

Adjusting Tapered Element Oscillating Microbalance Data for Comparison with Federal Reference Method PM_{2.5} Measurements in Region 5

Michael Rizzo

Region 5, U.S. Environmental Protection Agency, Chicago, Illinois

Peter A. Scheff

Environmental and Occupational Health Sciences, School of Public Health, University of Illinois, Chicago, Illinois

William Kaldy

Hamilton County Department of Environmental Services, Cincinnati, Ohio

ABSTRACT

Continuous monitoring of particulate matter (PM) with a diameter less than 2.5 μm (PM_{2.5}) is quickly gaining acceptance as an alternative means of measuring fine PM in the United States. For this project, data were taken from all monitoring sites within Region 5 that used the tapered element oscillating microbalance (TEOM) for PM_{2.5} and had a collocated Federal Reference Method (FRM) monitor. Scatter plots of TEOM versus FRM show that for a significant fraction of the observations, an independent factor causes the TEOM to underestimate the FRM value. This underestimation appears to increase as temperature decreases. For this analysis, a linear relationship was fit to the TEOM versus FRM data, allowing a break or knot in the relationship, modeled as a change of slope, at a site-specific temperature. To test whether the models are adequate for adjusting future measurements, models were also developed using the first year of data only, and the remaining observations were used to test the durability of

the relationships. For all but one monitor in Minnesota, the models developed for each site had consistently high R²s, were predictive of future measurements, and could be used to derive "FRM-like" results from the TEOM measurements. The temperature knots fitted by the model for individual sites ranged from 12.9 to 20.6 °C. Data from all six sites in the state of Michigan were also combined to determine if a single model could be developed for the entire state. While the single model for the state of Michigan worked reasonably well, some of the predicted concentrations at individual sites were systematically underestimating the observed concentrations on more polluted days. The same conclusion was drawn for a Region 5-wide model. This approach was also found to work very well for six individual TEOM monitors in New York State.

IMPLICATIONS

Continuous PM_{2.5} monitoring is quickly gaining acceptance as an alternative means of delivering real-time concentration data to the public. One major question regarding the use of continuous instrumentation is whether it is appropriate to compare and relate the results from the continuous monitor to the fine particle standard. This paper demonstrates how a linear model that allows for a change in slope at a site-specific temperature can be used to derive an FRM-like measurement from the TEOMs currently operated in Region 5. The models developed meet the proposed criteria for relating FRM and continuous PM_{2.5} measurements to report the Air Quality Index.

INTRODUCTION

Continuous monitoring of particulate matter (PM) with a diameter less than 2.5 μm (PM_{2.5}) is quickly gaining acceptance as an alternative means of measuring fine particulate in the United States. The purpose is to deliver data in real time to the public to be used as a supplement to the Federal Reference Method (FRM), which has a significant lag between sample collection and data reporting, as well as to provide valuable information regarding short-term exposure and health effects. One major question regarding the use of continuous instrumentation is whether it is appropriate to compare and relate the results from the continuous monitor to the fine particulate National Ambient Air Quality Standard (NAAQS).¹ Because the PM_{2.5} NAAQS specifies a gravimetric FRM to determine attainment status, a continuous device based on a different monitoring technology may require an adjustment of its

Table 1. Region 5 monitoring site information.

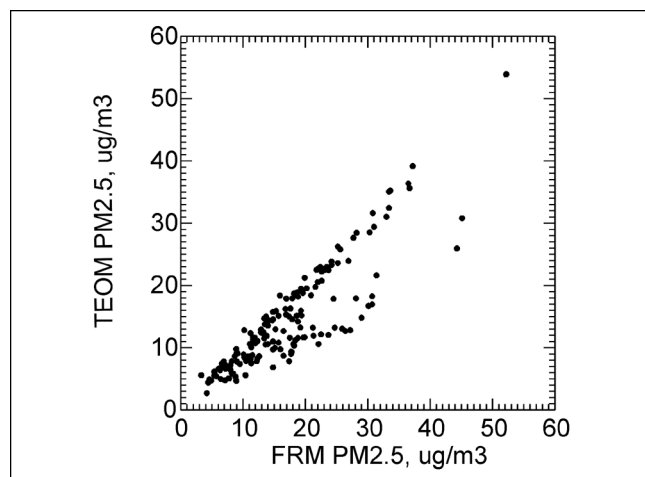
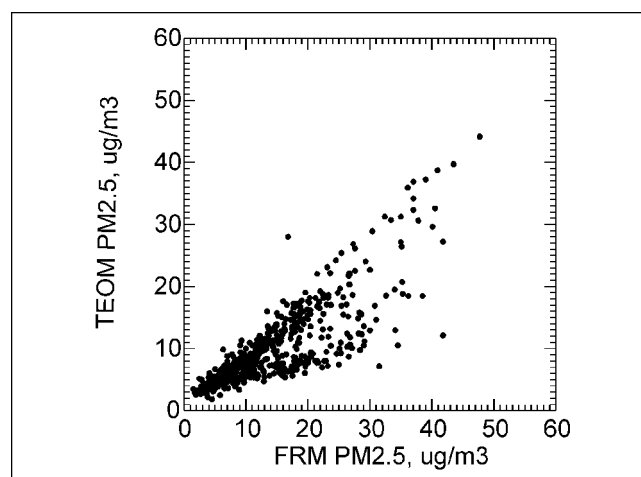
Monitor	Latitude	Longitude	Address	City	Land Use	Setting	Site Comment
180970078	39.81	-86.11	3120 E 30th Street	Indianapolis, IN	Residential	Suburban	In parking lot next to police station
260650012	42.74	-84.54	220 N Pennsylvania Avenue	Lansing, MI	Residential	Urban and center city	
260770008	42.28	-85.54	2500 Lake Street	Kalamazoo, MI	Commercial	Urban and center city	Kalamazoo Fairgrounds
260810020	42.98	-85.67	1179 Monroe Avenue NW	Grand Rapids, MI	Industrial	Urban and center city	
261450018	43.51	-83.97	2500 Pierce Road	Saginaw, MI	Residential	Suburban	Two lane paved roadway
261610008	42.24	-83.60	555 Towner Street	Ypsilanti, MI	Commercial	Urban and center city	Two lane paved roadway near hospital
261630001	42.23	-83.21	14700 Goddard Road	Allen Park, MI (Detroit)	Commercial	Suburban	
271230868	44.95	-93.10	555 Cedar Street	St. Paul, MN	Commercial	Urban and center city	St. Paul APEX site
390610040	39.13	-84.50	250 William Howard Taft Road	Cincinnati, OH	Commercial	Urban and center city	Hamilton County Department of Environmental Services building
550270007	43.44	-88.53	Near Madison Road	Mayville, WI	Agricultural	Rural	450 meters west of Madison Road

measured value to better agree with the FRM $PM_{2.5}$ measurement. Many air pollution regulatory agencies are currently deploying the tapered element oscillating microbalance (TEOM) as a continuous monitor for $PM_{2.5}$.² This monitoring methodology involves measuring the mass of deposited PM on a vibrating glass tube to determine the equivalent concentration of particulate collected. By locating the vibrating measurement element downstream of a size-selective inlet, the TEOM can be used as a continuous $PM_{2.5}$ or PM_{10} monitor.

