were found between westbound and eastbound traffic or between watered and unwatered surfaces.

The results of the tests of scraper transit emissions are given in Tables 3-2, 3-3, and 3-4. Table 3-2 presents wind speeds at the heights of the 40 cfm cyclone samplers.

Table 3-3 contains the individual PM-10 exposure values at each sampling height in the downwind vertical array. As discussed in Section 2, the point values of exposure are integrated over the height of the plume to develop the PM-10 emission factors, which are given in Table 3-4. Appendix C presents detailed spreadsheets for the BY runs and Appendix D presents an example calculation.

Table 3-1. Test Site Parameters

Run no.	u/c[a]	Equipment[b]	Date	Start time	Duration (min)	Operational passes	Air temp (°F)	Barometric pressure (in. Hg)
BY-201	u	Cat 613	9/15/99	12:49	26	20	75.0	28.80
		Cat 621				14		
BY-202	u	Cat 613	9/15/99	12:54	16	15	76.0	29.00
		Cat 621				11		
BY-301	c	2-Cat 613	9/16/99	9:05	78	40	64.5	28.90
		3-Cat 621				60		
BY-302	c	2-Cat 613	9/16/99	9:46	80	42	64.5	28.90
		3-Cat 621				63		
BY-303	c	2-Cat 613	9/16/99	10:28	38	36	67.0	28.90
		3-Cat 621				24		
BY-401	c	2-Cat 613	9/17/99	9:13	61	37	59.5	28.80
		3-Cat 621				56		
BY-402	c	2-Cat 613	9/17/99	10:03	70	41	69.0	28.90
		3-Cat 621				59		
BY-403	c	2-Cat 613	9/17/99	10:21	67	40	69.0	28.90
		3-Cat 621				57		
BY-501	c	2-Cat 613	9/17/99	12:59	73	40	75.0	28.90
		3-Cat 621				73		
BY-502	c	2-Cat 613	9/17/99	13:38	81	45	78.0	28.90
		3-Cat 621				73		
BY-503	c	2-Cat 613	9/17/99	14:19	38	19	78.0	28.90
		3-Cat 621				34		
BY-601	u	2-Cat 613	9/22/99	9:28	56	36	58.0	28.78
		2-Cat 621				35		
		623				18		
BY-602	u	2-Cat 613	9/22/99	9:28	56	36	58.0	28.78
		2-Cat 621				35		
		623				18		
BY-701	c	Cat 613	9/22/99	12:42	61	2	78.8	28.88
		2-Cat 621				45		
		623				22		
BY-702	c	Cat 613	9/22/99	13:09	92	5	80.0	28.92
		2-Cat 621				57		
		623				27		

(continued)

Table 3-1. (continued)

Run no.	u/c[a]	Equipment[b]	Date	Start time	Duration (min)	Operational passes	Air temp (°F)	Barometric pressure (in. Hg)
BY-703	c	2-Cat 613	9/22/99	13:50	76	6	80.0	28.92
		2-Cat 621				44		
		623				20		
BY-1001	c	3-Cat 613	9/23/99	8:44	81	41	58.8	28.50
		2-Cat 621				48		
		623				24		
BY-1002	c	2-Cat 613	9/23/99	9:26	54	30	58.5	28.50
		2-Cat 621				29		
		623				16		
BY-1003	c	2-Cat 613	9/23/99	10:14	46	30	72.0	28.55
		2-Cat 621				25		
		623				14		

[a] Uncontrolled/controlled test.
[b] All passes were by empty scrapers.

Table 3-2. Isokinetic Correction Parameters (By Runs)

Run	Wind speed 2 m (cm/s)	Wind speed 2 m (ft/min)	Wind speed 4.5 m (cm/s)	Wind speed 4.5 m (ft/min)	Wind speed 7 m (cm/s)	Wind speed 7 m (ft/min)	Profiler isokinetic flow ratios 2m	Profiler isokinetic flow ratios 4.5 m	Profiler isokinetic flow ratios 7 m
BY-201	111	218	135	265	147	290	4.28	3.51	3.24
BY-202	103	202	124	244	135	266	4.53	3.82	3.51
BY-301	240	473	292	575	320	630	1.96	1.62	1.48
BY-302	307	604	377	743	416	818	1.50	1.24	1.14
BY-303	298	586	369	727	408	803	1.58	1.27	1.16
BY-401	211	415	266	523	295	582	2.23	1.76	1.60
BY-402	312	613	396	780	442	869	1.48	1.19	1.07
BY-403	346	680	437	860	486	957	1.37	1.07	0.98
BY-501	289	569	364	716	405	797	1.61	1.51	1.38
BY-502	274	539	340	669	376	740	1.74	1.89	1.72
BY-503	260	512	319	627	350	690	1.79	1.49	1.84
BY-601	254	501	326	642	364	717	1.85	1.43	1.29
BY-602	254	501	326	642	364	717	1.81	1.43	1.29
BY-701	365	719	464	913	517	1017	1.27	1.02	0.92
BY-702	372	732	475	935	532	1046	1.28	0.99	0.90
BY-703	384	756	488	960	544	1072	1.24	0.97	0.88
BY-1001	160	315	205	403	229	451	2.93	2.27	2.08
BY-1002	151	297	186	367	206	406	3.05	2.52	2.28
BY-1003	148	291	181	357	200	394	3.20	2.59	2.36

Table 3-3. Plume Sampling Data

Run	Sampling height (m)	PM-10 Sampling rate		Net PM 10 exposure (mg/cm²)
		m³/hr	ft³/min	
BY-201	2	69.35	40.82	0.3253
	4.5	68.93	40.57	0.2131
	7	69.67	41.01	0.0428
BY-202	2	67.98	40.01	0.1571
	4.5	69.08	40.66	0.0635
	7	69.28	40.78	0.0378
BY-301	2	68.88	40.54	0.0246
	4.5	69.10	40.67	0.0815
	7	69.05	40.64	0.0586
BY-302	2	67.38	39.66	0.1353
	4.5	68.62	40.39	0.0406
	7	68.99	40.61	0.0694
BY-303	2	68.81	40.50	0.0450
	4.5	68.40	40.26	0.0319
	7	68.98	40.60	0.0126
BY-401	2	68.79	40.49	0.0606
	4.5	68.32	40.21	0.0671
	7	68.96	40.59	0.0345
BY-402	2	67.47	39.71	0.1779
	4.5	68.72	40.45	0.0423
	7	69.01	40.62	0.0492
BY-403	2	69.15	40.70	0.1631
	4.5	68.57	40.36	0.2022
	7	69.78	41.07	0.0290
BY-501	2	68.15	40.11	0.1942
	4.5	69.16	40.71	0.0417
	7	69.54	40.93	0.0712
BY-502	2	69.59	40.96	0.3009
	4.5	69.01	40.62	0.1590
	7	69.76	41.06	0.0720

(continued)

Table 3-3. (continued)

Run	Sampling height (m)	PM-10 Sampling rate m³/hr	PM-10 Sampling rate ft³/min	Net PM 10 exposure (mg/cm²)
BY-503	2	68.06	40.06	0.2397
	4.5	69.16	40.71	0.0542
	7	69.54	40.93	0.0000
BY-601	2	68.57	40.36	0.2514
	4.5	67.94	39.99	0.1128
	7	68.52	40.33	0.0302
BY-602	2	66.99	39.43	0.1182
	4.5	68.01	40.03	0.0567
	7	68.52	40.33	0.0015
BY-701	2	68.03	40.04	0.1026
	4.5	69.13	40.69	0.0120
	7	69.50	40.91	0.0145
BY-702	2	69.71	41.03	0.2549
	4.5	69.06	40.65	0.0000
	7	69.88	41.13	0.0000
BY-703	2	69.56	40.94	0.5428
	4.5	69.13	40.69	0.0843
	7	69.64	40.99	0.0173
BY-1001	2	68.62	40.39	0.0173
	4.5	67.84	39.93	0.0150
	7	69.84	41.11	0.0343
BY-1002	2	67.41	39.68	0.0180
	4.5	68.57	40.36	0.0190
	7	68.79	40.49	0.0180
BY-1003	2	69.16	40.71	0.0295
	4.5	68.60	40.38	0.0146
	7	69.18	40.72	0.0206

Table 3-4. Emission Factors

Run	Test conditions	Silt content (%)	Moisture content (%)	PM-10 emission factor (lb/VMT)
BY-201	uncontrolled	7.9	3.8	1.798
BY-202	"	10.8	4.6	1.133
BY-301	1.1 gal/yd²	14.9	17.5	0.164
BY-302	"	"	12.4	0.251
BY-303	"	"	7.14	0.153
BY-401	0.21 gal/yd²	9.58	19.2	0.168
BY-402	"	"	10.1	0.297
BY-403	"	"	8.51	0.386
BY-501	0.31 gal/yd²	5.87	13.6	0.296
BY-502	"	"	8.24	0.485
BY-503	"	"	5.58	0.687
BY-601	uncontrolled	7.32	7.08	0.491
BY-602	"	"	7.08	0.225
BY-701	0.14 gal/yd²	9.4[a]	12.0	0.224
BY-702	"	"	6.46	0.391
BY-703	"	"	3.86	1.154
BY-1001	0.54 gal/yd²	9.4[a]	14.3	0.052
BY-1002	"	"	8.68	0.098
BY-1003	"	"	8.12	0.107

[a] Mean silt content found for site.

Table 3-4 also presents the soil surface moisture value associated with each test. These values are averages of appropriate point values (from grab samples) along the decay curves shown in Figure 3-1.

