# 6.1 EMISSION FACTORS FOR FUGITIVE DUST FROM BULLDOZERS WORKING ON A COAL PILE

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## 1. INTRODUCTION

Fugitive emissions are emitted gaseous or aerosol materials that do not pass through vents, stacks or other openings. These emissions can affect air quality near a source and are regulated by federal and state agencies. By their nature, fugitive emissions are difficult to quantify. Indirect techniques have been used to estimate emissions and relate them to some kind of human activity or physical process (e.g., wind erosion of soils).

A study of a PRB (Powder River Basin) coal pile collected thousands of hours of particulate and meteorological data near the pile plus video imagery in an effort to quantify fugitive dust emissions. In the present context "dust" refers to particles smaller than 10 µm in size ($PM_{10}$). Enhanced particulate levels were measured downwind of the pile both in the absence and presence of human activity on the pile. The primary human activity that produced fugitive dust was the movement of bulldozers across the crushed coal surface. Bulldozers worked to move coal between points on the pile and to scrape the coal surface. The latter activity was needed to suppress the spontaneous combustion of coal dust and is referred to here as "grooming".

Quantifying coal dust fugitive emissions from bulldozer activity required that natural dust contributions to downwind concentrations be removed from the total observed concentrations. Hourly bulldozer activity was documented using a camera. Dust transport and dispersion from the coal pile were simulated. Together with concentration data we estimated dust emission rates and emission factors due to bulldozer activity. Here we summarize the analysis used to estimate the emission factors. The primary focus is to report the results, compare them with previously derived emission factors and provide an example of how the new emission factor formulation can be applied to a site using readily available meteorological data.

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## 2. EMISSION FACTOR AS ENGINEERING TOOL

The emissions factor *E* is an engineering tool to facilitate fugitive emissions estimates in terms of a more easily derived quantity. For example, fugitive dust emissions can be estimated for an unpaved road using a dust emissions factor expressed as mass of dust emitted per vehicle distance traveled. When multiplied by vehicle travel distance per unit time (such as an annual value) this factor yields a mass emission rate.

Emission factors are typically used when emission estimates are needed for air permit applications or when there is a requirement to explicitly model the downwind air quality impacts of a fugitive dust source. In many situations formulas for *E* do not exist for the type of source in question. When this happens engineers usually must resort to using *E* formulations that exist for similar sources. The primary source of these formulations is the U.S. Environmental Protection Agency (EPA) *AP-42 Emissions Han*dbook (EPA, 1995). *AP-42* contains fugitive dust emission factor formulations for aggregate dropping operations and for vehicles driving on unpaved surfaces. In the case of bulldozers driving across a coal pile, the formulation for vehicles driving on unpaved roads at an industrial facility is the one most closely related:

$$E_{ir} = 0.282\, k_{ir} \left(\frac{S}{12}\right)^{a} \left(\frac{W}{3}\right)^{0.45} \quad . \qquad (1)$$

In (1), *S* is the silt content of the surface, *W* is vehicle weight (English or short tons), and $E_{ir}$ is the particulate emission factor expressed as kilograms per vehicle distance (km) traveled. Constant $k_{ir}$ is a particle size fraction adjustment factor equal to 1.5 for the $PM_{10}$ size fraction. Coefficient $a$ =0.9 for $PM_{10}$. This formulation was not based on data from a coal pile. Also, unlike the *E* formulation for unpaved public roads (EPA, 1995), (1) does not include corrections for surface moisture content or vehicle speed, probably because these factors were not well represented by the experimental data.

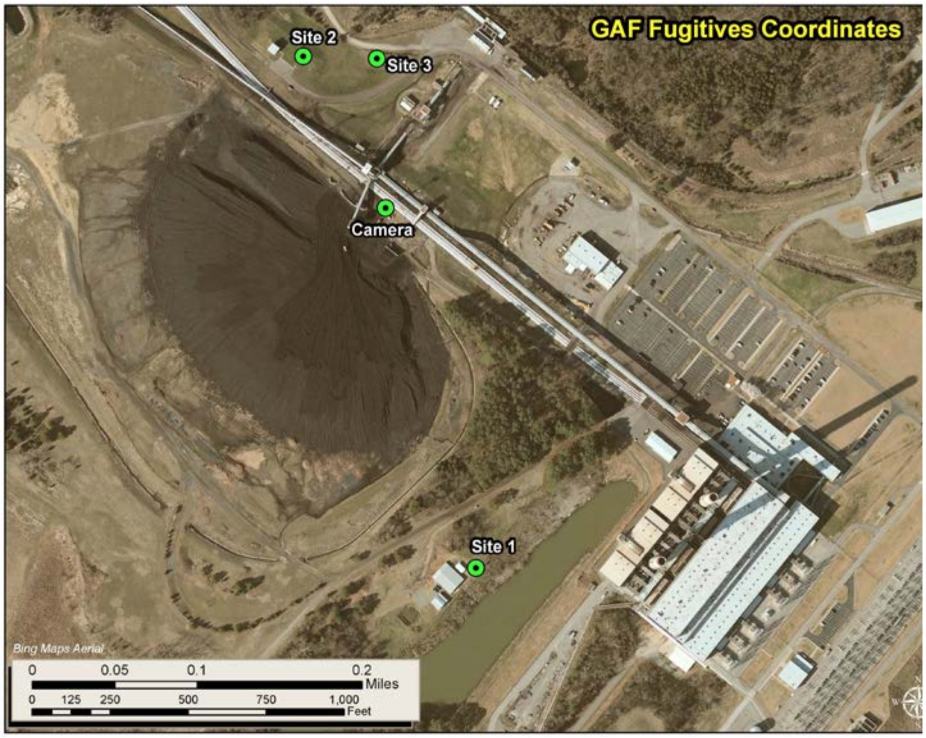


**Figure 1.** Environs surrounding the coal pile (oval black area) at the Tennessee study site. The photograph is oriented north-south from top to bottom. Monitoring sites are denoted by green circles.

Coal piles exposed to varying weather conditions can have moderate or even large variations in surface moisture content in all but the driest climates. In addition, water spraying is one method used to control wind erosion from coal piles. Therefore, there is a need to derive a dust emission factor formulation for coal piles that considers the influence of moisture.

