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Open-Path Transmissometry to Determine Atmospheric Extinction Efficiency Associated with Feedyard Dust

Auermann, B. W., A. N. Paila, N. Hiranuma and J. Bush

Abstract. Open-lot, concentrated animal feeding operations (CAFOs) in the southern High Plains, such as cattle feedyards and open-lot dairies, generate fugitive emissions of particulate matter that occasionally reduce downwind visibility. The long-path visibility transmissometer (LPV) is used to measure total atmospheric extinction, a direct measure of path-averaged visibility impairment. To our knowledge, no researchers have used transmissometry to quantify aerosol concentrations downwind of open-lot livestock facilities. This work compares time-resolved PM_{10} mass concentration ($\mu\text{g m}^{-3}$) and atmospheric extinction (km^{-1}) data measured simultaneously along the downwind boundary of a commercial cattle feedyard to compute “extinction efficiency,” which is the change in atmospheric extinction that results from a unit change in PM mass concentration. Expected values for the actual extinction efficiency (as contrasted with dry extinction efficiency) of total suspended particulate (TSP) and its fraction less than 10 microns aerodynamic equivalent diameter (PM_{10}) are 0.2-0.4 and 0.3-2.9 $\text{m}^2 \text{g}^{-1}$, respectively. Determination of the humidity-dependent atmospheric extinction efficiency of feedyard dust will facilitate the use of transmissometry as an intuitive, reliable, and real-time surrogate for measuring PM mass concentration.

Keywords. Atmospheric extinction, transmissometry, fugitive dust, feedyard

Introduction

Theoretical Background. The atmospheric extinction coefficient (B_{ext}) is a measure of light attenuation in the atmosphere resulting from the absorption and scattering of light by gases and particles. Expressed in units of inverse distance (e.g., km^{-1}), B_{ext} is calculated as the sum of the *absorption* and the *scattering* coefficients (Malm *et al.*, 1986),

$$B_{\text{ext}} = B_{\text{scat}} + B_{\text{abs}} = B_{\text{Ray}} + B_{s,p} + B_{a,g} + B_{a,p} \dots\dots\dots[1]$$

In Equation [1], the subscripts “scat” and “abs” refer to total scattering and total absorption, respectively; “s” and “a” refer to scattering and absorption, respectively; “g” and “p” refer to gases and particles, respectively; and B_{Ray} refers to so-called Rayleigh scattering, which is frequency-dependent scattering by the native gases in the earth’s atmosphere. The Rayleigh extinction coefficient is zero in the limit as barometric pressure tends to zero; its value in clear air at sea level is approximately 0.010-0.012 km^{-1} (Malm *et al.*, 1986).

The extinction coefficient may be used to compute the radiant intensity at any point some distance from a radiant source of known intensity, as in:

$$I(r) = \left(\frac{K \bullet I_0}{r^2} \right) e^{-B_{\text{ext}}r} \dots\dots\dots[2]$$

in which $I(r)$ is the irradiance detected at a given location (W km^{-2}), I_0 is the radiant intensity (W) of the source, r is the linear distance (km) between the source and detector, K is a dimensionless parameter defined by the geometry of the radiant source, and B_{ext} is the total atmospheric extinction coefficient (km^{-1}).

Two methods are available to measure atmospheric extinction. (1) An open-path transmissometer can be used to compute the path-averaged atmospheric extinction directly. The transmissometer installation fixes k , I_0 and r ; it then measures $I(r)$ at the detector and infers B_{ext} from Equation [2]. (b) Aerosol mass-concentration measurements can be used to estimate the atmospheric extinction if the “atmospheric extinction efficiency” (Sisler *et al.*, 1996) and mass fraction of each aerosol component are known. The atmospheric extinction efficiency is defined as

$$\varepsilon_i = 10^3 \bullet \frac{\partial B_{ext}}{\partial C_i} \dots\dots\dots [3]$$

in which C_i is the mass concentration ($\mu\text{g m}^{-3}$) of each aerosol component (denoted by the subscript i), B_{ext} is as previously defined, ε_i is the extinction efficiency ($\text{m}^2 \text{g}^{-1}$) of aerosol component i , and 10^3 is a units-conversion constant ($\mu\text{g km g}^{-1} \text{m}^{-1}$). Provided that all of the aerosol components i are independent, the total extinction efficiency, ε_T , can then be calculated as

$$\varepsilon_T = \sum_{i=1}^n w_i \varepsilon_i \dots\dots\dots [4a]$$

in which

$$w_i = \frac{C_i}{\sum_{j=1}^n C_j} \dots\dots\dots [4b]$$

is the mass fraction of independent component i in the combined aerosol.