Discussion of the Watering Test Results

Control efficiency was determined as the percent reduction in the emission factor for each test compared to the mean uncontrolled emission factor. The mean uncontrolled PM-10 emission factor of 1.46 lb/vmt was based on test series 201-202. Note that the other uncontrolled test series (601-602) was not included in determining the mean, because the 601 test series had been performed after rain at the site. Although the route had visibly appeared uncontrolled during the test, gravimetric analysis of the 601-series filters resulted in emission factors substantially below those from the 201 series. The moisture content of the 601 series was also almost twice that for the 201 series.

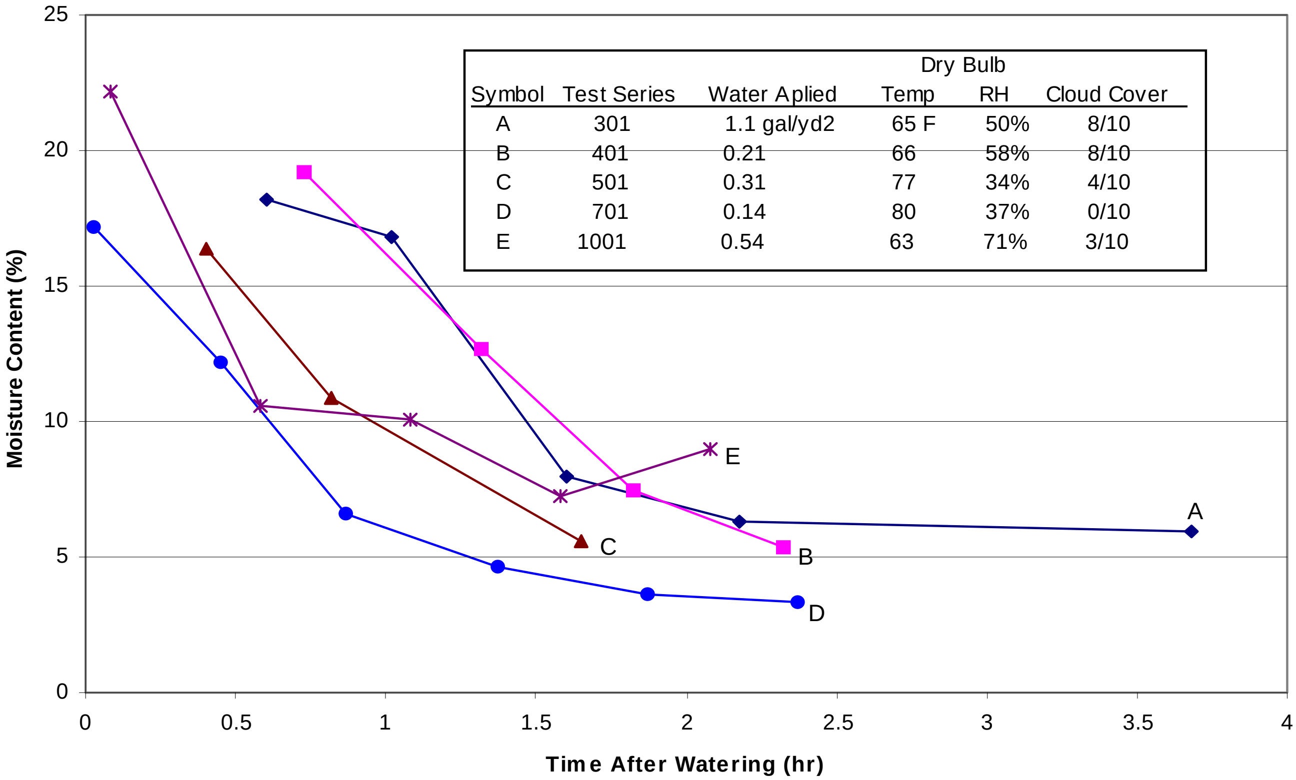


Figure 3-1. Decay of moisture content with time after watering (NCKTC).

Figure 3-1 presented a time history of the moisture content after watering. Figure 3-2 provides a similar time history, except that the (instantaneous) control efficiency is plotted against the mid-point time for each test. Figure 3-3, on the other hand, plots **average** control efficiency values. Note that, due to the integration process described in Chapter 2, average control efficiency values result in a "smoother" time history.

Fitting the Figure 3-3 data to least-squares lines of the form:

$$C(t) = B - mt \tag{3-1}$$

where $C(t)$ = average control efficiency (%)
B = intercept (%)
m = decay rate (%-hr^{-1})
t = time after watering (hr)

provides a means to explore decay rates in terms of service environment variables. Table 3-5 lists the test series and decay rates, and Figure 3-4 shows the lines of best fit.

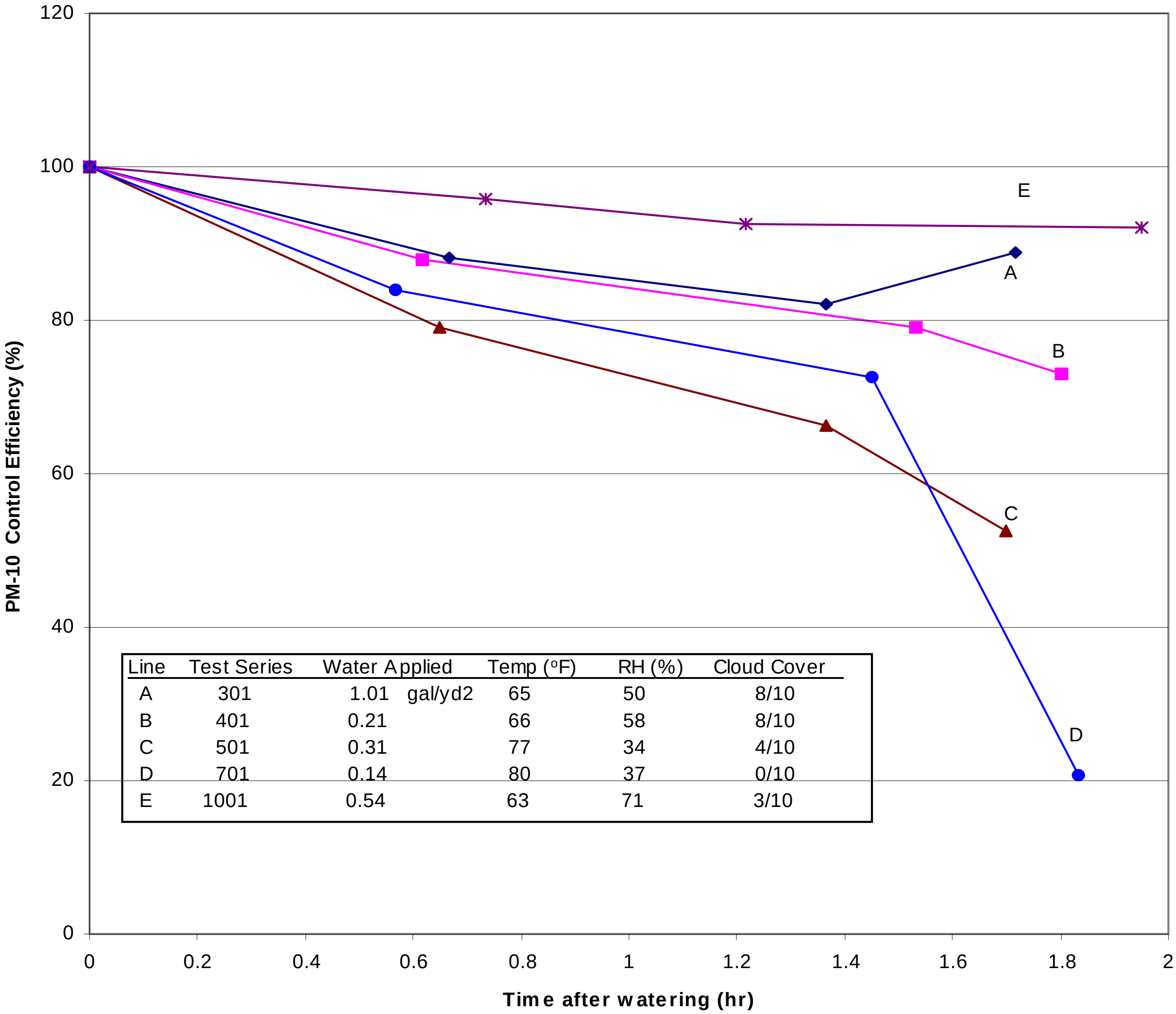


Figure 3-2. Decay of instantaneous control efficiency with time after watering (NCKTC).

Also given in Table 3-5 are measures of the service environment in which water acted as a control measure. Service environment variables include ambient variables such as amount of water applied, ambient temperature, relative humidity, cloud cover, and solar radiation. Recall that these are viewed as second-tier, semi-quantitative measurements to assess how well the primary variable (surface moisture content) relates to environmental conditions. Appendix E contains a listing of the second-tier measurements.