## 3. EMISSION DERIVATION

### 3.1 *Measurements*

A study of fugitive dust emissions from a PRB coal pile was conducted at the Gallatin (Tennessee) electric power generating station during the summer and autumn of 2012. The area around the coal pile is shown in Figure 1. Beta attenuation monitors (BAMs) measured hourly $PM_{10}$ concentrations at sites labeled "1", "2" and "3" in the figure. Frequent southerly winds made site 1 the prevailing upwind site while sites 2 and 3 were most often downwind. A 10-m meteorological tower near site 2 collected data on winds (3-dimensional sonic anemometers), temperature and humidity at two levels (2.3 and 9.6 m) and net radiation. A nearby rain gage, buried resistance sensor and nephelometer collected data on precipitation, soil moisture content (-5 cm) and light scattering at 525 nm. At sites 1 and 2, low-volume Federal Reference Method particle filter samplers collected $PM_{10}$ mass on Teflon and quartz filters for subsequent chemical analysis. The instrumentation used in this study was the same as that described by Mueller et al. (2013) for a previous study.

A time-lapse camera (see Figure 1) with a 90-degree field of view lens imaged the coal pile and provided invaluable information on both human (e.g., bulldozers, other vehicles) and natural (e.g., dust devils, fires) activity at the pile. Site logs provided information on quantities of coal processed along with the movement of coal through the handling system. On four separate occasions during the study coal samples were collected on the pile. These samples were later analyzed to determine silt and moisture content.

### 3.2 *Separating contributions from different dust sources*

The excess particulate concentration, $C_{xs}$, is defined in terms of the upwind and downwind concentrations:

$$C_{xs} = C_{down} - C_{up} \quad . \qquad (2)$$

Occurrences of the desired upwind-downwind configuration were determined by the 10-m wind direction. Winds from the south-southeast clockwise through west-southwest provide conditions when airflow passed over the coal pile and was sampled by monitors at sites 2 and 3. An additional adjustment was applied to normalize all concentrations by the fraction of time *f* airflow during an hour passed over the pile based on 1-min wind measurements. This adjusted concentration $C_{xs}$* was, therefore, computed as

$$C_{xs}^* = C_{xs}/f \qquad (3)$$

and provided a consistent measure of coal pile impact on downwind particulate levels across all hours.

**Table 1.** Average adjusted $PM_{10}$ concentration $C_{xs}$* for hours without and with human activity on the coal pile.

| Monitoring Site | Concentration, µg m$^{-3}$ | |
|---|---|---|
| | Without activity | With activity |
| 2 | 19.7 | 60.7 |
| 3 | 21.1 | 59.9 |

Average values of $C_{xs}$* for hours without and with human activity on the coal pile are summarized in Table 1. Values <4 µg m$^{-3}$ are not significant because of BAMs measurement limitations (Mueller et al., 2013). Concentrations in the presence of human activity (i.e., active bulldozers) were far greater than concentrations without activity. The preponderance of non-zero $C_{xs}$* for hours without activity implies a “natural” source of particulates.

Analysis of $C_{xs}$* versus meteorological variables and time-of-day for hours without activity identified wind erosion and the action of micro-scale turbulence on the coal pile as the most probable sources of natural fugitive emissions (Mueller et al., 2014). For some hours statistical modeling provided a method for calculating the natural fugitive dust concentration excess $C_{xs}{*}^{(n)}$ using measured meteorological variables such as wind speed, air temperature and various turbulence metrics. These statistically estimated values were constrained to be no more than the 95$^{th}$ percentile value observed during non-activity hours. During mid-day hours with low wind speeds (i.e., below the wind erosion threshold) for which no statistical model was available, median hourly values of $C_{xs}{*}^{(n)}$ determined for non-activity hours were applied to hours with pile activity. Estimates of $C_{xs}{*}^{(n)}$ representing natural downwind background particles were then subtracted from $C_{xs}$* to produce estimated $PM_{10}$ concentrations attributable to human activity, $C_{xs}{*}^{(h)}$:

$$C_{xs}^{*(h)} = C_{xs}^{*} - C_{xs}^{*(n)} \quad . \qquad (4)$$

### 3.3 *Inverse modeling to derive fugitive emission rates*

Concentration *C* of material emitted from a source at rate *Q* are related as

$$C = QF \qquad (5)$$

where *F* is the dispersion function that describes the dilution and spatial distribution of particulate matter in the air. For a one-hour average concentration,

$$\overline{C} = Q\overline{F} \qquad (6)$$

if *Q* is assumed to be constant during the averaging period. Thus,

$$Q = \frac{\overline{C}}{\overline{F}} \quad . \qquad (7)$$

If $\overline{C}$ is taken to be the observed hourly concentration then $\overline{F}$ must be computed as the corresponding average dispersion function by using hourly meteorological parameters or by averaging results from sub-hourly periods. An alternate way to estimate *Q* is to replace $\overline{C}$ with $C_{xs}^{*(h)}$ which has essentially been averaged for the sub-hourly period when winds were observed blowing across the coal pile. In this approach, $\overline{F}$ is modeled using only the meteorological conditions occurring when the airflow was across the pile.

We simulated coal dust transport and dispersion using the EPA AERMOD model (EPA, 2004) by dividing the pile into 3 direction

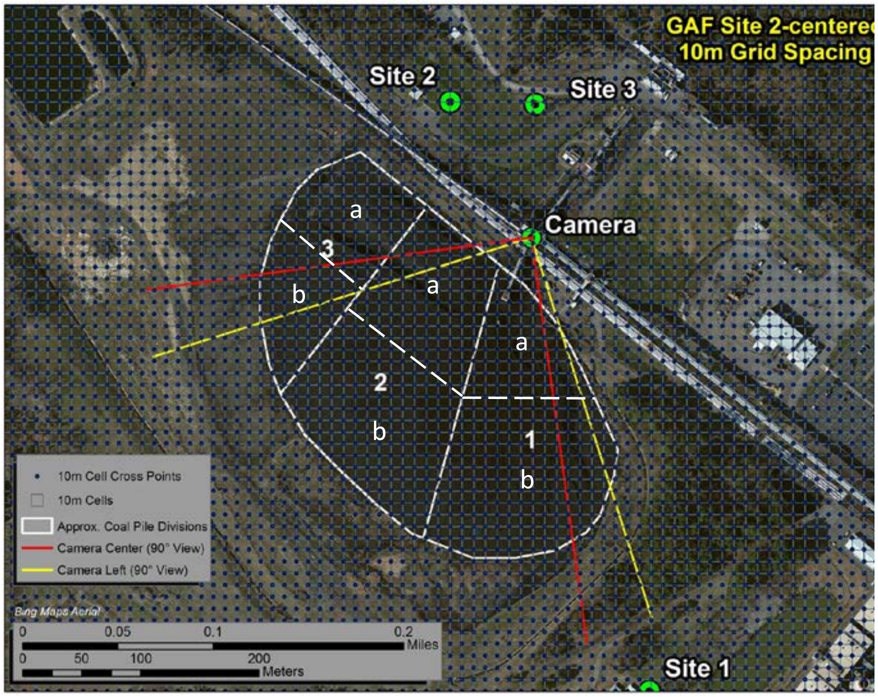


**Figure 2.** Coal pile direction sectors (numbered 1 through 3) and sub-sectors (labeled "a" and "b" within each direction sector) for which hourly bulldozer activity was quantified by use of camera imagery. The camera was initially oriented to acquire images within the yellow-delineated field of view but was adjusted (red delineation) to capture a more central field of view—and more of sector 3--in September.

sectors, each with two sub-sectors "a" and "b" (Figure 2). The direction sectors were each about 30° wide and aligned with the downwind monitoring sites. Table 2 lists the frequencies associated with airflow across each sector toward sites 2 and 3 along with the observed frequency of bulldozer activity inside each sub-sector for the hours modeled. Airflow and bulldozer activity were most frequent in sector 1 and least frequent for sector 3. Thus, most of the dust impacting the monitoring sites originated in sector 1.