The $PM_{2.5}$ and PM_{10} filter-based FRMs specify that the filter and deposited PM be weighed after a minimum of 24 hr of equilibration at reduced humidity to remove water from the mass deposited on the filter. However, it is not possible to remove water by long-term equilibration with a continuous measurement system. To standardize the TEOM monitor, the filter and air stream are held at a

constant 50 °C to ensure that the sample is always above the dew point and to maintain a low relative humidity, minimizing water uptake for all ambient temperatures. However, heating the air stream can also cause volatilization of PM, which has the potential to lower the observed $PM_{2.5}$ concentrations, particularly in cold areas of the country.

A limited number of reports describe TEOM performance compared with filter-based FRM methods. A report on the evaluation of the TEOM method for 10 locations in North America shows that under most conditions, the TEOM underreports concentration when compared with reference filter-based methods.³ Measurements of $PM_{2.5}$ and PM_{10} in Kuopio, Finland, found variations in the ratio of filter-based concentration to TEOM-measured concentration.⁴ Field trials of the TEOM in Cornwall, United Kingdom, found a nonlinear relationship with

**Figure 1.** Uncorrected TEOM vs. FRM for site 180970078.**Figure 2.** Uncorrected TEOM vs. FRM for site 260810020.

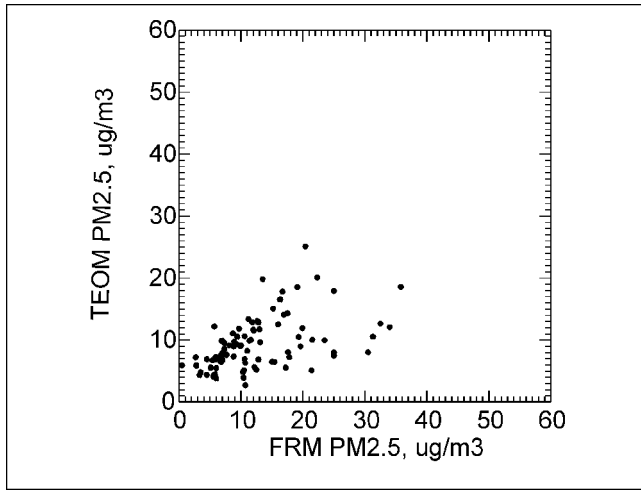


Figure 3. Uncorrected TEOM vs. FRM for site 271230868.

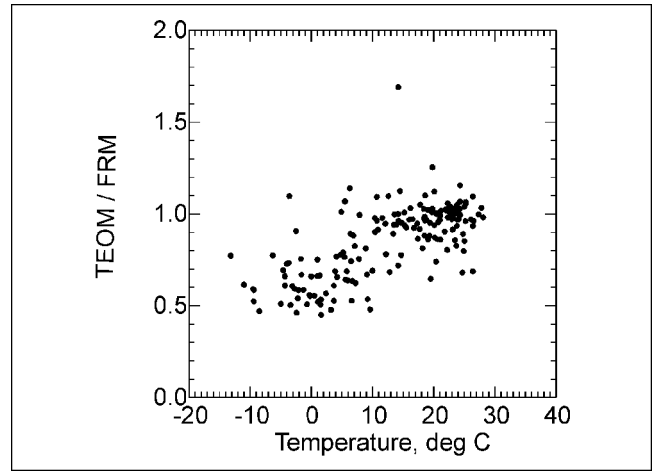


Figure 6. Ratio of TEOM to FRM for site 180970078.

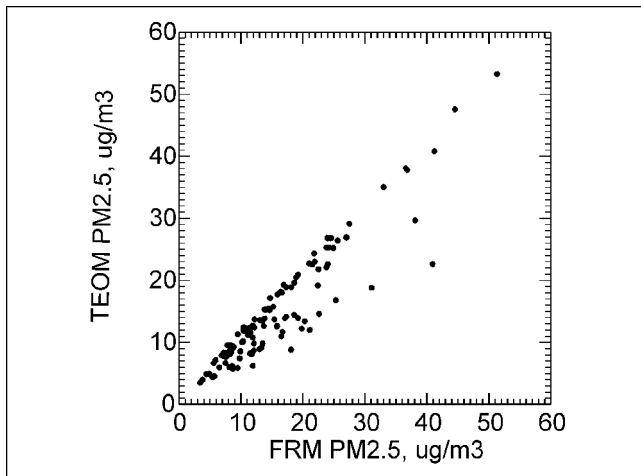


Figure 4. Uncorrected TEOM vs. FRM for site 390610040.

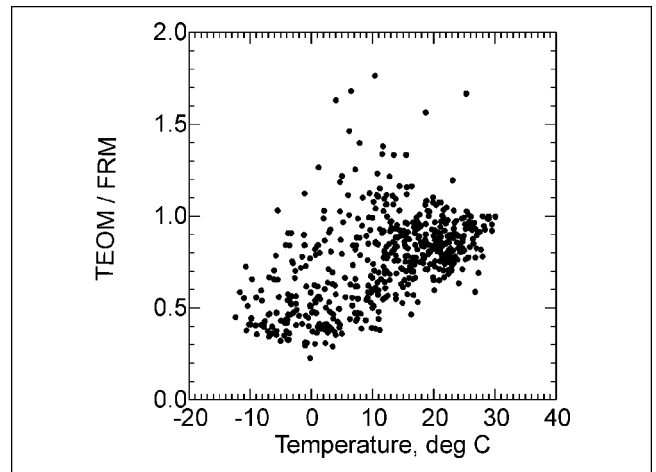


Figure 7. Ratio of TEOM to FRM for site 260810020.

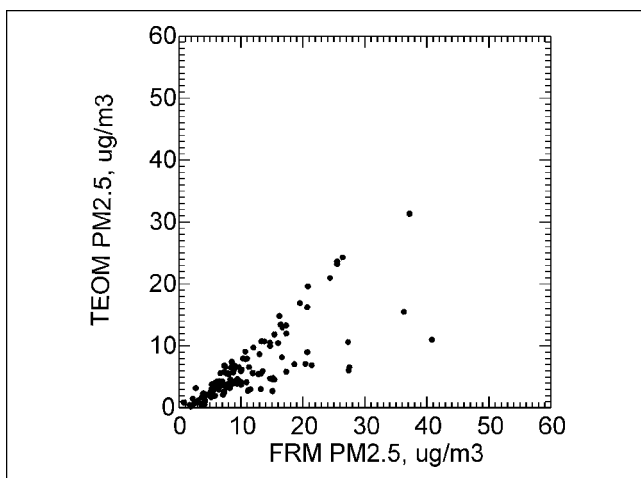


Figure 5. Uncorrected TEOM vs. FRM for site 550270007.