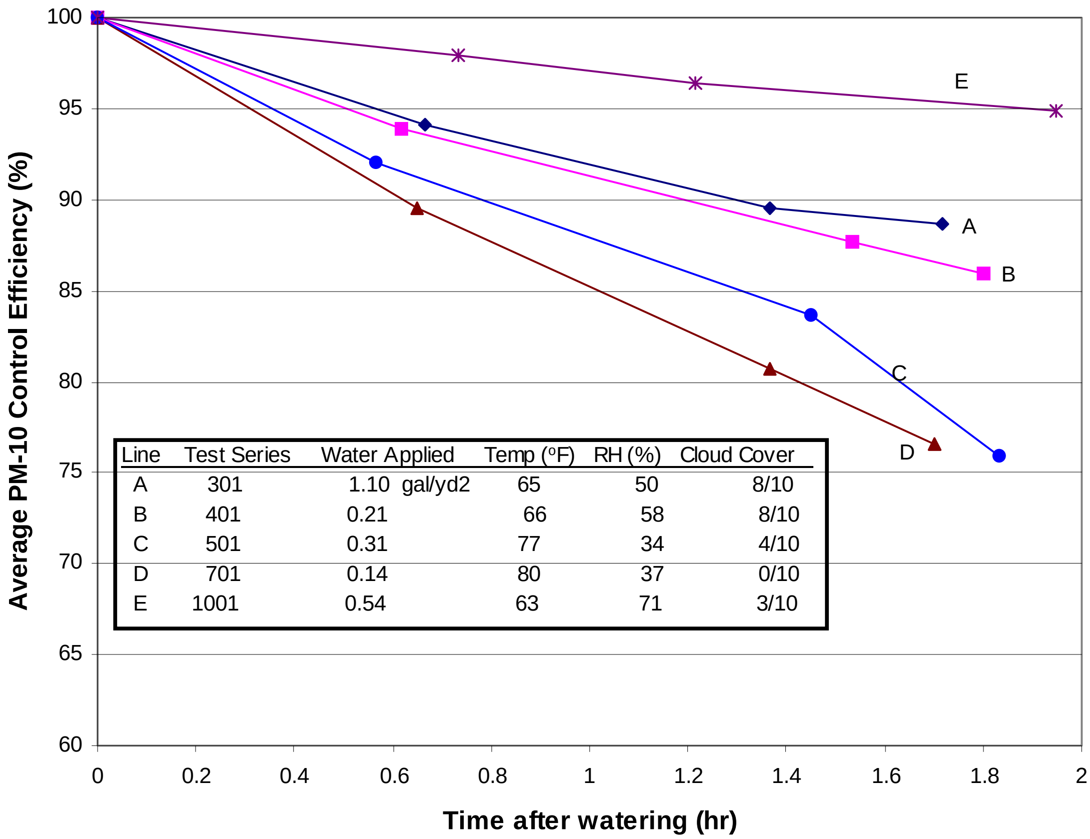


Figure 3-3. Decay of average control efficiency with time after watering (NCKTC).

Table 3-5. Decay Rates Fitted by Least-Squares Linear Regression

Test series	Water applied (gal/yd^2)	Dry bulb temp. (°F)	Wet bulb temp. (°F)	Relative humidity (%)	Cloud cover (tenths)	Traffic volume[a] (veh/hr)	Intercept, B (%)	Decay rate (%—hr^{-1})	r^2
301	1.10	65	55	50	8	84	99.4	6.71	0.9717
401	0.21	66	57	58	8	88	99.5	7.68	0.9917
501	0.31	77	59	34	4	88	99.4	13.70	0.9957
701	0.14	80	62	37	0	60	99.8	12.40	0.9835
1001	0.54	63	57	71	3	86	99.9	2.65	0.9930

[a] Average value of operating passes per unit time over the three tests in each test series.

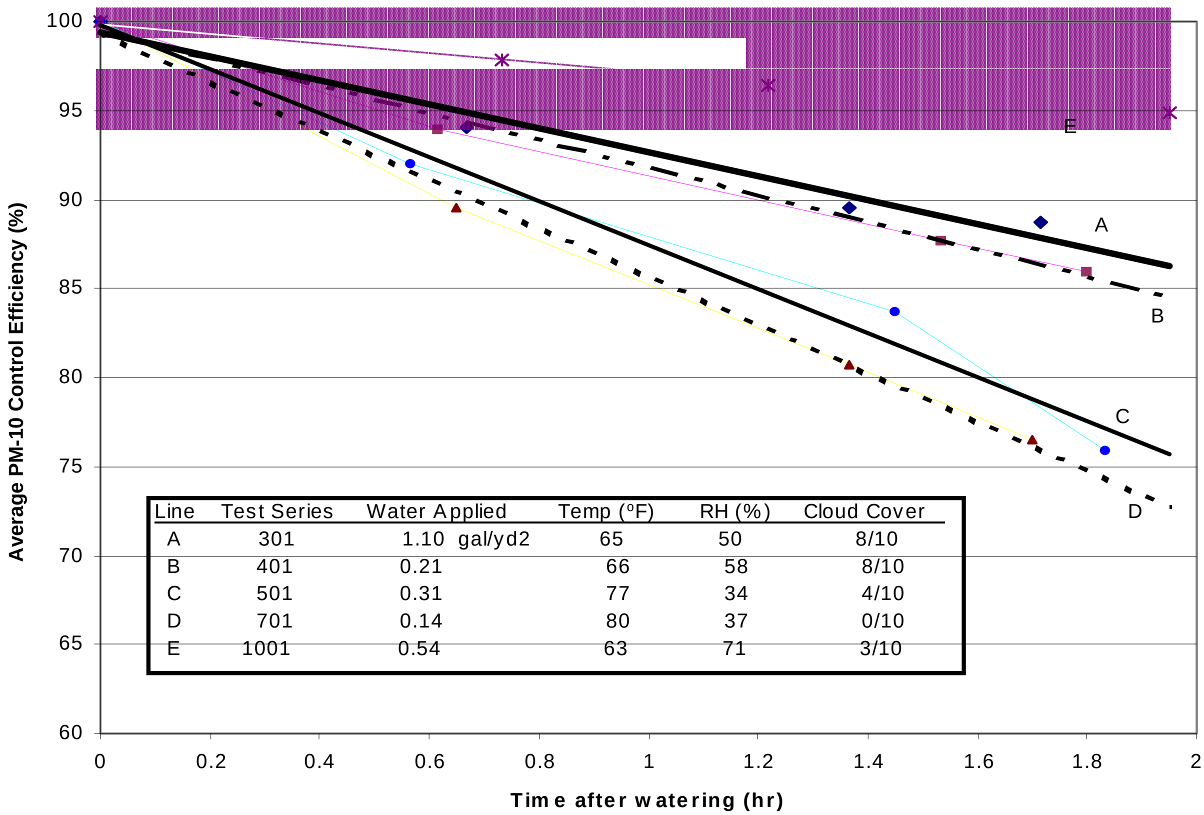


Figure 3-4. Best fit lines for average control efficiency decay with time after watering (NCKTC).

Table 3-6 presents the correlation matrix for the decay rate "m" against the different measures of the service environment.

Table 3-6. Correlation Matrix

	PM-10 decay rate	Water applied	Dry bulb temp.	Wet bulb temp.	Relative humidity	Cloud cover	Traffic rate
PM-10 decay rate	1	- 0.494	0.239	0.195	- 0.964	- 0.334	0.124
Water applied	- 0.494	1	- 0.402	- 0.689	0.263	0.517	0.273
Dry bulb temp.	0.239	- 0.402	1	0.893	- 0.053	0.484	- 0.647
Wet bulb temp.	0.195	- 0.689	0.893	1	0.05	0.248	- 0.774
Relative humidity	- 0.964	0.263	- 0.053	0.05	1	0.301	- 0.271
Cloud cover	- 0.334	0.517	0.484	0.248	0.301	1	- 0.606
Traffic rate	0.124	0.273	- 0.647	- 0.774	- 0.271	- 0.606	1

Table 3-6 shows that the PM-10 control efficiency decay rate is strongly correlated with relative humidity. A least-squares regression of decay rate against relative humidity results in:

$$m^* = 22.8 - 0.283\,(RH) \qquad (3\text{-}2)$$

where m^* = estimated decay rate (%-hr^{-1})
RH = relative humidity (%)

The r^2 value for Equation 3-2 is 0.929.

Soil surface moisture content provides an alternate variable that might be used as a basis for tracking the emission factor and control efficiency data developed from the field tests. However, there is no readily available "starting point" for the moisture content for which one could reasonably assume 100 percent control at time zero (i.e., when the road had just been watered). To illustrate this point, Figure 3-5 shows exponential decay functions fitted to the moisture time histories shown earlier as Figure 3-1. Extrapolated time-zero moisture values vary from 15 to 36 percent. Clearly, one could reasonably expect that the higher initial moisture contents should be associated with the higher water application rates. However, the extrapolations in Figure 3-5 do not generally follow that trend.

Figure 3-6 plots the instantaneous control efficiency against the surface moisture content associated with each test. The important aspects to notice about the figure are the steep slope at fairly low moisture values and the more shallow slope at high moisture levels. This is in keeping with past studies[6,7] which found that control efficiency data can be successfully fitted by a bilinear function, based on a "normalized" surface moisture value. The normalization is performed by dividing by the uncontrolled (unwatered) surface moisture content for the unpaved travel route. In this case, the BY moisture data are normalized by 4 percent, which is the mean moisture value from BY-201 and 202. Figure 3-7 compares the data collected in this study against a bilinear fit proposed in an EPA guidance document.[7] In general, the BY data match relatively well with the EPA guidance model, showing a sharp rise in control efficiency as the surface moisture content is raised to twice the uncontrolled value and a much slower rise beyond that moisture level. Use of the EPA function to predict the watering data is conservative in the sense that the predicted control efficiency values are somewhat lower than the observed values.