Table 3 summarizes sector-averaged meteorological parameters that controlled simulated coal dust transport and diffusion. Parameter averages were determined only for those 1-min periods during an hour when sector and monitor were aligned as determined by the 10-m wind direction. Wind speed in the sectors having the highest values averaged 4-8 percent more than speed in the sectors having the lowest. Vertical turbulence as represented by the standard deviation of the measured vertical wind component $w$ ($\sigma_w$) averaged 13 percent higher for the middle sectors than the lateral sectors. Overall, sector differences translated into values of turbulent kinetic energy (TKE) that averaged 15 percent more in the middle sectors compared with the flanking sectors. Higher TKE implies more dispersion for dust emitted from the middle sectors.

The sector-specific (i.e., based on sector-specific meteorology) dispersion function is denoted $\overline{F^*}$ and--when combined with the adjusted concentration--yields

**Table 2.** Average observed frequencies (weights) used to allocate simulated fugitive dust emissions to each coal pile sector.

| Frequency | Downwind Site | Coal Pile Sector | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1a | 1b | 2a | 2b | 3a | 3b |
| Airflow across pile[a] | 2 | 0.35 | | 0.27 | | 0.19 | |
| | 3 | 0.41 | | 0.18 | | 0.15 | |
| Pile Activity[b] | - | 0.41 | 0.31 | 0.10 | 0.14 | 0.02 | 0.01 |
| Airflow × activity[c] | 2 | 0.42 | 0.28 | 0.10 | 0.14 | 0.05 | 0.01 |
| | 3 | 0.45 | 0.29 | 0.10 | 0.11 | 0.03 | 0.01 |

[a]Average frequency during each hour that the observed 1-min 10-m wind aligned a 30° coal pile direction sector with a downwind site. Values in this row do not sum to 1.00 because of the minutes when airflow did not cross the pile (off-pile frequencies were 0.19 for site 2 and 0.26 for site 3).
[b]Observed frequency of total hourly bulldozer activity that occurred within a coal pile sector. Row does not sum to 1.00 due to rounding.
[c]Joint frequency of airflow and pile activity occurring relative to a downwind monitor. Rows may not sum to 1.00 due to rounding.

$$Q = \frac{C_{xs}^{*(h)}}{\overline{F^{*}}} \quad . \tag{8}$$

The advantage to using $C_{xs}^{*(h)}$ (i.e., the concentration normalized by *f*) is that it is more directly related to meteorological conditions over the dust source and this is a big plus in statistical modeling against other parameters. Likewise, by using $\overline{F^{*}}$ we are able to focus attention on modeling only those conditions relevant to dust transport from the pile to the monitoring site. This approach assumes that the dispersion of coal pile dust during periods when the wind did not cross the pile did not significantly impact monitored concentrations. The close proximity of the monitoring sites to the source helped with this assumption because the emitted dust was transported to the monitors quickly (40-75 s, on average), even when wind speeds were low. Although non-stationary winds could transport dust along a non-linear path toward the monitors, any contribution to sampled air in these situations was assumed to be much smaller than the contribution of dust transported directly from the source to the monitors.

The largest potential for modeling error was when wind speed was intermittent, allowing airborne dust to accumulate over the pile during wind lulls and then transporting dust downwind when winds increased and aligned with the monitors. However, this non-steady condition violates the steady-state assumption in AERMOD so there is little expectation that averaging out these periods over an hour would do a better job of representing the dispersion function than limiting the modeling to those sub-hourly periods when the airflow aligned the source and monitors. This reasoning was the basis for modeling the dispersion function using sub-hourly meteorological data for minutes when source and monitor were aligned.

The 6 coal pile sub-sectors were each assigned a weight $w_i$ based on the combined frequency of airflow and human activity. Polygonal areas representing each sub-sector were input into AERMOD and dust emissions were modeled as an area source. This approach facilitated computing *Q* because it allowed us to weight $\overline{F^{*}}$ for the *i*th sub-sector

**Table 3.** Sector-specific meteorological conditions at 10-m averaged for periods when airflow over the coal pile aligned with downwind monitoring sites.

| Site: Sector | $\theta_{10}$ (deg.) | $\sigma_\theta$ (deg.) | $u_{10}$ (m s$^{-1}$) | $\sigma_w$ (m s$^{-1}$) | TKE[a] (m$^2$ s$^{-2}$) |
|---|---|---|---|---|---|
| 2: 1 | 168 | 15.4 | 1.66 | 0.28 | 0.19 |
| 2: 2 | 195 | 17.2 | 1.80 | 0.33 | 0.23 |
| 2: 3 | 228 | 17.3 | 1.74 | 0.31 | 0.20 |
| 3: 1 | 179 | 15.6 | 1.77 | 0.30 | 0.20 |
| 3: 2 | 208 | 18.5 | 1.71 | 0.34 | 0.23 |
| 3: 3 | 238 | 16.8 | 1.71 | 0.30 | 0.19 |

[a]Per unit mass.

according to the frequency that airflow was aligned with a sector and the frequency that human activity occurred within each source region during each hour. From model results we computed the emission rate as

$$Q = \frac{C_{xs}^{*(h)}}{\sum_i (w_i \overline{F_i^*})} \quad . \qquad (9)$$

Table 4 lists source characteristics used to model dust emissions from each coal pile sub-sector. Sub-sectors ranged in size from about a half hectare to just over one hectare. Only sub-sector 3b was totally elevated above the pile base. In sub-sectors 1a and 2a the elevation variation was assumed to be zero such that the initial depth of the dust plume was assumed to roughly equal the vehicle height consistent with camera observations. Bulldozers were required to move vertically while working within sectors in which elevation varied and this created initial dust plumes with depths roughly equal to the change in elevation. Mean dust transport distances to the monitoring sites ranged between 214 and 306 m for sub-sectors 1a and 1b that experienced the most bulldozer activity.