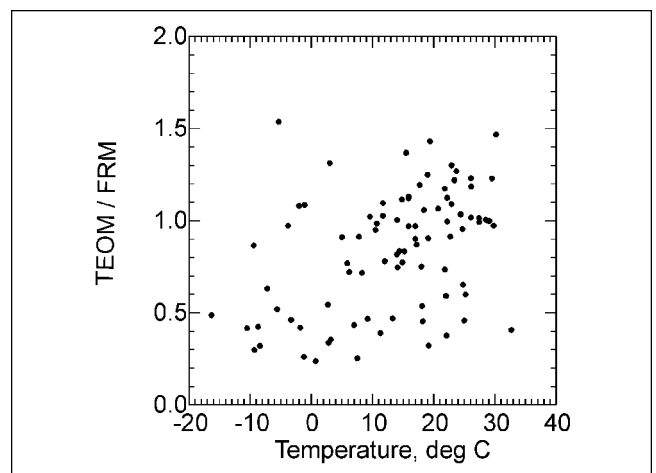


Figure 8. Ratio of TEOM to FRM for site 271230868.

gravimetric mass.⁵ A field test of the TEOM in four Australian cities found systematically lower results from the TEOM compared with gravimetric PM_{2.5} by an average of

30%.⁶ A test of the TEOM and personal PM₁₀ samplers in two cities in the United Kingdom found consistently lower concentrations from the continuous method.⁷

Field tests in Erfurt, Germany, found that concentrations measured by the TEOM were systematically lower than those obtained by the Harvard Impactor.⁸ A test of the TEOM in Bakersfield, CA, found that the TEOM measurements

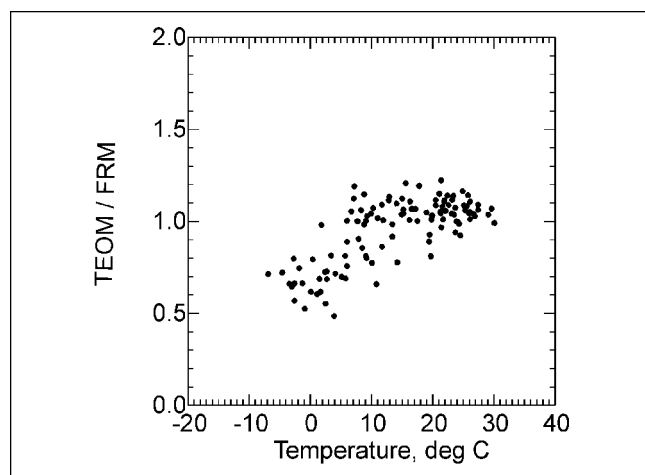


Figure 9. Ratio of TEOM to FRM for site 390610040.

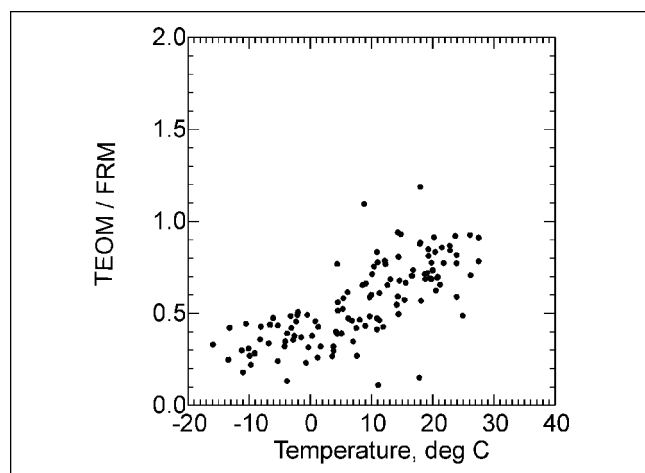


Figure 10. Ratio of TEOM to FRM for site 550270007.

were lower than the reference filter-based measurements by an amount approximately equal to the concentration of NH_4NO_3 in the airborne particles.⁹ For an evaluation of the TEOM for assessing the European Union PM_{10} Stage 1 limit, collocated TEOM concentrations were found to be systematically lower than filter-based measurements.¹⁰ Data from collocated TEOM and gravimetric PM_{10} samplers in a coal-mining region in the United Kingdom found that the discrepancy between the methods (TEOM < gravimetric) increased with increasing concentration.¹¹ Finally, a study of the effect of equilibrium temperature on PM_{10} concentrations in the Lower Fraser Valley showed that the volatilization of particulate semi-volatile material is greater at higher equilibrium temperatures.¹²

One common theme to these research reports is that because of volatilization of PM, the TEOM systematically measures a lower concentration compared with gravimetric filter-based methods. One approach to correcting the TEOM output to account for this negative bias involves using a linear model of continuous (dependent) and FRM (independent) measurements, adjusting the slope of the relationship during meteorological conditions when the bias is observed. This work will examine a two-segment linear model with interaction as a technique for obtaining “FRM-like” measurements from the TEOM. In an attempt to keep this approach generally applicable to any location with an FRM $\text{PM}_{2.5}$ monitor, temperature is the only other variable introduced in the model.

METHODOLOGY

Data were taken from the U.S. Environmental Protection Agency (EPA) Air Quality Subsystem (AQS) for all sites within Region 5 that used the TEOM for $\text{PM}_{2.5}$ and had a collocated FRM monitor. The temperature data represent the average daily temperature recorded by the FRM

Table 2. Region 5 model results: sampling dates and regression diagnostics.

Monitor	Start Date	End Date	No. of Obs.	Regression SS	Residual SS	Uncorrected Total SS	Corrected Total SS	Estimated R^2
180970078	07/02/00	12/30/01	173	62905.4	1127.3	64032.7	12773.3	0.91
260650012	12/02/99	10/30/01	208	49114.7	1907.4	51021.5	13745.4	0.86
260770008	08/19/00	09/28/01	126	39952.0	1523.7	41475.7	11076.9	0.86
260810020	11/04/99	10/31/01	556	144916.0	5266.7	150182.0	41662.3	0.87
261450018	12/20/99	09/28/01	183	31985.9	1565.0	33551.0	10807.7	0.86
261610008	02/24/00	09/28/01	175	45276.4	2207.3	47483.7	12366.9	0.82
261630001	02/01/01	09/29/01	214	85727.1	2159.0	87886.1	21583.4	0.90
271230868	01/01/01	10/31/01	92	16769.9	2533.5	19303.4	5055.6	0.50
390610040	01/01/01	12/31/01	116	38356.5	373.1	38729.6	9422.8	0.96
550270007	10/03/00	12/30/01	120	21152.5	727.1	21879.5	6716.8	0.89

Note: Estimated $R^2 = (1 - \text{SSE} / \text{Corrected SST})$.

Table 3. Region 5 model results: parameter estimates.