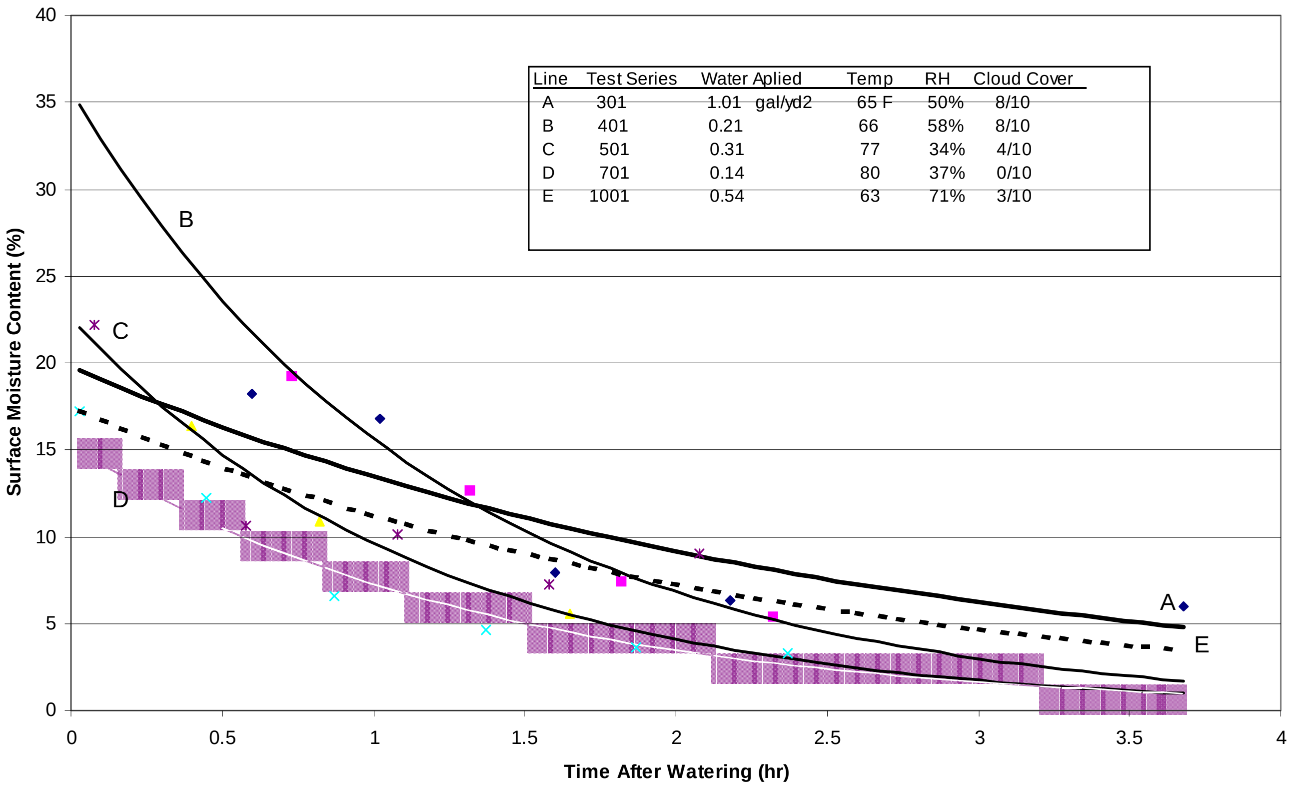
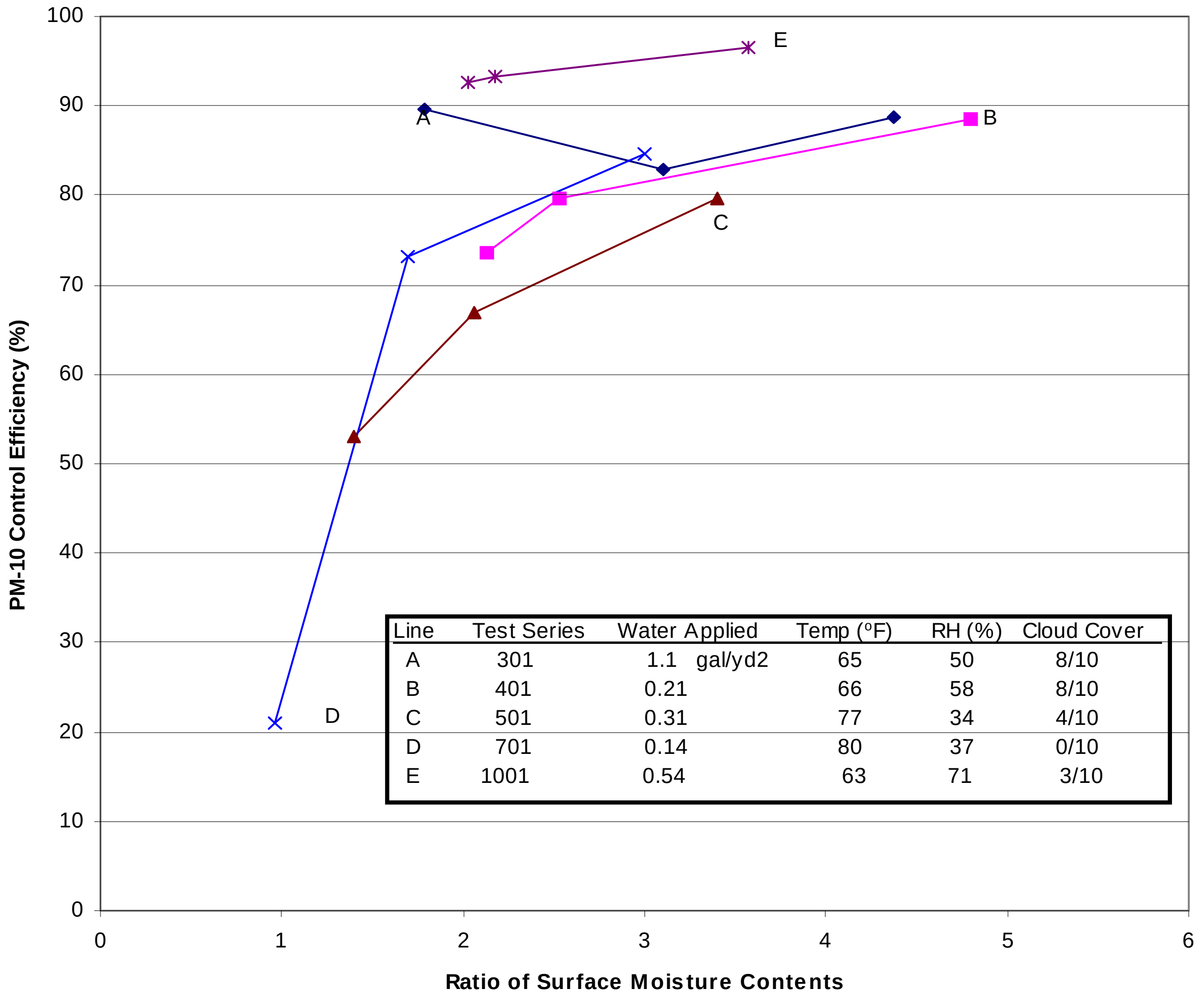


Figure 3-5. Exponential decay in surface moisture content with time after watering (NCKTC).

Particle Size Data for Watered and Unwatered Travel Routes

In addition to the mass flux profiling tests used to determine control efficiency values, the NCKTC portion of the field program collected particle size information for the particulate emissions. These data supplement the particle size data from the BV tests conducted during the 1998 test program[3]. Figure 3-8 presents the data collected at the 2- and 4.5-m downwind sampling locations during six 1998 scraper transit tests. The figure plots the cumulative fraction of PM less than the size shown on the horizontal axis. Note that the fraction is based on particles up to 15 mm in aerodynamic diameter, which is the 50 percent cutpoint for the cyclone operated at 20 acfm.[4]



Line	Test Series	Water Applied	Temp (°F)	RH (%)	Cloud Cover
A	301	1.1 gal/yd2	65	50	8/10
B	401	0.21	66	58	8/10
C	501	0.31	77	34	4/10
D	701	0.14	80	37	0/10
E	1001	0.54	63	71	3/10

Figure 3-6. Instantaneous PM-10 control efficiency versus surface moisture content (NCKTC).

Before discussing the new particle size information, it is important to recall the key difference between the two data sets. The 1998 tests referenced uncontrolled conditions while the 1999 program was directed toward control performance characterization.

Consequently, in 1998 the downwind monitors encountered much higher downwind concentrations and thus could collect adequate sample mass in a relatively brief period of time. In 1999, on the other hand, the watered surfaces resulted in much lower downwind concentrations, thus posing a problem in collecting adequate sample mass. In general, only the 2-m downwind cyclone/cascade impactor combination collected