Given the variability in both natural and human dust emissions it was not surprising that hours occurred when $C_{xs}^{*(n)} \geq C_{xs}^*$. In these cases

$$C_{xs}^{*(h)} = \max\left[\left(C_{xs}^* - C_{xs}^{*(n)} + 4\right), 1\right] \quad . \qquad (10)$$

This formula serves two purposes. First, when the estimated natural component of $C_{xs}^*$ exceeded the observed value of $C_{xs}^*$ it added 4 µg $m^{-3}$ to the difference to account for the potential measurement uncertainty in $C_{xs}^*$. Second, it tested the estimated value of $C_{xs}^{*(h)}$ to ensure that, at a minimum, it had the lowest possible measureable value (1 µg $m^{-3}$) by the BAM. Thus, for hours when the human activity signal from the coal pile was low and within the combined noise of the $PM_{10}$ measurement and the estimate of $C_{xs}^{*(n)}$, a minimum value was assigned to $C_{xs}^{*(h)}$ equal to the lowest detectable value of $C_{xs}^*$. This $C_{xs}^{*(h)}$ adjustment was needed in 35 percent of the hours analyzed and in most cases was probably necessary because of the small level of human activity on the pile.

### 3.4 *Computing emission factors*

The $PM_{10}$ fugitive particulate emission flux of coal dust produced by bulldozers operating on the coal pile (denoted $Q_{10}$) was calculated from $C_{xs}^{*(h)}$ and the total simulated emission rate attributable to all 6 pile sectors weighted using the joint wind direction and activity frequencies determined for each sector. Table 5 summarizes $Q_{10}$ and several other related particulate fluxes and emission rates. The mean values were skewed because of a small number of high values so the median values are also provided because they better represent the central tendency of the derived emission flux distributions. The mean values are more than a factor of 10 greater than the medians.

The mass emission rate $Q_e$ represents the total emission rate (mass per hour) computed as

$$Q_e = \sum_i 3600 A_i q_i \qquad (11)$$

where $q_i$ is the emission flux (mass per hectare per second) for the *i*th pile sub-sector and $A_i$ is

**Table 4.** Source characteristics used to model area emissions from the coal pile.

| Characteristic | Pile Sector | | | | | |
|---|---|---|---|---|---|---|
| | 1a | 1b | 2a | 2b | 3a | 3c |
| Area (ha) | 0.72 | 1.15 | 1.09 | 1.09 | 0.69 | 0.46 |
| Mean source elevation[a] (m) | 0 | 0 | 0 | 0 | 0 | 15 |
| Initial plume depth[b] (m) | 2 | 15 | 2 | 15 | 12 | 2 |
| Distance (m) from sector center to site 2 | 225 | 306 | 170 | 265 | 146 | 207 |
| Distance (m) from sector center to site 3 | 214 | 299 | 187 | 285 | 214 | 255 |

[a]Height relative to pile base.
[b]The minimum depth was roughly the height of the bulldozer. Larger values were selected to model dispersion from sectors in which the variation in pile elevation caused bulldozers to drive from lower to higher points on the pile.

the sub-sector area. Emission rate distributions were computed using data from each downwind monitoring site. Site distribution medians of both $Q_{10}$ and $Q_e$ are nearly the same. Thus, the calculations based on different monitoring data and slightly different mixes of meteorological conditions and pile sectors yield very similar results (note: using data from sites 2 and 3 separately, 10th percentile $Q_e$ values were 0.09 and 0.10 kg hr$^{-1}$, respectively, and 90th percentile values were 18 and 33 kg hr$^{-1}$, respectively). This similarity also exists for the mass emission rate per unit time of bulldozer operation given by

$$E_v = \frac{Q_e}{t_v} \qquad (12)$$

where $t_v$ is the total minutes of bulldozer activity per hour. We combined $E_v$ data from both downwind sites into a single data set. The result appears to be a lognormal distribution.

One way to evaluate the $E_v$ data set is to compare its geometric mean with equivalent values computed using the *AP-42* formula for the $PM_{10}$ fugitive emission factor (mass per distance traveled) for unpaved surfaces at an industrial site [i.e., eq. (1)]. The mean $S$ =5 percent for the PRB coal with a range of 3.2-9.7 percent. Using the observed distribution of $S$ and assuming a mean vehicle speed $U$ =8 km hr$^{-1}$ we computed a geometric mean of *AP-42* $E_v$ (note: $E_v$=$U$ $E_{ir}$) of about 0.13 kg per minute of bulldozer operations. The emission factor based on the mean $S$ was slightly lower at about 0.12 kg min$^{-1}$. This compares (Table 5) to the geometric mean $E_v$ from field data analysis of about 0.03 kg min$^{-1}$.

A comment is needed here regarding the number of valid data values for determining emission factors. We identified 177 hours for site 2 and 178 for site 3 when, with human activity on the pile and valid concentration data, the hourly 10-m wind direction indicated airflow across the coal pile in the absence of precipitation. We simulated dispersion for all hours when sub-hourly (1-min) 10-m wind direction aligned a portion of the pile with the downwind monitors. For some hours there were no sub-hourly winds that aligned the pile and the monitors. This happened because the hourly wind direction was a resultant-vector that was occasionally derived from winds blowing from directions on either side of the coal pile but not over the pile. Without sub-hourly airflow across the pile we had no basis for computing dust plumes that blew toward sites 2 and 3. A small number of hours that were modeled produced no non-zero dust concentrations at sites 2 or 3. This was likely caused by winds that blew across the edge of the pile and, under stable conditions with little dispersion, did not produce plumes that were sufficiently wide to impact sites 2 or 3. Consequently, we had 38 hours at site 2 and 40 hours at site 3 when conditions were not conducive for plume impacts at our monitors. The remaining joint (sites 2 and 3) data set contained 277 hours with valid, non-zero dust emission factors.

**Table 5.** Calculated non-zero $PM_{10}$ coal dust emission rates due to bulldozer activity.

| Metric | Site 2 | Site 3 |
|---|---|---|
| Sample Size | 139 | 150 |
| Mean $Q_{10}$, g ha$^{-1}$ s$^{-1}$ | 5.5 | 3.2 |
| Median $Q_{10}$, g ha$^{-1}$ s$^{-1}$ | 0.09 | 0.10 |
| Median $Q_e$, kg hr$^{-1}$ | 0.76 | 0.71 |
| Median $E_v$, kg min$^{-1}$ | 0.016 | 0.022 |
| Geo. Mean $E_v$, kg min$^{-1}$ | 0.026[a] | |
| *AP-42* $E_v$ from mean $S$, kg min$^{-1}$ | 0.121[a] | |
| Geo. Mean of *AP-42* $E_v$, kg min$^{-1}$ | 0.131[a] | |

[a]Data from both downwind sites combined.