The independence of the aerosol components is vital to the process of reconstructing the total extinction efficiency of the combined aerosol using Equations 4a and 4b. For example, it would be incorrect to reconstruct ε_T from a combination of the extinction efficiencies of (a) sulfate, (b) organic carbon and (c) urban $\text{PM}_{2.5}$ because the typical, urban $\text{PM}_{2.5}$ fraction contains a significant proportion of the sulfate and organic-carbon aerosol. Likewise, it would be incorrect to reconstruct ε_T from $\text{PM}_{2.5}$ and PM_{10} concentrations because the PM_{10} fraction contains the $\text{PM}_{2.5}$ fraction by definition. Ignoring for the moment the important issue of performance bias in the inertial preseparators of federal reference method $\text{PM}_{2.5}$ and PM_{10} monitors deployed in agricultural settings (Buser *et al.*, 2003), the proper way to reconstruct the latter ε_T would be to compute the $\text{PM}_{10-2.5}$ (otherwise known as PM coarse or PM_c) concentration by difference and apply the appropriate extinction efficiency, if known, to that fraction.

Regulatory and Industrial Significance. There are currently no federal guidelines that regulate visibility impairment caused by episodic, fugitive dust emissions specifically from CAFOs. Because the interpretive difficulties surrounding PM monitoring, sampler bias and time-averaged measurements are nuanced and somewhat arcane to the public at large and the CAFO community in particular, we intend to build on this work to develop more intuitive, visibility-based surrogate measurements that can inform routine CAFO-management decisions.

Technical Objective. This study was designed to determine the atmospheric extinction efficiency associated with the fugitive dust from a commercial cattle feedyard. As a reference value, Malm (1999) published a value of $0.6 \text{ m}^2 \text{g}^{-1}$ for the dry extinction efficiency of generic coarse particles.

Experimental Design

Field studies were conducted at a commercial beef cattle feedyard (capacity 45,000+) in the Texas Panhandle. PM_{10} and TSP mass concentrations ($\mu\text{g m}^{-3}$) and atmospheric extinction (km^{-1}) were simultaneously measured along the downwind boundary of the feedyard (see Figure 1).

Monitoring Equipment. The long-path visibility transmissometer (LPV) measures the atmospheric extinction (scattering + absorption) of green light by atmospheric gases and particles along a line between a transmitter and a photometer. The transmissometer compares the actual luminous intensity of a narrow beam of light with the intensity that would have been measured at the same location in an aerosol-free vacuum. The ratio of the measured and expected values of light intensity is an indirect measure of the path-averaged atmospheric extinction, B_{ext} , between the transmitter and photometer.

The tapered-element, oscillating microbalance (TEOM) is a quasi-real-time aerosol monitor in which aerosol particles impinge on a filter attached to a vibrating element. As the mass of particles retained on the filter increases, the characteristic frequency of the element decreases, and the change in frequency over time

is a measure of the particle mass deposited on the filter during that time interval. TEOMs may be configured with a variety of inertial, size-selective inlets to measure TSP or any smaller size fractions of interest.

Figure 1 shows the experimental design employed for this study. We calibrated the LPV at a path length of 300 m as per manufacturer's specifications and deployed it on an E-W path along the northern perimeter of the feedyard corrals. The transmitter (Figure 2a) was installed atop a large water tank on the NE corner of the feedyard, the photometer (Figure 2b) on a short pillar at ground level on the NW corner of the feedyard. Under prevailing winds from the S-SSW, this LPV measured the downwind extinction, the visibility impairment resulting from the combination of the background aerosol load (assumed negligible) and the fugitive emissions of particulate matter from the feedyard surface. The path length from transmitter (location A) to receiver (location B) was approximately 900 meters. PM mass concentrations were measured at one upwind and one downwind location (locations D and C, respectively). One TEOM was installed at location D with an inlet for total suspended particulate (TSP) measurement on the upwind side. Two TEOMs were installed at location C, one with a TSP inlet and one with a size-selective inlet for PM_{10} . The TEOMs at location C were assumed to approximate the path-averaged aerosol concentrations corresponding to the LPV's open path, although that assumption is subject to criticism. To validate that assumption would require at least 5 or 6 additional TEOMs distributed along the LPV path, which would be cost-prohibitive.

In addition to the visibility and PM concentration measurements, we deployed an automatic weather station at location C to measure wind speed and direction, rainfall, temperature, solar radiation, relative humidity and barometric pressure. Although the full suite of weather data will be useful for dispersion modeling to infer emission rates from the ground-level, area source (GLAS), in this case we used the wind direction data simply as a basis for removing out-of-sector data from our regression analysis.