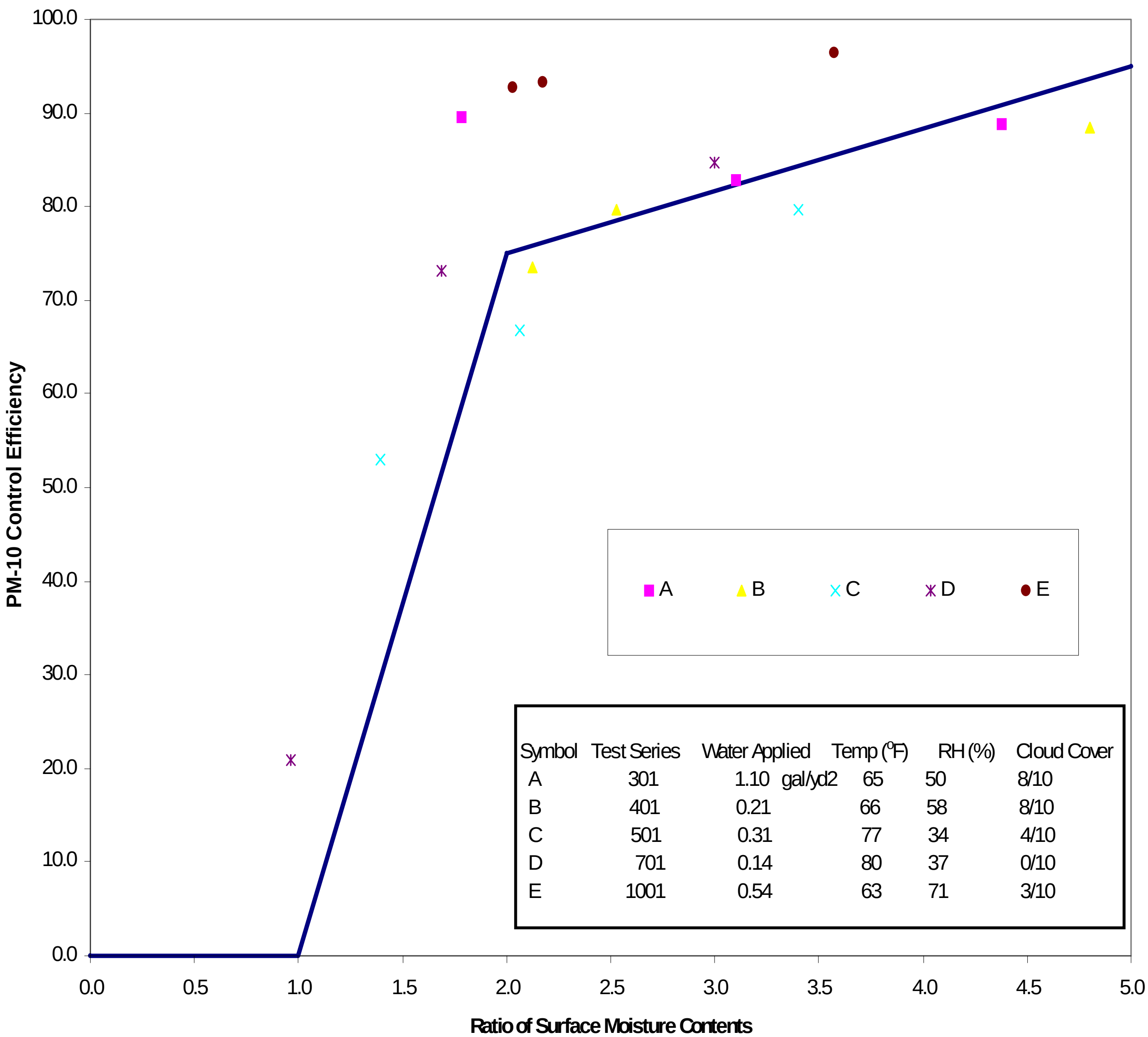


Figure 3-7. Comparison of instantaneous control efficiency with previously published function (NCKTC).

adequate sample mass for the controlled test series. Appendix F contains detailed data for the impactor tests.

Figure 3-9 compares particle size data collected during the 1999 tests at NCKTC with the data collected in 1998. Solid and dashed lines indicate tests conducted on surfaces which had or had not been watered, respectively. The vertical lines in Figure 3-9 indicate 1 standard deviation bounds on the geometric mean from the 1998 (BV) tests

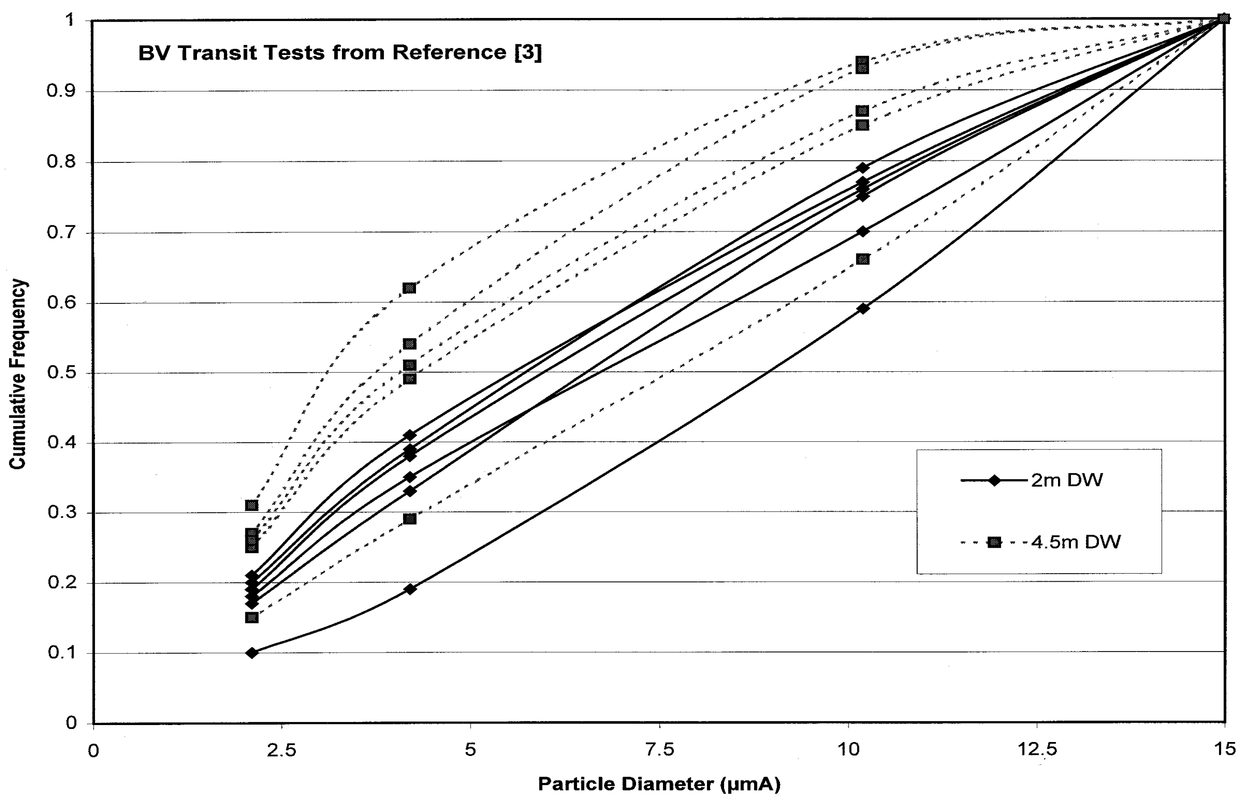


Figure 3-8. Particle size distributions for 1998 uncontrolled scraper transit emissions (BV runs) from reference 3.

(i.e., the data from Figure 3-8). The lefthand and righthand lines are for the 4.5-m and 2-m downwind sampling heights, respectively. In spite of difficulties collecting adequate sample mass, the 1999 particle size data generally compare well with BV data.

An additional series of analyses were performed on the PM-2.5-to-PM-10 ratio (as approximated by catches associated with the third impactor stage (50 percent cutpoint of 2.1 µm in aerodynamic diameter) and the first stage (50 percent cutpoint of 10.2 µm in aerodynamic diameter). The variation in the PM-2.5/PM-10 ratio was explored in terms of variations in the following variables.

- mean PM-10 emission factor for a test series
- average control efficiency decay rate
- volume of water applied

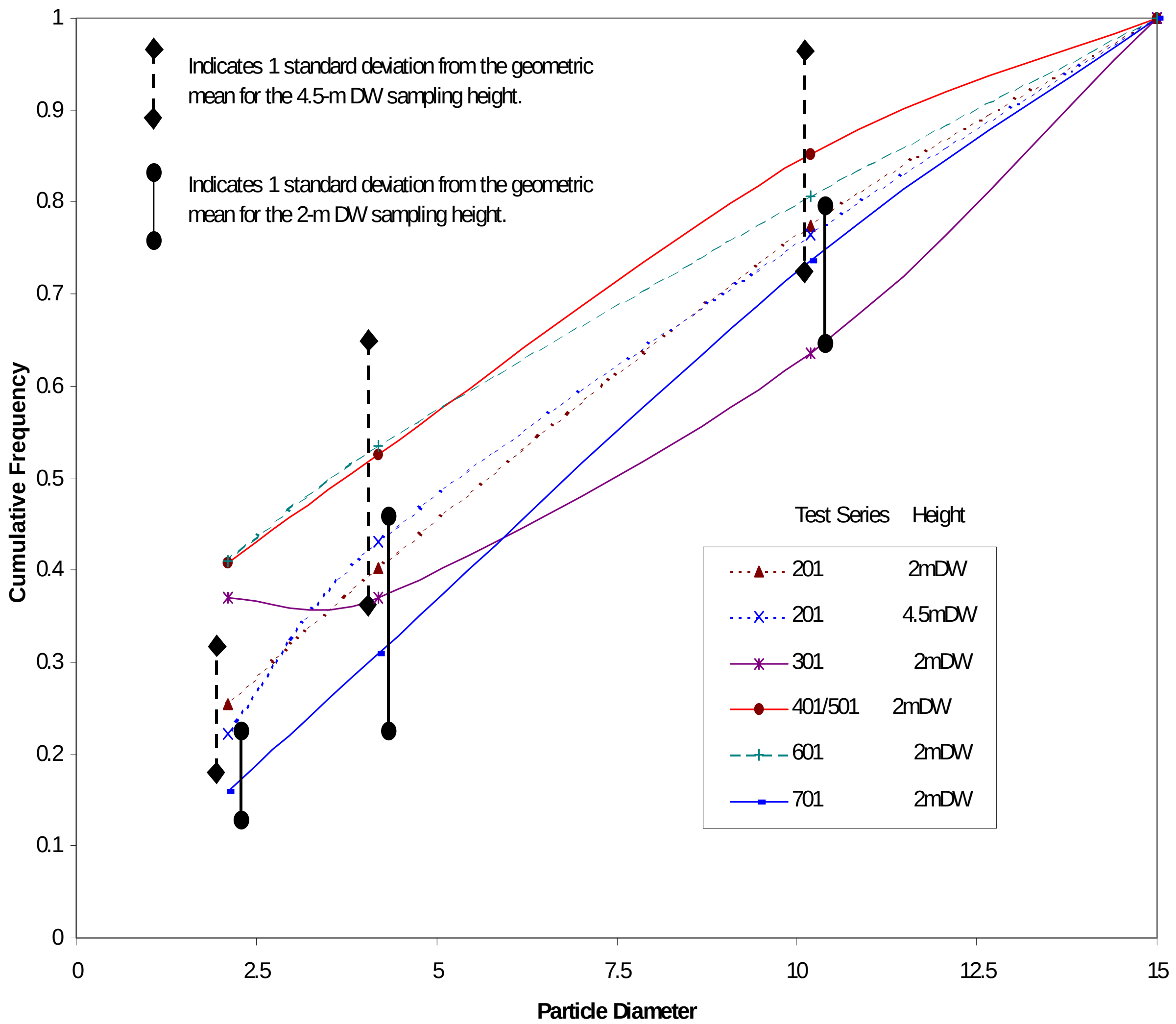


Figure 3-9. Comparison of particle size distributions for 1999 BY runs and 1998 BV runs.