## 4. METEOROLOGICAL VARIABILITY

### 4.1 *Derivation of $E_v$ formula*

It is important to know what drives the variation in $E_v$ so that these results can be applied for maximum accuracy. The first step is computing daily averages of $\log_{10}(E_v)$ denoted $E_v^T$. The logarithmic transformation is needed to prevent extremely high values from controlling the results. Several potential predictors of $E_v^T$ were explored but the strongest candidate was $M_c$. Coal moisture content can be measured from coal samples by comparing sample weights before and after oven drying. The loss in weight is attributable to water and is used to calculate $M_c$, usually expressed as a percent. This sampling could not be done all the time so a surrogate method was needed to determine $M_c$. Soil moisture content, $M_s$, was found to be a suitable surrogate for $M_c$. Soil moisture content was measured adjacent to the meteorological tower using an electronic sensor buried roughly 5 cm below the soil surface. Twenty-four coal samples collected on four separate days were analyzed for $M_c$. Daily average standard deviations of measured $M_c$ were only 2.4 percent, similar to that for $M_s$ during corresponding rain-free periods. Daily average $M_c$ and $M_s$ were compared and found to share 85 percent of their variance. The resulting regression equation, $M_c = 0.38M_s + 19.69$ (both $M_s$ and $M_c$ expressed as percent), was the basis for values of $M_c$ used in the $E_v^T$ analysis.

The $E_v^T$ analysis was based on daily average values (to reduce data noise) compared with corresponding averages of other variables, including $M_c$, $R_{sol}$ (solar radiation flux) and $T_2$ (2-m air temperature). Vehicle weight and speed were constant or nearly so and did not provide good predictors. The resulting data set contained 44 sets of $E_v^T$ and corresponding values. Multivariate modeling of $E_v^T$ identified only one predictor, $M_c$, with statistical confidence at >99 percent.

The study was divided into two periods distinguished by whether routine coal removal (reclamation) from the pile was occurring. Reclamation began 15 October and continued through the end of the study. Thus, before 15 October work on the pile was heavily oriented toward suppressing coal dust combustion. This coal surface grooming, occurring less than 8 hr/day, involved a bulldozer scraping its blade across the top of the coal to mix the top layer with underlying coal containing higher moisture content. Beginning 15 October bulldozers worked more than 12 hours each day pushing coal toward an underground hopper for conveyance to the plant. During reclamation bulldozers also had to continually reshape the pile as coal was removed and this involved more pushing of surface coal.

We performed a statistical comparison of $E_v^T$ with $M_c$ for the two different periods. Results are illustrated in Figure 3. There is a clear negative association between $E_v^T$ and $M_c$ that is different for each period. The regression for each period captures about half (46-52 percent) of the variance in $E_v^T$. The remaining variability is due to measurement and modeling error, uncertainty in the correction to remove the natural dust component and unknown variations in $M_c$ across different portions of the pile. Regression slopes for the two periods are dramatically different with less sensitivity to $M_c$ before coal reclamation began, a period that also corresponds with the lowest $M_c$. This difference could be influenced by the nature of the bulldozer work as previously described or a seasonal effect (summer versus autumn). However, there is a tendency for $E_v^T$ to decline faster as $M_c$ increases and that could be independent of season and bulldozer mode of action. Sub-bituminous coal becomes “sticky” (i.e., poses handling problems) with high moisture content. This change in physical characteristic—observed first-hand when taking coal samples for analysis—is likely the reason for the faster decline in $E_v$ with increasing $M_c$ because “sticky” coal has higher cohesive forces binding particles together.

Daily average values of $E_v^T$ versus $M_c$ were fitted with different regression curves (i.e., linear and polynomial formulations for $M_c$). None provided a more satisfactory fit than those illustrated in Figure 3. Given the differences in the two data subsets previously described, we recommend that either one or two linear regression formulas be used depending on circumstances. There is little data to support the $E_v^T$ extrapolated behavior at the extremes of $M_c$. so caution is advised. A single formulation would be most appropriate in situations where $M_c$ is always <30 percent (i.e., the “Before” data set regression in Figure 3). This is because the two linear equations shown in Figure 3 intersect at $M_c$ ≈29.5 percent. For $M_c$ >30 percent the second formulation (the “After” data set regression in Figure 3) would be better because it reflects what we expect to be a rapid decline in $E_v$ as the coal pile takes on the consistency of wet concrete.

Thus, for $M_c$ <29.5 percent,

$$E_v = (689 \text{ kg min}^{-1}) \times 10^{-0.152\, M_c} \qquad (13a)$$

with $M_c$ expressed as a percentage. Note that PRB coal--the type studied here--tends to maintain a high moisture content so that $M_c$ values <15 percent are highly unlikely. When $M_c$ >29.5 percent the best formulation is

$$E_v = (1.07 \times 10^{11} \text{ kg min}^{-1}) \times 10^{-0.427\, M_c} \,. \qquad (13b)$$

Beware that (13b) would greatly overestimate $E_v$ for low $M_c$. For applications where a single formulation is most convenient, the following (regression $r^2$=0.52) is applicable across a larger range in $M_c$ (but $E_v$ overestimates at high $M_c$ may be a problem):

$$E_v = (3175 \text{ kg min}^{-1}) \times 10^{-0.177\, M_c} \;. \qquad (13c)$$

Using (13c), the dust emission factor essentially goes to zero (i.e., <1 g min$^{-1}$) for $M_c$ >37 percent, although no data were collected for $M_c$ this high.