Monitor	Parameter	Estimate	Standard Error	Lower 95% CL	Upper 95% CL	Monitor	Parameter	Estimate	Standard Error	Lower 95% CL	Upper 95% CL
180970078	β_0	0.4204	0.7689	-1.0977	1.9384	261610008	β_0	-0.0235	1.0481	-2.0928	2.0457
	β_1	0.0413	0.0611	-0.0794	0.1619		β_1	0.00451	0.0887	-0.1705	0.1795
	β_2	0.2907	0.2293	-0.162	0.7434		β_2	0.2242	0.2660	-0.3010	0.7494
	β_3	0.9809	0.0539	0.8745	1.0874		β_3	0.9772	0.0782	0.8227	1.1316
	β_4	-0.0329	0.0046	-0.042	-0.0238		β_4	-0.0456	0.00977	-0.0649	-0.0263
	β_5	-0.00785	0.00926	-0.0261	0.0104		β_5	-0.00226	0.0139	-0.0296	0.0251
	knot	18.81	1.2641	16.31	21.30		knot	19.15	1.3081	16.56	21.73
260650012	β_0	-0.099	0.8261	-1.728	1.5301	261630001	β_0	-0.9438	0.9576	-2.8317	0.9442
	β_1	0.1579	0.0686	0.0226	0.2932		β_1	0.2056	0.0866	0.0348	0.3763
	β_2	0.1845	0.2358	-0.2805	0.6494		β_2	0.2947	0.2129	-0.125	0.7145
	β_3	0.8267	0.0554	0.7175	0.9359		β_3	1.1806	0.0768	1.0293	1.332
	β_4	-0.0428	0.00627	-0.0552	-0.0304		β_4	-0.0636	0.00877	-0.0809	-0.0463
	β_5	-0.00377	0.00915	-0.0218	0.0143		β_5	-0.0197	0.0104	-0.0401	0.000757
	knot	18.01	1.4585	15.13	20.88		knot	18.79	1.343	16.14	21.44
260770008	β_0	-0.5448	1.2664	-3.0524	1.9629	271230868	β_0	2.5407	2.6923	-2.8123	7.8936
	β_1	0.2824	0.1392	0.0068	0.5579		β_1	0.1848	0.1639	-0.1411	0.5106
	β_2	0.059	0.2354	-0.4071	0.5252		β_2	0.6664	0.6267	-0.5796	1.9125
	β_3	1.237	0.1178	1.0037	1.4703		β_3	0.7739	0.3046	0.1684	1.3795
	β_4	-0.064	0.0156	-0.095	-0.033		β_4	-0.0602	0.0188	-0.0976	-0.0227
	β_5	-0.011	0.0131	-0.037	0.0149		β_5	-0.0447	0.0451	-0.1344	0.045
	knot	15.00	3.258	8.549	21.45		knot	20.62	3.5236	13.61	27.62
260810020	β_0	-2.2173	0.5073	-3.2137	-1.2208	390610040	β_0	-1.6864	0.7842	-3.2406	-0.1322
	β_1	0.1982	0.0463	0.1073	0.2891		β_1	0.073	0.0752	-0.0761	0.2221
	β_2	0.4717	0.1483	0.1804	0.763		β_2	0.1372	0.1498	-0.1596	0.4341
	β_3	1.3995	0.0622	1.2772	1.5217		β_3	1.0391	0.0535	0.9331	1.1451
	β_4	-0.0818	0.0063	-0.0941	-0.0694		β_4	-0.0418	0.00684	-0.0553	-0.0282
	β_5	-0.042	0.00683	-0.0554	-0.0286		β_5	-0.00685	0.00554	-0.0178	0.00414
	knot	18.22	0.8308	16.59	19.85		knot	17.36	1.4119	14.56	20.16
261450018	β_0	-0.7685	0.6994	-2.1489	0.6118	550270007	β_0	2.385	0.751	0.8971	3.8729
	β_1	0.0578	0.0487	-0.0382	0.1539		β_1	0.1323	0.0624	0.00871	0.256
	β_2	0.5672	0.3106	-0.0456	1.1801		β_2	-0.0451	0.1242	-0.2912	0.201
	β_3	0.9685	0.0659	0.8385	1.0985		β_3	1.0315	0.1135	0.8066	1.2563
	β_4	-0.0568	0.00701	-0.0707	-0.043		β_4	-0.1067	0.0123	-0.131	-0.0824
	β_5	-0.00469	0.0173	-0.0388	0.0294		β_5	0.00257	0.0117	-0.0206	0.0257
	knot	20.03	0.8224	18.41	21.66		knot	12.96	1.3481	10.29	15.63

Note: Estimated $R^2 = (1 - SSE/Corrected\ SST)$.

monitor. Hourly concentrations from the TEOMs were averaged from midnight to midnight for each day, yielding a daily average fine particulate concentration. A completeness criterion of 75% (at least 18 hr of valid data) was used to determine what constituted a complete 24-hr average. The extent of the sampling period varies according to when monitoring was started by each individual state. Most sites had data that covered a year, thereby allowing the model to take into account the seasonal variations in fine particulate concentrations as well as the seasonal cycle of temperatures. Table 1 summarizes information for each site used in the analysis.

Figures 1–5 are scatter plots of TEOM and FRM $PM_{2.5}$ concentrations. (Note that data from only one of the six monitors in Michigan are shown. Monitor 260810020 was selected because it had the longest measurement record. The other five Michigan monitors show similar patterns.) While these plots show a fairly strong and consistent relationship between the TEOM and FRM measurements, they also suggest that for a significant fraction of the observations, an independent factor causes the slope of the relationship to drop below 1. To further evaluate what this variable might be, the data were replotted to show the ratio of the TEOM to the FRM versus the average temperature. These plots are shown in Figures 6–10 and

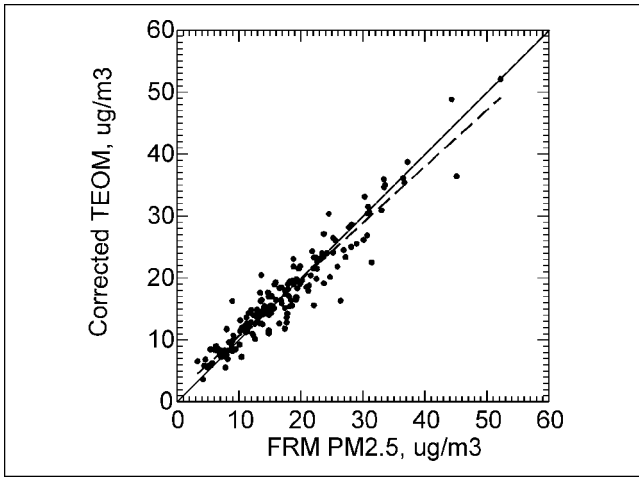


Figure 11. Corrected TEOM vs. FRM for site 180970078.