A slight negative correlation (significant at the 10 percent level, but not at the 5 percent level) between emission factor and PM-2.5/PM-10 ratio was found, as shown in Figure 3-10. This indicates that, as emissions increase, the ratio of PM-2.5 to PM-10 decreases. That is, higher emission levels (i.e., either uncontrolled or several hours after watering) are associated with higher fractions of mass in the 2.5 to 10 µmA size range. This is to be expected because when the road is highly controlled immediately after the water is applied, emissions consist almost entirely of diesel exhaust emissions in submicron size range. As the road surface dries, increasing amounts of coarse road dust are emitted while the diesel exhaust emissions remain constant. This discussion points out an obvious – but still worth mentioning – feature of watering: water controls only surface dust and not diesel exhaust emissions. Because diesel exhaust is a far

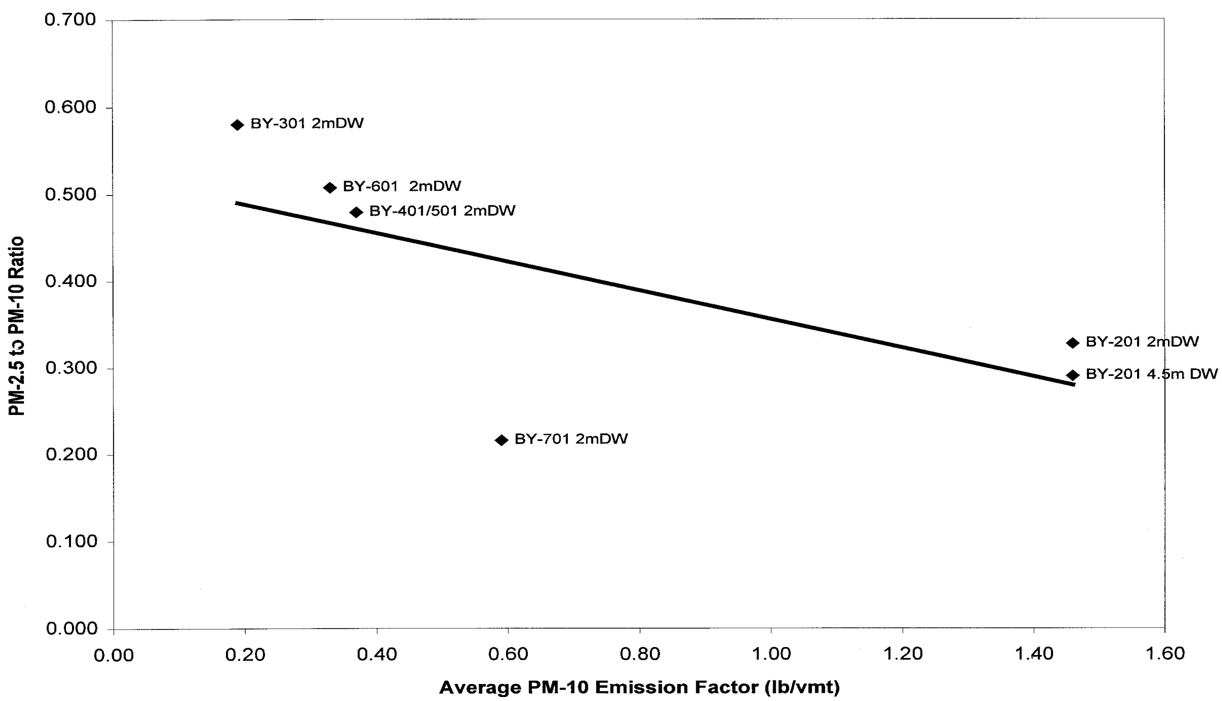


Figure 3-10. Correlation between PM-2.5/PM-10 ratio and PM-10 emission factor.

more important component of PM-2.5 emissions than of PM-10 emissions and because diesel exhaust is unaffected by watering, these observations lead to the logical conclusion that watering scraper routes should give lower control efficiency for PM-2.5 than for PM-10.

As noted earlier, in order to collect adequate sample mass on the various media, the cyclone/impactors were operated over the entire test series. As a result, it is not possible to develop a time history of PM-2.5 control efficiency in the manner that PM-10 efficiency was presented in Figures 3-2 to 3-4. Instead, PM-2.5 control efficiency is based on the average controlled emission factor determined over the test series.

Based on both the BV and BY test data, the average PM-2.5-to-PM-10 ratio for uncontrolled tests is 0.267. When combined with the mean uncontrolled PM-10 emission factor of 1.46 lb/vmt, this leads to a mean uncontrolled PM-2.5 emission factor of 0.39 lb/vmt. Because of difficulties collecting adequate sample mass on the impactor substrates and backup filters during the watered tests, only impactor data from the

401/501 and 701 test series are considered reliable. When the two sets of watered test data are combined, an average PM-2.5-to-PM-10 ratio of 0.374 is obtained. These ratios are used to develop the scaled emission factors shown in Table 3-7.

Table 3-7. PM-2.5 Control Efficiency Values

Test series	Average PM-10 emission factor[a] (lb/vmt)	Average PM-2.5 emission factor[a] (lb/vmt)	Average PM-2.5 control efficiency[b] (%)	Average PM-2.5 control efficiency decay rate[c] (% - hr^{-1})
201	1.46	0.39	_[d]	_[d]
301	0.189	0.072	82	9
401	0.284	0.11	72	14
501	0.489	0.18	54	23
701	0.590	0.22	44	28
1001	0.0857	0.032	92	4

[a] PM-10 emission factor found by averaging emission factors in Table 3-4 over each test series. PM-2.5 factors found by scaling average PM-10 factors by 0.267 or 0.374, for uncontrolled or watered tests, respectively.

[b] PM-2.5 control efficiency based on percent reduction in average PM-2.5 emission factor from average uncontrolled PM-2.5 factor (i.e., 0.39 lb/vmt).

[c] Average decay rate based on assumed linear decay from 100% control at time zero and nominal 2-hour test period for test series.

[d] Uncontrolled test series.

Average control efficiency decay rates for PM-10 (from Table 3-5) and PM-2.5 are compared against relative humidity in Figure 3-11. Control efficiency for PM-2.5 decayed at least 30 percent more quickly than did PM-10 control efficiency in each case. In most instances, the rate of decay was at least 50 percent faster. The difference between PM-10 and PM-2.5 control efficiency decay rates was greater for low relative humidity values. In other words, under dry conditions, watering appears to be far more effective in controlling coarse PM rather than fine PM emitted during scraper travel operations.

Mud/Dirt Trackout Study Test Results

As noted in the Introduction, the second part of the field testing program explored an unwelcome consequence of watering unpaved surfaces at construction sites—namely, the increase in mud/dirt trackout onto surrounding paved streets. Testing employed a captive site at MRI's Deramus Field Station (DFS). The captive nature of the operation meant that one could tightly control experimental variables such as the moisture level of the access area and the number and type of vehicles leaving the site. The impact of trackout emissions was measured in terms of mass of mud/dirt deposited onto the paved test area.

Table 3-8 presents test site parameters associated with the DFS field exercise. Tests were conducted during an unseasonably warm period in November 1999. In the table,