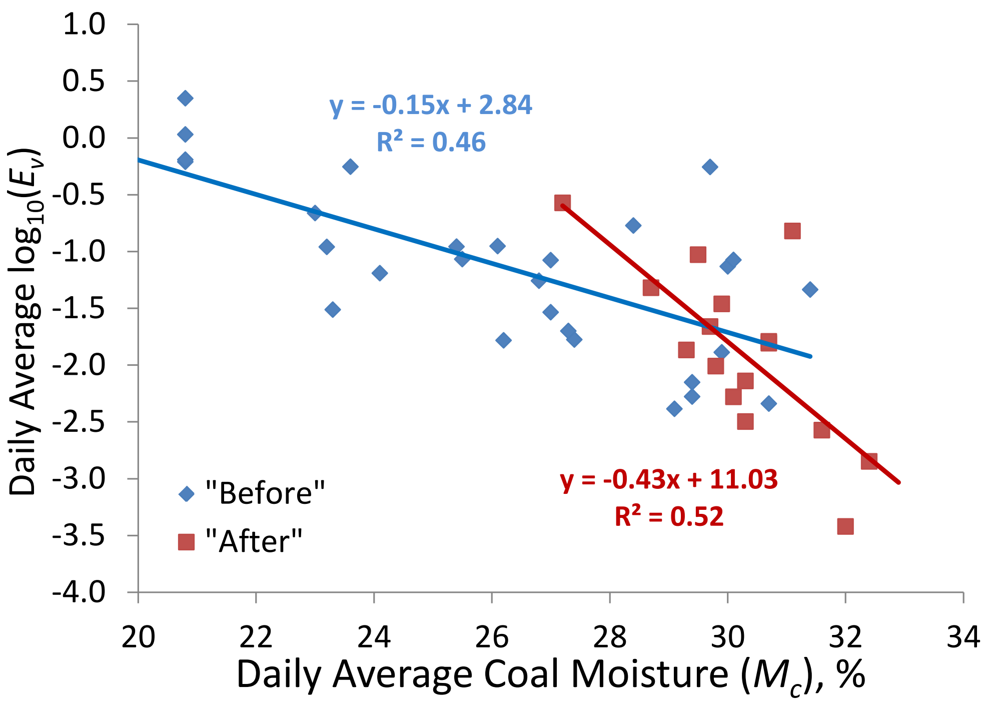


**Figure 3.** The graph compares daily average $\log_{10}(E_v)$ versus $M_c$ for periods characterized by coal pile maintenance ("before") and coal reclamation ("after") with separate linear regression lines for each set.

Figure 4 compares $E_v$ [using (13a) and (13b)] with $E_{ir}$ based on typical conditions for bulldozers operating on the PRB coal pile ($S$=5 percent; $W$=66 tons; $V$=8 km hr$^{-1}$). The formula for $E_{ir}$ does not include a variation with surface moisture so it is a constant 104 g min$^{-1}$ in the plot (the likely range in $E_{ir}$ due to $S$ and $V$ variability is also illustrated). On average, $E_v$ >$E_{ir}$ for $M_c$ <25 percent. This comparison suggests that a very dry surface of PRB coal is capable of emitting $PM_{10}$ at a rate above that indicated by $E_{ir}$ for dry surfaces. However, the emission rate drops quickly and becomes negligible for damp surfaces. The fugitive dust field study was conducted in part during a summer with unusually hot and dry conditions and the summer data reflect the impact of those conditions on $E_v$. The autumn data show lower emission factors and that corresponds with the cooler weather that occurred during that period. This implies that air temperature affects $E_v$. For reference, Figure 4 also shows the *AP-42* moisture-dependent emission factor for unpaved public roads, assuming the same bulldozer speed and surface conditions as the coal pile.

The $E_v$ formulation can readily be applied to any site with representative meteorological data. This is because we developed a model of $M_c$ as a function of ambient meteorological parameters measured on site adjacent to the pile. We found that hourly $M_c$ was correlated most strongly with air temperature, precipitation amount and wind speed. Precipitation represents the moisture input to the coal while temperature and wind are factors that control drying. The tested predictors included precipitation totals for the preceding 1, 3, 6 and 24 hr (denoted $P_1$, $P_3$, $P_6$ and $P_{24}$, respectively). The significant predictors are, in decreasing order of partial variance represented in the model (percent variance in parentheses): $T_2$ (30), $P_6$ (4), $U_{10}$ (3), relative humidity (1) and $R_{sol}$ (1). The stepwise regression also identified $P_{24}$ and $P_3$ as being significant but the associated variance was <1 percent.

This result suggested that we examine the relationship between daily average $M_c$ ($\overline{M}_c$) and environmental predictors to reduce the hourly noise in the data. The resulting model was even better for $\overline{M}_c$ because more variance was explained by fewer predictors. Only $T_2$ and $P_6$ are needed to estimate 60 percent of the variance in $\overline{M}_c$. The formulation is

$$\overline{M}_c = a_0 + a_1\overline{T}_2 + a_2\overline{P}_6 \quad . \qquad (14)$$

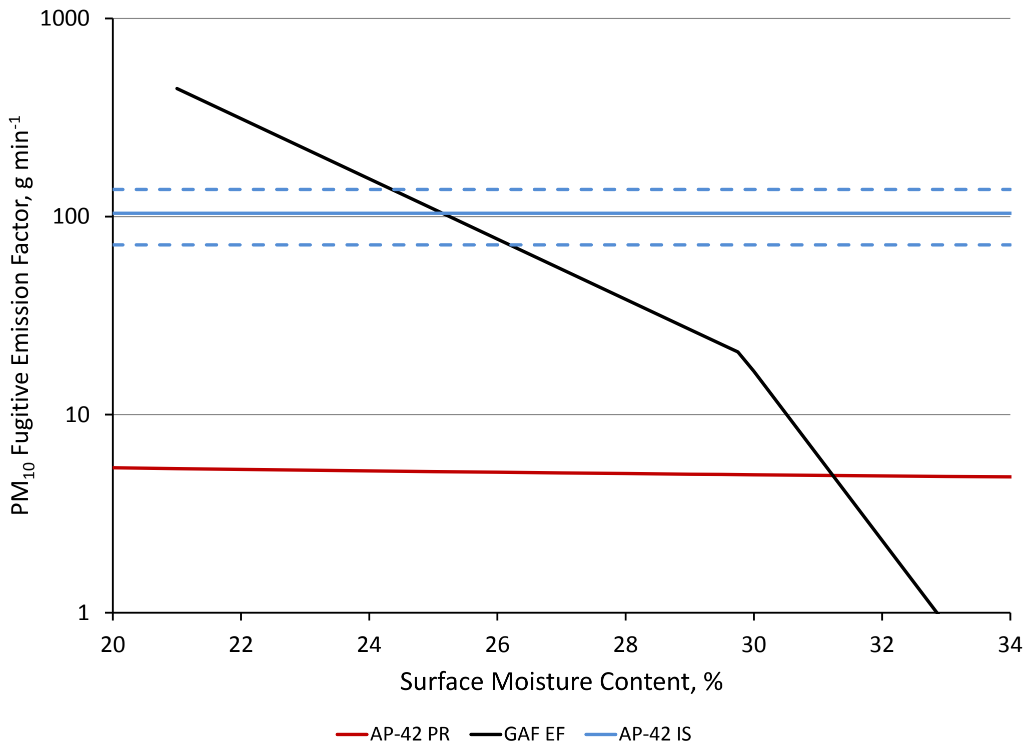


**Figure 4.** Comparison of different values of $E_v$ versus $M_c$ using emission factors from AP-42 for unpaved public roads ("AP-42 PR"), unpaved industrial surfaces ("AP-42 IS") and from this study ("GAF EF"). The potential variability of the AP-42 $E_v$ for industrial sites—assuming 25 percent variability in vehicle speed and surface silt content—is illustrated using dashed lines above and below the AP-42 IS line.