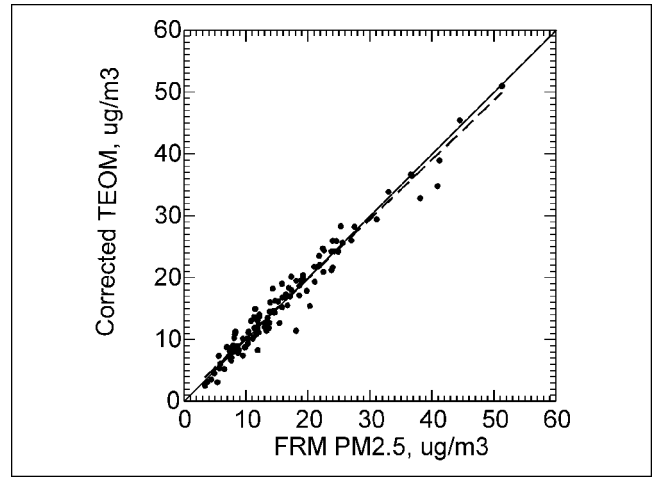


Figure 14. Corrected TEOM vs. FRM for site 390610040.

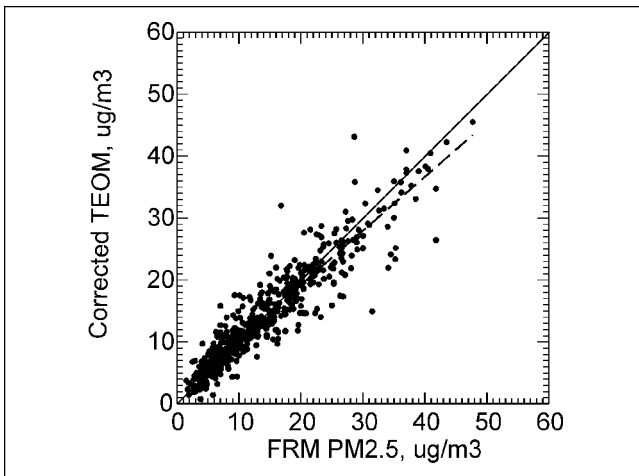


Figure 12. Corrected TEOM vs. FRM for site 260810020.

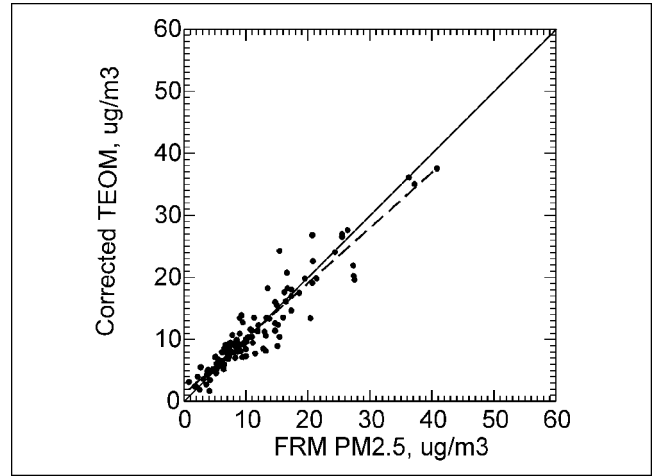


Figure 15. Corrected TEOM vs. FRM for site 550270007.

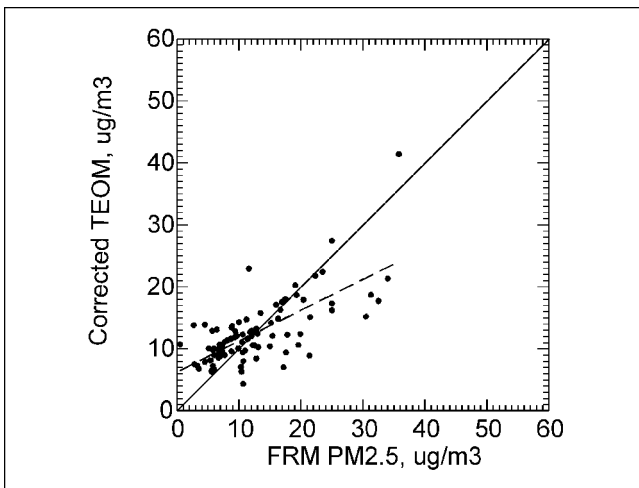


Figure 13. Corrected TEOM vs. FRM for site 271230868.

Table 4. Comparison between corrected continuous and FRM measurements.

Monitor	Intercept	Slope	R ²
180970078	0.4204	0.9809	0.91
260650012	-0.099	0.8267	0.86
260770008	-0.5448	1.237	0.86
260810020	-2.2173	1.3995	0.87
261450018	-0.7685	0.9685	0.85
261610008	-0.0235	0.9772	0.82
261630001	-0.9438	1.1806	0.89
271230868	2.5407	0.7739	0.49
390610040	-1.6864	1.0391	0.96
550270007	2.385	1.0315	0.88

Note: Five of these relationships are shown in Figures 11–15.

indicate what appears to be a decrease in the ratio of TEOM to FRM for cooler temperatures. These plots suggest a nonlinear relationship between the ratio of the two monitors and the average temperature.

For this analysis, we fit linear relationships to TEOM versus FRM data allowing a “break” or knot in the relationship (modeled as a change of slope) at a given temperature. For these relationships, temperature was

Table 5. Results of Region 5 fit and test analysis.

Monitor	Type	Start Date	End Date	<i>n</i>	<i>R</i> ²	Parameter	Estimate	Standard Error	Lower 95% CL	Upper 95% CL
180790078	Fit	07/02/00	07/21/01	120	0.91	β_0	0.8613	0.9798	-1.0798	2.8024
						β_1	0.00889	0.0768	-0.1433	0.1611
						β_2	0.147	0.2736	-0.395	0.6889
						β_3	0.9658	0.0686	0.8299	1.1017
						β_4	-0.0314	0.00532	-0.042	-0.0209
						β_5	-0.00486	0.0133	-0.0312	0.0215
						knot	18.07	1.7559	14.59	21.55
260650012	Fit	12/02/99	01/25/01	121	0.84	β_0	-0.9198	1.3243	-3.5431	1.7036
						β_1	0.0968	0.0936	-0.0885	0.2822
						β_2	0.3933	0.5133	-0.6234	1.4101
						β_3	0.9479	0.1515	0.6478	1.248
						β_4	-0.0367	0.00807	-0.0527	-0.0207
						β_5	-0.0351	0.0208	-0.0763	0.00615
						knot	16.80	4.51	7.87	25.73
260810020	Fit	11/04/99	11/05/00	343	0.87	β_0	-1.5394	0.6765	-2.8702	-0.2085
						β_1	0.2214	0.0606	0.1022	0.3406
						β_2	0.1873	0.2762	-0.356	0.7306
						β_3	1.4383	0.1093	1.2233	1.6533
						β_4	-0.0757	0.00796	-0.0913	-0.06
						β_5	-0.0321	0.0176	-0.0668	0.00249
						knot	18.71	1.7496	15.27	22.16
261450018	Fit	12/20/99	03/14/01	121	0.85	β_0	-1.2626	0.9401	-3.1249	0.5997
						β_1	0.00311	0.0563	-0.1084	0.1147
						β_2	0.3482	0.7793	-1.1956	1.892
						β_3	1.0341	0.1174	0.8016	1.2667
						β_4	-0.0477	0.00764	-0.0628	-0.0325
						β_5	-0.0206	0.0395	-0.0989	0.0576
						knot	19.65	2.4437	14.81	24.49
261610008	Fit	02/24/00	04/07/01	119	0.81	β_0	-3.076	1.4924	-6.033	-0.1191
						β_1	-0.1552	0.1065	-0.3662	0.0557
						β_2	0.86	0.6773	-0.4819	2.2019
						β_3	1.2264	0.1426	0.9439	1.5089
						β_4	-0.0343	0.0103	-0.0547	-0.014
						β_5	-0.0656	0.0348	-0.1346	0.00346
						knot	18.62	2.1388	14.38	22.85
261610008	Test	04/07/01	09/28/01	57	0.89					