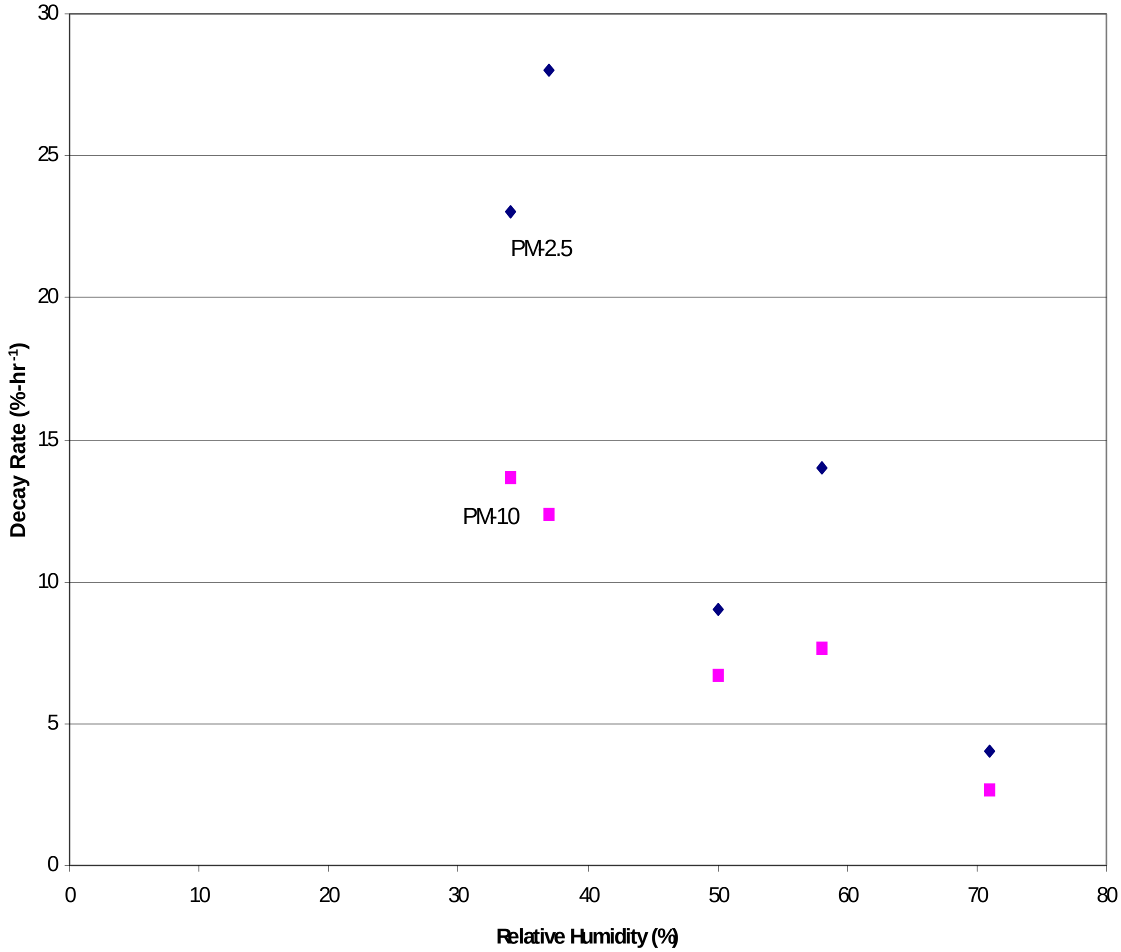


Figure 3-11. Average control efficiency decay rates for PM-10 and PM-2.5 versus relative humidity.

tests are referenced by a numerical code of the form "x-y" where "x" indicates the phase and "y" indicates a sequential number to uniquely identify tests within a specific phase.

A total of 58 paved road surface samples were collected during the field exercise. Table 3-9 presents the analysis results for those samples. In the table, the average moisture content refers to average of the two to four composite samples collected while captive traffic traveled over the access area during a given test. A thorough listing of the sample data collected at DFS is provided in Appendix G.

Table 3-8. Trackout Study Test Parameters

Test ID	Date	Vehicle	Type of test	Vehicle start time	Duration (min)	Operational passes	Air Temp (°F)
1-1	11/8/99	pickup	calibration	1600	45	100	73.9
1-2	11/9/99	pickup	calibration	1323	60	100	75
1-3	11/9/99	pickup	calibration	1533	26	50	73.5
1A-1	11/10/99	pickup	calibration	950	19	50	61
2-1	11/10/99	pickup	uncontrolled	1027	19	50	63
2-2	11/10/99	pickup	uncontrolled	1440	18	50	70
2-3	11/10/99	pickup	uncontrolled	1531	19	50	67.5
2-4	11/10/99	pickup	uncontrolled	1621	18	50	65
2-5, 3-1	11/11/99	pickup	uncont./paved apron	1143	26	50	57
2-6, 3-2	11/11/99	pickup	uncont./paved apron	1340	16	50	61
2-7, 3-3	11/11/99	pickup	uncont./paved apron	1422	21	50	60
2-8, 3-4	11/11/99	pickup	uncont./paved apron	1519	18	54	59
2-9, 3-5	11/11/99	pickup	uncont./paved apron	1610	18	50	58
2-10, 3-6	11/12/99	pickup	uncont./paved apron	923	15	50	61
2-11, 3-7	11/12/99	pickup	uncont./paved apron	953	22	50	63
2-12, 3-8, & 1A-2	11/12/99	pickup	uncont./pav.apr./calib.	1045	17	50	65
2-13, 3-9	11/12/99	pickup	uncont./paved apron	1126	15	50	68
2-14, 3-10	11/12/99	pickup	uncont./paved apron	1344	19	50	70
2-15, 3-11	11/12/99	pickup	uncont./paved apron	1420	14	50	73
2-16, 3-12	11/12/99	pickup	uncont./paved apron	1523	18	50	72
2-17	11/15/99	dump truck	uncontrolled	1431	61	50	62
2-18	11/15/99	dump truck	uncontrolled	1430	61	50	62
2-19	11/16/99	dump truck	uncontrolled	956	60	50	40
2-20	11/16/99	dump truck	uncontrolled	958	58	50	40
4-1	11/17/99	pickup	gravel apron	953	21	50	N/A
4-2	11/17/99	pickup	gravel apron	1030	16	50	N/A
4-3	11/17/99	pickup	gravel apron	1104	16	50	N/A
4-4	11/17/99	pickup	gravel apron	1248	17	50	N/A
4-5	11/17/99	pickup	gravel apron	1330	21	50	N/A
4-6	11/17/99	pickup	gravel apron	1421	22	50	N/A
4-7	11/17/99	pickup	gravel apron	1535	22	50	N/A
4-8	11/17/99	pickup	gravel apron	1613	20	50	N/A
4-9	11/18/99	pickup	gravel apron	905	24	50	62
4-10	11/18/99	pickup	gravel apron	938	27	50	63
4-11	11/18/99	pickup	gravel apron	1025	23	50	65
4-12	11/19/99	pickup	gravel apron	901	19	50	38
4-13	11/19/99	pickup	gravel apron	948	18	50	39

Table 3-9. Surface Loading Results (DFS)

Test ID	Average moisture content (%)	Soil type	Vehicle type	Distance (ft) from access point	Total loading (g/m^2)	Silt loading (g/m^2)
1-1	4.6	native	pickup	10	1.54	0.26
1-1	4.6	native	pickup	50	0.20	0.03
1-1	4.6	native	pickup	90	0.57	0.06
1-1	4.6	native	pickup	130	0.21	0.02
1-2	9.5	native	pickup	10	2.27	0.16
1-2	9.5	native	pickup	50	1.32	0.13
1-3	21.4	native	pickup	130	4.40	0.35
1-3	21.4	native	pickup	90	2.96	0.19
1-3	21.4	native	pickup	50	6.40	0.61
1-3	21.4	native	pickup	10	7.88	0.40
1A-1	24.1	native	pickup	5	13.67	0.90
1A-1	24.1	native	pickup	45	12.03	0.97
2-1	5.5	sandy	pickup	5	2.48	0.44
2-2	12.1	sandy	pickup	5	6.81	0.72
2-3	7.9	sandy	pickup	5	4.02	0.54
2-4	17.4	sandy	pickup	5	7.34	0.93
2-5	9.4	sandy	pickup	5	4.73	0.99
3-1	9.4	sandy	pickup	25	1.80	0.45
2-6	14.5	native	pickup	5	9.33	1.52
3-2	14.5	native	pickup	25	2.78	0.50
2-7	19.3	sandy	pickup	5	4.00	0.87
3-3	19.3	sandy	pickup	25	2.31	0.66
2-8	25.0	native	pickup	5	16.52	1.46
3-4	25.0	native	pickup	25	11.48	0.76
2-9	16.7	sandy	pickup	5	3.66	0.83
3-5	16.7	sandy	pickup	25	2.20	0.45
2-10	20.1	native	pickup	5	9.34	1.59
3-6	20.1	native	pickup	25	6.59	1.01
2-11	18.4	sandy	pickup	5	1.57	0.33
3-7	18.4	sandy	pickup	25	1.30	0.24
1A-2	19.7	native	pickup	45	8.46	0.87
3-8	19.7	native	pickup	25	8.37	0.94
2-12	19.7	native	pickup	5	13.29	1.62
2-13	20.5	sandy	pickup	5	2.17	0.50
3-9	20.5	sandy	pickup	25	1.87	0.34
2-14	23.8	native	pickup	5	6.86	1.57
3-10	23.8	native	pickup	25	4.28	0.85
2-15	19.2	sandy	pickup	5	5.00	0.49
3-11	19.2	sandy	pickup	25	3.56	0.49
2-16	32.5	native	pickup	5	6.21	0.95
3-12	32.5	native	pickup	25	4.08	0.63
2-17	14.7	native	dump truck	5	19.07	4.12
2-18	14.7	sandy	dump truck	5	8.37	2.29
2-19	20.5	native	dump truck	5	13.46	3.00
2-20	17.6	sandy	dump truck	5	11.41	3.41

(continued)

Table 3-9. (continued)

Test ID	Average moisture content (%)	Soil type	Vehicle type	Distance (ft) from access point	Total loading (g/m^2)	Silt loading (g/m^2)
4-1	11.7	sandy	pickup	5	3.75	0.68
4-2	22.6	native	pickup	5	6.07	1.83
4-3	13.3	sandy	pickup	5	6.96	1.01
4-4	27.5	native	pickup	5	3.45	1.04
4-5	14.6	sandy	pickup	5	8.06	1.30
4-6	29.1	native	pickup	5	9.56	2.70
4-7	16.7	sandy	pickup	5	10.16	1.82
4-8	32.1	native	pickup	5	7.41	1.77
4-9	4.7	sandy	pickup	5	2.83	0.56
4-10	13.5	native	pickup	5	2.73	0.70
4-11	4.3	sandy	pickup	5	1.19	0.27
4-13	14.1	native	pickup	5	5.41	1.88
4-12	10.5	sandy	pickup	5	5.31	1.43

Discussion of the Mud/Dirt Trackout Results

Several considerations are necessary to place the DFS trackout results in the proper context. First, because only limited traffic was present at the site, primary emphasis was placed on the total loading in the immediate vicinity of the access point rather than the spatial distribution of silt loading along the road. Had additional traffic been present, the mud/dirt trackout material would have been more finely ground and more uniformly “smeared” along the roadway. In other words, additional traffic would have crushed the deposited material and carried it down (and across) the road.