Here $\overline{T}_2$ can be taken to be the daily average temperature (°C) and $\overline{P}_6$ is computed as the average of the hourly 6-hr precipitation totals (cm) for the day on which $\overline{M}_c$ is computed. This simple approach can be applied in any location for which representative meteorological data are available (e.g., from a National Weather Service station). The regression coefficients are $a_0$ = 33.0, $a_1$ = -0.318 °C$^{-1}$ and $a_2$ = 10.4 cm$^{-1}$ and, together with the predictors, give $\overline{M}_c$ expressed in percent. This formulation cannot be applied when $T_2$ ≤0°C but for practical reasons it is unlikely that moist coal will produce significant fugitive emissions when the air temperature goes below the freezing point. This formula can only be applied in locations where the temperature stays above freezing for a substantial portion of the year. Another method may be required to estimate $E_v$ during below-freezing periods. In the next section we describe an example of how to apply this method for estimating $M_c$ and $E_v$ from standard meteorological data readily available from any National Weather Service station.

### 4.2 *Application of $E_v$ formula*

The value of the formulation of coal dust emission factor $E_v$ using the coal dust moisture content ($M_c$) expression in (14) is that it allows for estimates of $E_v$ that vary with varying meteorology. This enables calculations of the moisture effects on $E_v$ and can be applied at sites that do not have on-site meteorological data by using representative data from a nearby National Weather Service (NWS) or similar meteorological station. An example of this is described here.

The NWS station at the Nashville International Airport provides continuous, hourly records of air temperature and precipitation amount. From 2012 data we computed the daily average surface air temperature ($\overline{T}_2$) and 6-hour cumulative precipitation ($\overline{P}_6$) needed to compute daily average $M_c$ (denoted $\overline{M}_c$) following (14).

**Table 6.** Different meteorological scenarios for the Nashville area and the associated impact on PRB coal moisture content ($\bar{M}_c$) and daily average fugitive dust $PM_{10}$ emission factor ($\bar{E}_v$) for bulldozer operations

| Conditions | Temperature (°C) | | Precipitation (cm) | | $\bar{M}_c$ (%) | Daily $E_v$ (g/min) | |
|---|---|---|---|---|---|---|---|
| | Mean | Departure from Normal | Mean | Departure from Normal | | Mean | Departure from Normal |
| Cooler & wetter[a] | 14.1 | -1.1 | 132.0 | +10% | 28.6 | 53 | -12% |
| Climatology[b] (NWS) | 15.2 | 0.0 | 120.0 | 0% | 28.2 | 61 | 0% |
| Actual 2012[c] | 16.8 | 1.6 | 126.2 | +5% | 28.5 | 66 | +8% |
| Hot and dry | 18.1 | 2.8 | 90.0 | -25% | 27.3 | 84 | +39% |

[a]Artificially lowered the temperature and raised precipitation by fixed amounts for comparison purposes.
[b]Based on 1980-2010 climatological normals.
[c]The year was warmer and wetter than average and this reflects actual conditions.

Here we examine four sets of conditions, summarized in Table 6. Actual conditions in 2012 were 1.6°C warmer than average and precipitation was 5 percent more than average. However, different years of "average" weather can have different average values of moisture content. One example of a cooler and wetter year could have an annual average temperature 1.1°C below normal and precipitation 10 percent above normal, but even cooler and wetter years can occur. We also considered an extremely hot and dry year that averaged 2.8°C warmer than normal with 25 percent less precipitation than climatology.

A time series plot of daily average $\bar{M}_c$ based on actual meteorological data is presented in Figure 5. The pattern that emerges is one in which $\bar{M}_c$ is highest (28-40 percent) in winter and autumn and lowest in the middle of summer (<25 percent). Daily variations in moisture content can be very large because of precipitation variability. Time series for the "climatological" and cooler/wetter conditions look very similar with slight deviations in the minima and maxima.

Variations in annual mean $E_v$ is potentially much larger than variations in $\bar{M}_c$ because of the non-linear responses of $E_v$ to $M_c$. As Table 6 shows, annual mean $E_v$ was 8 percent higher in 2012 than it would have been with "climatological" conditions even though moisture content differed from normal only slightly. The higher annual average was driven primarily by the high values in June. In contrast, a similar $\bar{M}_c$ for a cooler/wetter year would have produced a 12 percent lower average $E_v$ based on our assumptions. The influence on $E_v$ is especially sensitive to the time of year when the meteorological deviations from normal occur. The hot and dry year (Table 6) pushed $E_v$ 39 percent above the "climatological" value.

Figure 6 plots the time series of daily $\bar{E}_v$ derived using actual conditions. Emission factors tended to be lowest in winter and autumn--coinciding with higher $\bar{M}_c$--and highest in summer when moisture content was lowest. The *AP-42* value for $E_v$ is plotted for comparison. A value of 104 g $min^{-1}$ was computed for the coal pile activity at the study site. Moisture content is not a factor in the *AP-42*-derived $E_v$ so no daily variations exist. The *AP-42* $E_v$ is 72 percent greater than the annual average $E_v$ derived from field data. In itself this difference is not very large given the uncertainty in the $E_v$ estimates. What makes the *AP-42* formulation inadequate is its inability to account for the effect of coal moisture on $E_v$ and this can produce large annual overestimates of fugitive emissions in regions where precipitation is plentiful for at least a portion of the year.

## 5. CONCLUSIONS

This study identified two major sources of fugitive dust emissions from a PRB coal pile. One was natural, occurring in the complete absence of any human activity on the pile. The forces at work appear to be wind and turbulence