allowed to interact with the independent variable (FRM measurement), and the relationships were required to be continuous through the knot (no break in the model was allowed). This approach assumes that the relationship between the FRM and continuous TEOM measurements is linear but that the linear relationship may change at a fixed temperature. In other words, within a range of average daily temperatures, the FRM and TEOM measurements have a linear relationship with slope β_1 , while within another range of temperatures, the readings from the two

instruments are related to one another with slope β_2 where β_1 does not equal β_2 . It is also possible to add the appropriate interactions between temperature and the TEOM measurement based on the level of the knot. Thus, for this analysis, a model was used in the form of eqs 1 and 2.

If the temperature is less than the value of the knot

$$FRM = \beta_0 + \beta_1 \times (avetemp - knot) + \beta_3 \times cont + \beta_4 \times cont \times (avetemp - knot) \quad (1)$$

Table 6. Results of combining Michigan's data into a single model.

No. of Obs.	Estimated R^2	Parameter	Value	Standard Error	Lower 95% CI	Upper 95% CI	P-Value
1463	0.80	β_0	-0.2496	0.3720	-0.9793	0.4801	0.5024
		β_1	0.0442	0.0281	-0.0109	0.0993	0.1157
		β_2	0.4860	0.1382	0.2149	0.7572	0.0005
		β_3	1.0487	0.0310	0.9879	1.1096	<0.0001
		β_4	-0.0424	0.00309	-0.0485	-0.0363	<0.0001
		β_5	-0.0171	0.00589	-0.0286	-0.00552	0.0038
		knot	19.90	0.5608	18.80	21.00	<0.0001

where *FRM* is the Federal Reference Method measurement, β_0 is the intercept, β_1 is the coefficient for the temperature term for temperatures less than the knot, *avetemp* is the daily average temperature, *knot* is the temperature at which the linear relationship between the FRM and continuous measurement changes, β_3 is the coefficient for the continuous measurement, *cont* is the continuous TEOM measurement, and β_4 is the coefficient of the interaction between the TEOM and temperature measurements for temperature less than the knot

If the temperature is greater than the value of the knot

$$FRM = \beta_0 + \beta_2 \times (avetemp - knot) + \beta_3 \times cont + \beta_5 \times cont \times (avetemp - knot) \quad (2)$$

where *FRM* is the Federal Reference Method measurement, β_0 is the intercept, β_2 is the coefficient for the temperature term for temperatures greater than the knot, *avetemp* is the daily average temperature, *knot* is the temperature at which the linear relationship between the FRM and continuous measurement changes, β_3 is the coefficient for the continuous measurement, *cont* is the continuous TEOM measurement, and β_5 is the coefficient of the interaction between the TEOM and temperature measurements for temperature greater than the knot.

Table 7. Comparison between corrected continuous and FRM values for the state of Michigan.

Monitor	Intercept	Slope	R^2
260650012	3.76250	1.03842	0.86
260770008	3.64404	0.76426	0.85
260810020	2.60371	0.70670	0.84
261450018	2.07901	0.83430	0.84
261610008	2.42152	0.84639	0.81
261630001	2.60050	0.81352	0.89

Equations 1 and 2 were solved simultaneously using the SAS nonlinear regression (NLIN) procedure with the Gauss-Newton method.¹³ This method solves the equations by searching for the global minimum or best solution that provides the lowest error sum of squares. Note that the NLIN procedure allows the specification of an equation within an If-Then-Else statement, allowing for the conditional fit of the data. The process is iterative until the error sum of squares does not change by a difference of 0.001. In the analysis, *FRM*, *cont*, and *avetemp* are measured, and β_0 , β_1 , β_2 , β_3 , β_4 , β_5 , and *knot* are parameters that are fitted to the data.

To test whether the relationship is adequate in adjusting future continuous measurements, tests were conducted on monitoring sites with more than one full year of data. According to EPA's *Data Quality Objectives for Relating Federal Reference Method and Continuous PM_{2.5} Measurements to Report an Air Quality Index*¹⁴ to ensure that the population R^2 is at least 0.7 with a false rejection decision error of 0.10, a false acceptance decision error of 0.30, and the size of the uncertainty region of 0.10, one needs at least 63 observations and a corresponding sample R^2 of at least 0.77. All of the sites in Michigan and the Indianapolis, IN, site satisfy these requirements. For these locations, a year's worth of data totaling at least 63 observations were used to reproduce the relationship described previously. The remaining data were used to test the durability of the resulting relationship to adequately adjust the continuous measurement to provide an "FRM-like" measurement.

RESULTS AND DISCUSSION

Figures 1–5 display the scatter plots of the continuous TEOM versus FRM measurement for five of the 10 monitors (plots for only one Michigan monitor are included). These plots show that a large fraction of the data fall approximately on the $y = x$ line. However, the figures also show a separate group of points that cluster near a second line with the slope significantly less than 1. For these

points, the TEOM measures a lower concentration than does the FRM.

To determine if temperature could be used to explain this pattern, the data were plotted as the ratio of the TEOM to FRM versus temperature. These plots are shown in Figures 6–10 for the same monitors. (Note that Figures 6–10 are all plotted with the y axis ranging from 0 to 2 to allow for easy plot-to-plot comparisons. Because of this, a small number of points with a TEOM-to-FRM ratio of greater than 2 are not shown. However, this is not a major problem because all of these points are from days with very low absolute concentrations [lower left corner of Figures 1–5] and represent observations with the lowest signal to noise ratio.) These figures show that the average ratio of TEOM to FRM is approximately 1 for warmer conditions but less than 1 for cooler conditions.

Tables 2 and 3 show the results of the conditional regression analysis. Table 2 includes the start and end dates and total number of observations of the individual monitoring data sets, the sums of squares for regression, the sum of squares for error, the uncorrected and corrected total sum of squares, and the estimated R^2 . Table 3 shows the parameter estimates, standard errors, and confidence intervals for the full data set for each monitor listed in Table 1. As shown in Table 3, the temperature “knots” fitted by the model range from 12.9 to 20.6 °C. The statistical significance of the coefficients associated with temperature below and above the knot (β_1 and β_2 , respectively) and the interaction terms (β_4 and β_5 , respectively) helps to describe the effect of temperature on the aerosol. For most of the sites, the coefficient for temperature greater than the knot (β_2) is not significantly different from 0 (the 95% confidence intervals contain 0). This is also the case for the interaction term between the continuous PM measurement and temperature above the knot (β_5). This is consistent with the observation that the relationship between the TEOM and the FRM does not depend on temperature for warmer days. However, for temperatures below the knot, the interaction term (β_4) is always significantly less than 0, and the temperature term (β_1) is frequently significantly different from 0, which implies that for cooler temperatures, the relationship between the TEOM and FRM is changing as some component of the PM is not being measured by the TEOM. Finally, it is interesting to note that most of the estimates for β_3 are not statistically different from 1 (the confidence intervals for 6 of the 10 models contain 1), suggesting that with temperature in the model, the mean relationship between the TEOM and FRM is not biased.