Furthermore, the area used to calculate total and silt loading values was based on a nominal width of 12.5 ft for each of the 20-ft long sampling strips. This approach was taken (rather than using the actual pavement width for each strip) because the only traffic on the test road was that supplied for purposes of testing. Mud/dirt was carried out along the vehicle tracks and was not smeared over the full road width. That is to say, for this sampling program, a linear measurement was more appropriate than an area measurement.

Because of the interest in control effectiveness, emphasis was placed on a relative measurement–namely, the percent reduction in total loading in the immediate vicinity of the access point. That is to say, the absolute mass of material tracked out should not be construed as necessarily representative of mud/dirt trackout from typical construction sites. Tests at DFS were conducted with fairly light-duty vehicles traveling over relatively short stretches of watered access areas. One would reasonably expect “typical” amounts of mud and dirt trackout to be much higher than that measured here because of the contributions of larger vehicles (with more weight and wheels) and longer travel distances at construction site access areas.

Additionally, the sampling method required cleaning the road surface. Thus, there was no cumulative buildup of material on the roadway during the test exercise. Again, this lowers the DFS silt and total loading results, as compared to what one would expect at an actual construction site.

These points are illustrated when one compares the DFS results to those from an earlier study.[8] That 1994 study evaluated mud/dirt trackout onto a 1200 ft-long arterial road segment from a construction site with extensive haulage of earth from the site. During the approximate 3-month duration of the 1994 study, more than 5,000 vehicles left the construction site. Those vehicle passes were supplemented by approximately 500,000 vehicle passes which further crushed and spread the trackout along the arterial road.

The 1994 report[8] presents a geometric mean silt loading between 2 to 4 g/m^2 for uncontrolled conditions, a value several times higher than the corresponding value of 0.67 g/m^2 calculated from Table 3-9. Even more importantly, on-site roads in the 1994 study were not watered to control dust. Had the trackout been from watered roads, the 1994 study would have produced even higher silt loading values.

Examination of the data in Table 3-9 began by determining the correlation coefficient between total loading values and moisture content of the access areas when data were grouped by both soil type (native soil, soil/sand mixture) and control treatment (uncontrolled, gravel apron, paved apron). Thus, six combinations (two soils and three controls) were of interest.

A significant (5-percent level) correlation was found for only one combination of test conditions – a gravel apron in conjunction with the sand/soil mixture. None of the other combinations exhibited a discernible trend between moisture of the access area surface and the amount of mud/dirt tracked onto the paved road. This was an unexpected finding because one can reasonably expect that more material would be tracked out from wetter access areas.

One other factor may affect the DFS trackout results. As one would expect, the access areas became increasingly compacted as the surface was repeatedly watered and driven over. Toward the end of the test program, both the native soil and the sand/soil mixture had a hard crust several millimeters thick. It appeared that most trackout during later tests was due to wetted loose material on the surface being carried out during the first few passes.

For the five combinations of test conditions that did not produce significant correlations, the surface loading values were simply averaged. Summary statistics for those cases are shown in Table 3-10. Note that, for the uncontrolled conditions, the native soil produced roughly twice as much trackout on average as did the sand/soil mixture.

Table 3-10. Summary Statistics for Loading Values

Soil type	Control measure	Sample size	Total loading (g/m^2)[a]
Native soil	Uncontrolled	7	11.0 $\pm$ 3.8
	Gravel apron	6	5.8 $\pm$ 2.5
	Paved apron	6	6.3 $\pm$ 3.2
Sand/soil mixture	Uncontrolled	10	4.2 $\pm$ 1.9
	Gravel apron	6	–[b]
	Paved apron	7	2.2 $\pm$ 0.8

[a] Entries represent arithmetic mean $\pm$ standard deviation.
[b] This source condition exhibited a significant correlation between loading and moisture content.

Table 3-11 presents control efficiencies based on percent reduction in mean loading values. Little variation in control efficiency was seen, with values ranging from 42 to 48 percent. The 46 percent control for a gravel apron in conjunction with the native soil compares fairly well with the 1994 study[8] finding of 56 to 58 percent control for a gravel apron. (The 1994 result is based on reduction in silt loading rather than total loading.)

Table 3-11. Control Efficiency Values

Soil type	Control measure	Total loading control efficiency
Native	Gravel apron	46%
	Paved apron	42%
Sandy	Gravel apron	–[a]
	Paved apron	48%

[a] This source condition exhibited a significant correlation between loading and moisture content. See discussion in text.

The most surprising finding from the DFS study was the relatively poor performance of the gravel apron in combination with the sandy soil. As noted above, this combination produced a statistically significant correlation between surface loading and access area moisture content. That relationship is illustrated in Figure 3-12 for both total loading and silt loading.

What is important to note in Figure 3-12 is that, for an access area moisture content higher than 8 percent, the relationship predicts a total loading value at least comparable to the mean uncontrolled value of 4.2 g/m^2 in Table 3-10. In other words, the gravel apron results in no net control when the sandy soil moisture content higher than about 8 percent. Moreover, for moisture contents higher than about 8 percent, the 25-foot long gravel apron appeared to aggravate the amount of mud/dirt trackout from the sandy soil access area.

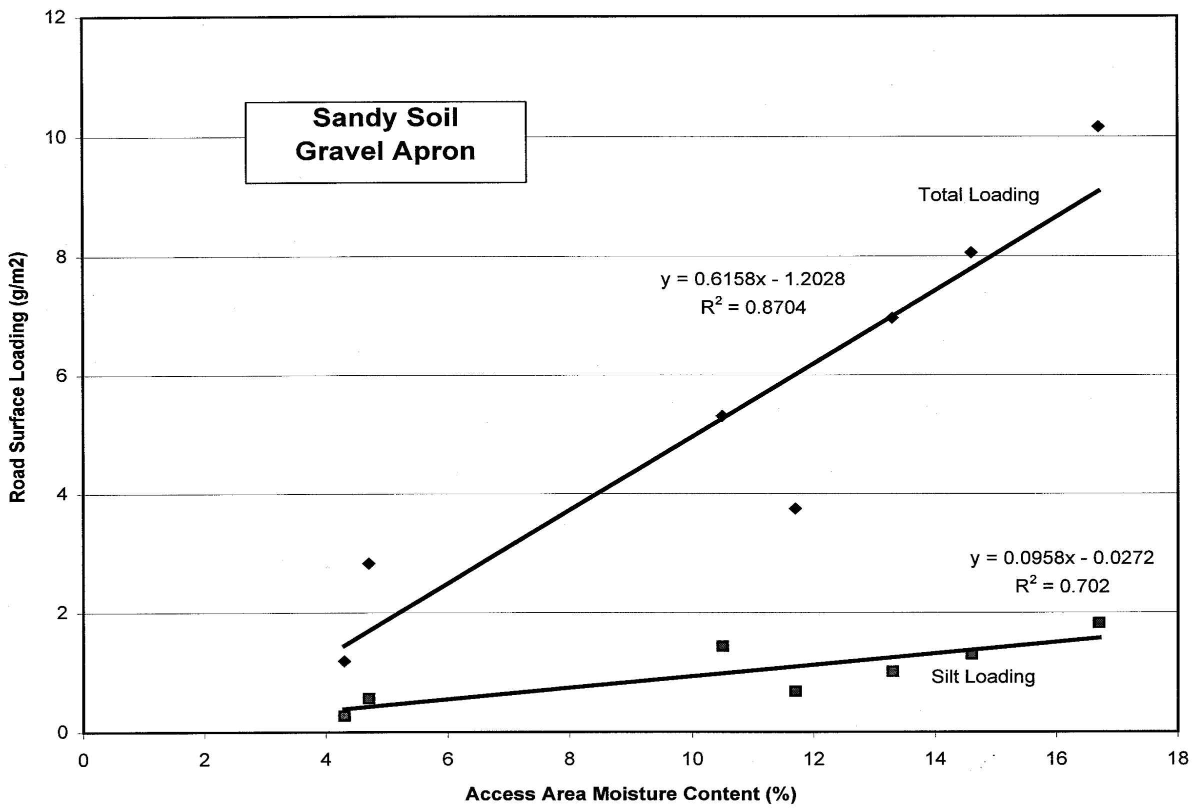


Figure 3-12. Correlation between loading and moisture content for sandy soil in conjunction with gravel apron (DFS).

A further examination as to whether the gravel apron compounds trackout from the sandy soil area was conducted. This involved culling 26 total loading data associated with an access area moisture content of at least 8 percent from Table 3-9. The distribution of tests is as follows:

	Sand/Soil Mixture	Native Soil
Uncontrolled Tests	8	7
Gravel Apron Tests	5	6
Totals	13	13

The uncontrolled and gravel apron test results were combined for each soil type and then ranked lowest to highest to perform a Mann-Whitney "U" test [9] The U test used the sum of ranks to test the null hypothesis that, for moisture levels higher than 8 percent, trackout for the gravel apron is the same as that for uncontrolled. The null hypothesis is tested against the alternative hypothesis that trackout from the two surfaces is different. For both the sandy and the clay soils, the null hypothesis is rejected at the 5 percent level of significance. In other words, for both soil types, total loading trackout with the gravel apron was significantly different than when no apron is used if the access area moisture content was at least 8 percent.