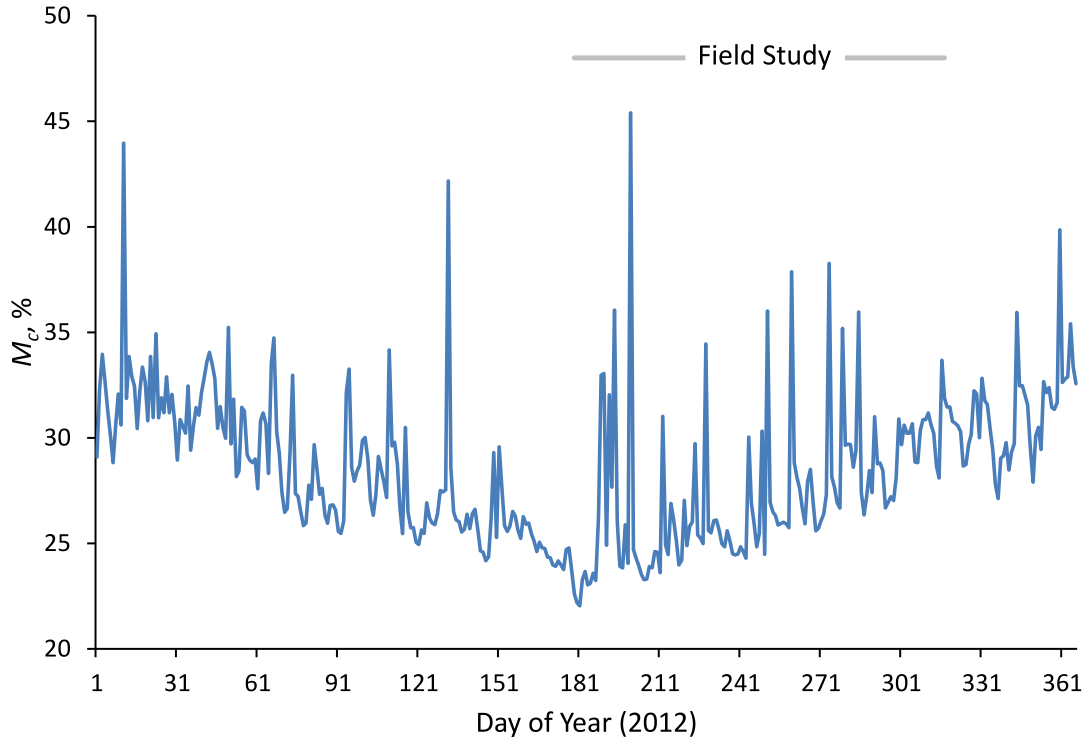


**Figure 5.** Daily average coal moisture content for 2012 computed from hourly Nashville NWS data and eq. (14). The period of the field study is denoted by the solid horizontal line in the upper part of the graph.

induced by the solar heating of the coal pile (Mueller et al, 2014). The other was bulldozers working on the pile to either groom (scrape) the coal to minimize dust combustion or push coal toward an underground bunker for reclamation to the plant. Coal dropping (onto the pile from the conveyor system)—another source of fugitive dust—occurred too infrequently to capture its impact on dust levels.

One conclusion is that downwind fugitive dust levels (as $PM_{10}$) from natural processes can be as high (or even higher) than levels from human activity. This makes it imperative that natural impacts on downwind concentrations be considered when using monitored concentrations to estimate fugitive dust impacts from human activity.

The movement of bulldozers across the coal pile was clearly associated with an increase in downwind concentrations of $PM_{10}$. An analysis that removed the natural influences on $PM_{10}$ found that anthropogenic and natural contributions were roughly the same magnitude. Dispersion modeling of dust transported from the pile coupled with estimated anthropogenic levels of $PM_{10}$ derived emission factors that were somewhat smaller than those computed using an *AP-42* formulation which was not developed using coal pile data. Uncertainty in the emission factors was large because of the uncertainty in estimated levels of natural particles. However, daily averaging of emission factors and coal moisture content revealed that the latter is an important predictor of emissions. In fact, the data indicate that the emission factor for fugitive coal dust decreases by two orders of magnitude as coal moisture content increases from 21 to 33 percent and essentially vanishes for $M_c$>33 percent. This is a valuable finding because the applicable *AP-42* formulation does not allow for variation with coal moisture content.

An additional analysis determined that daily average coal moisture content was strongly associated with precipitation and air temperature. These meteorological parameters are readily available from climatological records and can be used to estimate fugitive coal dust emissions for periods when it is not raining and temperatures average above freezing. An alternate estimation methodology would be needed for wintertime in cold climates. The value of this approach is evident for plants located where frequent rainfall tends to add moisture to the coal, with the resulting emissions

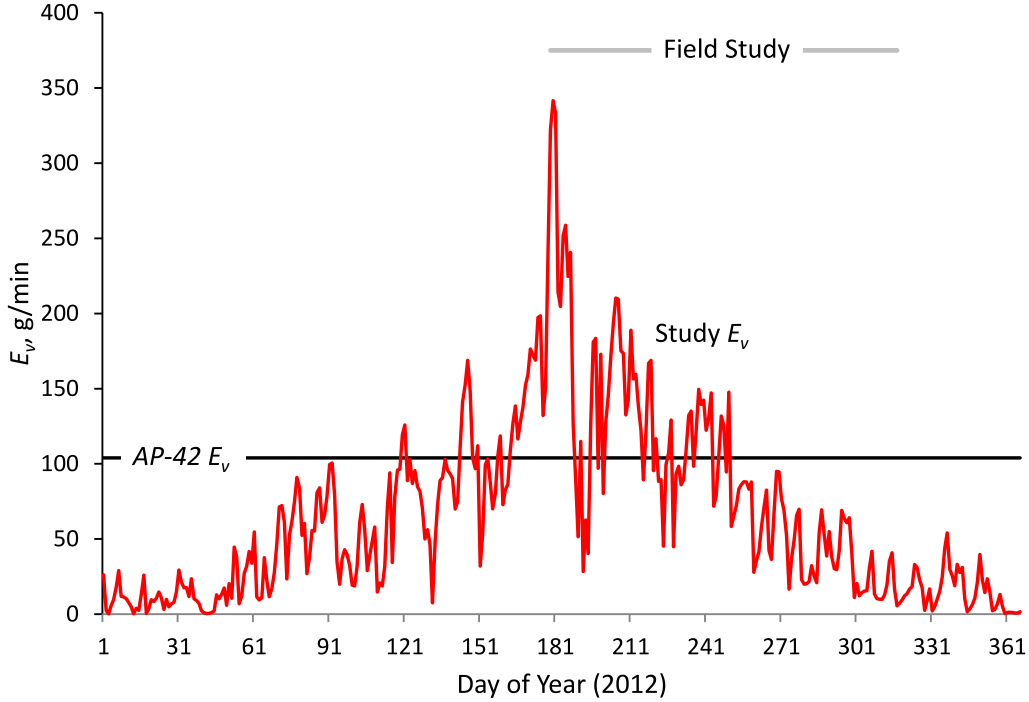


**Figure 6.** Daily emission factors for fugitive $PM_{10}$ coal dust calculated using the formulations for $E_v$ versus $M_c$ (eqs. 13a b) and Nashville meteorological data. The period of the field study is denoted by the solid horizontal line in the upper part of the graph. The *AP-42* derived $E_v$ (equal to $U\ E_{ir}$) is represented by the horizontal line near 100 g min$^{-1}$.

being lower than those otherwise derived using *AP-42*. Realistic variations in annual temperature and precipitation are capable of changing the annual average fugitive coal dust emission factor by a considerable amount.

All of the preceding conclusions are for a PRB coal pile. The characteristics of PRB coal (average silt content of 5 percent) are such that the emission factors derived in this study may overstate emissions from work on piles composed of different coal types. However, the moisture effect may also be unique to PRB coal. Additional research is needed to determine whether the emission factors derived here are applicable to other coals.

## 6. ACKNOWLEDGMENTS

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