Figures 11–15 show the relationship between the predicted or adjusted TEOM $PM_{2.5}$ values using the models in Table 2 (y axis) and the FRM measurement (x axis). These figures include a $y = x$ reference line and show how

effective the model is at reproducing “FRM-equivalent” concentrations from TEOM and temperature data only. Table 4 shows summary statistics for the regression lines between adjusted TEOM and measured $PM_{2.5}$ for these relationships. Note that the regression relationships are also shown in the figures as dashed lines.

From Table 4 and Figures 11–15, all of the TEOM instruments with the exception of the monitor in Minneapolis (271230868) satisfy the requirement of an R^2 greater than or equal to 0.77 as specified in *Data Quality Objectives for Relating Federal Reference Method and Continuous $PM_{2.5}$ Measurements to Report an Air Quality Index*. However, the differing degrees of correlation as well as the differences in the fitted parameters suggest that the relationship between the continuous TEOM, FRM, and temperature may have to be formulated independently for each monitoring site. It is also possible that each state may be operating its TEOMs differently from its counterparts. However, to the best of our knowledge, all of the TEOMs in Region 5 are operated with heated inlets at 50 °C with no additional correction factor other than the automatic factory-activated offset.

The results of splitting the data to fit the model with one full year of observations and then using the remainder as a hold-back sample to test whether the relationship holds for future observations could only be accomplished for the sites in Michigan and Indianapolis and is shown in Table 5. The sites that could be tested show that the adjusted data can satisfy the R^2 requirement of 0.77 for both the test and fit data and can be used to adjust TEOM data for use with the Air Quality Index (AQI) on a real-time basis. However, it is not clear at this time if the relationships are sufficiently strong to allow the use of the TEOM for determination of compliance with the NAAQS.

The possibility of having a single state- or regionwide model representing several sites was also examined. The data from all of Michigan’s sites were combined and modeled to determine if a single model could be developed for the entire state. Table 6 lists the parameters and their associated values for the state of Michigan model. Table 7 lists the slope, intercept, and R^2 for the Michigan model when comparing the corrected continuous or predicted FRM value to the actual FRM measurement. Likewise, Tables 8 and 9 show the results of using a single model for all of the TEOM sites in Region 5. Note that because of poor model performance (Figure 13), the data from Minnesota are not included in the Region 5 model.

Table 6 shows that the single model for the state of Michigan works reasonably well with an estimated R^2 of 0.80. Table 7 shows that this model is able to reproduce each monitor’s values with acceptable R^2 s greater than 0.80. However, Table 7 also shows that some of the slopes of these relationships are less than 0.80, suggesting that

Table 8. Results of combining the data from all sites.

No. of Obs.	Estimated R^2	Parameter	Value	Standard Error	Lower 95% CL	Upper 95% CL	P-Value
1871	0.81	β_0	-0.0628	0.3108	-0.6723	0.5466	0.8398
		β_1	-0.0132	0.0224	-0.0572	0.0308	0.5564
		β_2	0.4392	0.1176	0.2087	0.6698	0.0002
		β_3	1.0245	0.0249	0.9757	1.0733	<.0001
		β_4	-0.0351	0.00237	-0.0397	-0.0304	<.0001
		β_5	-0.0142	0.00472	-0.0234	-0.00490	0.0027
		knot	19.86	0.5114	18.86	20.87	<.0001

the statewide model may be systematically underestimating the concentrations on more polluted days. The same conclusion can be drawn from the results in Tables 8 and 9. Although the R^2 s are high for the Region 5 model, many of the slopes of the predicted versus measured FRM relationships are less than 0.80.

The model was also tested for TEOMs operated in the state of New York. Table 10 shows monitoring site information for six TEOMs operated in New York State with more than one full year of operation. Table 11 shows the results of fit and test analyses for the six New York State TEOM monitors. As for Table 5, the first year of data was

used to develop the adjustment models and the remaining holdback sample was used to test the model. As shown in Table 11, the performance of the model for all six fit-and-test periods was excellent, with all R^2 s greater than 0.85.

CONCLUSIONS

- (1) For the Region 5 TEOMs, the relationships between the TEOM and the FRM measurements are affected by temperature.
- (2) Initial tests to determine if the TEOM adjustment equations will remain valid for future observations indicate that the relationship will hold and satisfy the correlation coefficient requirements under the data quality objectives, thus allowing the TEOM data to be used for AQI reporting purposes.
- (3) The relationship between the corrected TEOM and the FRM measurements appears to work best when developed using an individual model for each site. When a single model is used for more than one site, the resulting correlation between the corrected continuous measurement and the FRM are acceptable. However, the slopes sometimes change considerably.

Table 9. Comparison between corrected continuous and FRM values for all sites.

Monitor	Intercept	Slope	R^2
180970078	1.80151	0.95316	0.90
260650012	4.03470	0.99561	0.86
260770008	3.97723	0.73111	0.85
260810020	2.99781	0.67932	0.84
261450018	2.60791	0.79584	0.84
261610008	2.73780	0.81648	0.82
261630001	2.80315	0.78995	0.89
390610040	3.27851	0.93649	0.96
550270007	0.41539	0.73603	0.83

Table 10. Monitoring site information for New York State.

Monitor	Latitude	Longitude	Address	City	Land Use	Setting	Comment
360050110	40.81616	-73.90207	E 156th Street	New York City	Commercial	Urban and center city	Between Dawson and Kelly Streets
360290005	42.878056	-78.809444	185 Dingens Street	Buffalo	Residential	Urban and center city	Trailer
360310003	44.364722	-73.901667	Base of Whiteface Mountain	Not in a city	Forest	Rural	ASRC, SUNY
360556001	43.162222	-77.604167	Andrews and N Chestnut Streets	Rochester	Commercial	Urban and center city	Fire HQ building
360610010	40.739444	-73.986111	240 2nd Avenue	New York City	Residential	Urban and center city	Mabel Dean High School annex
360632008	43.081944	-79.003056	Frontier Avenue and 55th Street	Niagara Falls	Industrial	Suburban	

Table 11. Results of fit and test analysis for New York State.

Monitor	Type	Start Date	End Date	n	R ²	Parameter	Estimate	Standard Error	Lower 95% CL	Upper 95% CL
360050110	Fit	01/01/00	12/31/00	304	0.91	β_0	-1.4801	0.6463	-2.752	-0.2082
						β_1	0.1173	0.0505	0.018	0.2166
						β_2	0.533	0.2953	-0.0481	1.1141
						β_3	0.984	0.0464	0.8927	1.0753
						β_4	-0.026	0.00367	-0.0332	-0.0187
						β_5	-0.0221	0.00984	-0.0415	-0.00279
						knot	21.15	1.4763	18.24	24.06
360290005	Fit	03/25/00	04/10/01	104	0.9	β_0	-1.5153	1.1826	-3.8625	0.8318
						β_1	0.3707	0.112	0.1484	0.5929
						β_2	0.0184	0.2767	-0.5308	0.5675
						β_3	1.1379	0.1033	0.9328	1.3429
						β_4	-0.0713	0.00966	-0.0904	-0.0521
						β_5	-0.0128	0.0168	-0.0461	0.0205
						knot	14.00	1.609	10.81	17.19
360310003	Fit	01/01/00	12/30/00	316	0.96	β_0	-1.0536	0.2106	-1.4681	-0.6391
						β_1	0.0608	0.0209	0.0196	0.102
						β_2	0.00584	0.0404	-0.0737	0.0854
						β_3	0.9528	0.0377	0.8785	1.0271
						β_4	-0.0152	0.00403	-0.0231	-0.00722
						β_5	-0.00249	0.00462	-0.0116	0.00661
						knot	10.80	3.8433	3.238	18.36
360556001	Fit	05/15/00	05/31/01	96	0.92	β_0	-1.0373	0.8568	-2.7397	0.6651
						β_1	0.2719	0.0708	0.1311	0.4126
						β_2	0.3101	0.3824	-0.4497	1.0698
						β_3	0.9587	0.0826	0.7946	1.1229
						β_4	-0.0576	0.00809	-0.0736	-0.0415
						β_5	-0.0212	0.0205	-0.062	0.0196
						knot	17.20	1.7812	13.67	20.74
360610010	Fit	07/31/99	07/31/00	265	0.9	β_0	0.7562	0.7618	-0.7439	2.2564
						β_1	0.267	0.0651	0.1388	0.3953
						β_2	0.6797	0.3577	-0.0247	1.3841
						β_3	0.7902	0.0461	0.6995	0.881
						β_4	-0.0428	0.00481	-0.0522	-0.0333
						β_5	-0.0016	0.0127	-0.0267	0.0235
						knot	22.26	0.724	20.83	23.69
360632008	Fit	04/21/00	04/22/01	110	0.87	β_0	-1.5218	1.0998	-3.7029	0.6594
						β_1	0.1251	0.0796	-0.0328	0.283
						β_2	0.7631	0.7992	-0.822	2.3482
						β_3	1.0023	0.0889	0.826	1.1785
						β_4	-0.0397	0.00779	-0.0551	-0.0242
						β_5	-0.0398	0.037	-0.1132	0.0336
						knot	18.56	1.6771	15.23	21.88
360632008	Test	04/25/01	12/27/01	75	0.97					

- (4) This approach was also found to work very well for six monitors in New York State.

DISCLAIMER

The views expressed in this paper are those of the authors and not necessarily those of the U.S. Environmental Protection Agency.

REFERENCES

- 40 CFR Part 50: National Ambient Air Quality Standards for Particulate Matter. *Fed. Regist.* **1997**, 62 (138), 2-102.
- Patashnick, H.; Rupprecht, E.G. Continuous PM₁₀ Measurements Using the Tapered Element Oscillating Microbalance; *J. Air & Waste Manage. Assoc.* **1991**, 41, 1079-1083.
- Allen, G.; Sioutas, C.; Koutrakis, P.; Reiss, R.; Lurmann, F.W.; Roberts, P.T. Evaluation of the TEOM Method for Measurement of Ambient Particulate Mass in Urban Areas; *J. Air & Waste Manage. Assoc.* **1997**, 47, 682-689.
- Mirme, A.; Ruuskanin, J. Comparison of Aerosol Measurements in Urban Environment; *J. Aerosol Sci.* **1996**, 27, s23-s24.
- Salter, L.F.; Parsons, B. Field Trials of the TEOM and Partisol for PM₁₀ Monitoring in the St Austell China Clay Area, Cornwall, U.K.; *Atmos. Environ.* **1999**, 33, 2111-2114.
- Ayers, G.P.; Keywood, M.D.; Gras, J.L. TEOM vs. Manual Gravimetric Methods for Determination of PM_{2.5} Aerosol Mass Concentrations; *Atmos. Environ.* **1999**, 33, 3717-3721.
- Soutar, A.; Watt, M.; Cherrie, J.W.; Seaton, A. Comparison between a Personal PM₁₀ Sampling Head and the Tapered Element Oscillating Microbalance (TEOM) System; *Atmos. Environ.* **1999**, 33, 4373-4377.
- Cyrys, J.; Dietrich, G.; Kreyling, W.; Tuch, T.; Heinrich, J. PM_{2.5} Measurements in Ambient Aerosol: Comparison between Harvard Impactor (HI) and the Tapered Element Oscillating Microbalance (TEOM) System; *Sci. Total Environ.* **2001**, 278, 191-197.
- Chung, A.; Chang, D.P.Y.; Kleeman, M.J.; Perry, K.D.; Cahill, T.A.; Dutcher, D.; McDougall, E. M.; Stroud, K. Comparison of Real-Time Instruments Used to Monitor Airborne Particulate Matter; *J. Air & Waste Manage. Assoc.* **2001**, 51, 109-120.
- Green, D.; Fuller, G.; Barratt, B. Evaluation of TEOM Correction Factors for Assessing the EU Stage 1 Limit for PM₁₀; *Atmos. Environ.* **2001**, 35, 2589-2593.
- King, A.M.; Pless-Mulloli, T.; Merefield, J.; Stone, I. New Directions: TEOMs and the Volatility of U.K. Non-Urban PM₁₀: A Regulatory Dilemma?; *Atmos. Environ.* **2000**, 34, 3209-3212.
- Mignacca, D.; Stubbs, K. Effects of Equilibrium Temperature on PM₁₀ Concentrations from the TEOM Method in the Lower Fraser Valley; *J. Air & Waste Manage. Assoc.* **1999**, 49, 1250-1254.
- SAS/STAT User's Guide*; Release 8.2; SAS Institute: Cary, NC, 1999.
- Data Quality Objectives for Relating Federal Reference Method and Continuous PM_{2.5} Measurements to Report an Air Quality Index*; EPA-454/B-02-002; U.S. Environmental Protection Agency: Research Triangle Park, NC, November 2002.

About the Authors

Michael Rizzo is an environmental scientist with the Air Monitoring Section, Region 5, U.S. Environmental Protection Agency, in Chicago, IL. Peter A. Scheff is a professor of environmental and occupational health sciences at the School of Public Health, University of Illinois, in Chicago, IL. William Kaldy is a scientist with the Hamilton County Department of Environmental Services in Cincinnati, OH. Address correspondence to: Dr. Peter A. Scheff, School of Public Health (M/C 922), University of Illinois, 2121 West Taylor Avenue, Chicago, IL 60612; phone: (312) 996-0800; fax: (312) 413-9898; e-mail: pscheff@uic.edu.