Figure 1. Overhead photograph of the cooperating feedyard. Instruments were deployed so that we could measure PM_{10} and TSP mass concentration and atmospheric extinction simultaneously measured along the downwind boundary of the feedyard. Transmitter is at A; receiver (photometer) is at B; upwind TEOM is at D; and downwind TEOMs are at C.

Objective Criteria for Data Filtering. Because of the relative placement of the TEOMs and the LPV's open path, we removed from the regression analysis all data collected while the wind direction was outside the 90-degree sector subtended by SE and SW vectors (135-225 degrees azimuth). In addition, occasionally the dust concentrations along the downwind boundary of the source area were so great that the LPV photometer did not measure any of the transmitted light. In that case, the LPV returned an extinction value of 0 km^{-1} ; those data were also removed from the analysis. Finally, truck traffic along the downwind feed alley intermittently created transient road-dust spikes in the TEOM data. Because our primary focus was the fugitive, manure-derived dust from the open lots, we excluded the data points that were clearly asso-



Figure 2. (a) Looking E at the transmitter shelter atop a large water tank at location A (left). (b) Looking NW at the pedestal-mounted photometer/receiver at location B (right).



Figure 3. Downwind samplers at location C (left). From left are a federal reference method, high-volume TSP sampler; a TEOM configured for PM₁₀; a TEOM configured for TSP; and a federal reference method, high-volume PM₁₀ sampler. (Right) Upwind monitors at location D.

ciated with vehicle traffic. From the remaining data, we plotted one- and five-minute average extinction values and PM₁₀ and TSP mass concentrations. We then subjected daily ensembles of those data to simple, linear regression to estimate the extinction efficiencies of PM₁₀ and TSP.

Results and Discussion

Figure 4 is an example of the raw data collected by our TEOMs and LPV on September 5, 2005. Vehicle traffic on a nearby, unpaved road is clearly visible in the extinction data; because the TEOMs are located at a single point, vehicle dust plumes that show up within the 900-m LPV path do not necessarily envelop the TEOMs every time. Vehicles responsible for those spikes in atmospheric extinction include the night watchman's pickup truck (generally between 1700h and 0600h), feed trucks (0500h to 1300h) and feedyard management and consultants (0800h to 1700h). The diurnal peaks in dust concentrations and atmospheric extinction characteristic of cattle feedyards occur, as usual, between 1800h and 2200h, and they coincide nicely.

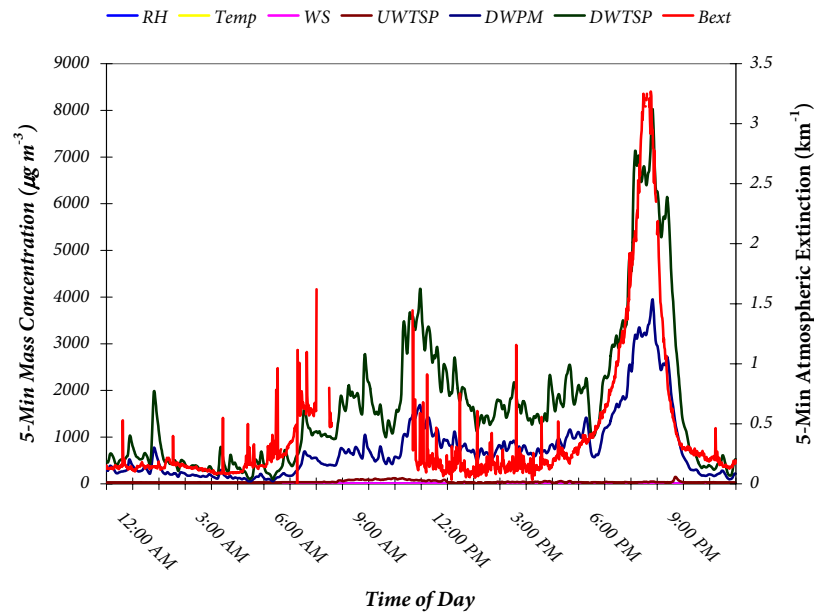


Figure 4. Time-series plot of 5-minute average B_{ext} , mass concentrations and selected weather variables on September 5, 2005. Spikes in B_{ext} are attributable to vehicle traffic on the unpaved feed alley immediately upwind of the transmissometer path. Note the well documented “evening dust peak” during which peak PM concentrations and extinction values coincide.

The daily extinction efficiencies inferred from regression analysis of our measurements (Figures 5 and 6) corresponded well to expected absolute and relative values. For TSP and PM_{10} , monthly extinction efficiencies ranged from 0.2-0.4 and 0.3-2.9 $\text{m}^2 \text{g}^{-1}$, respectively, as compared to Malm’s (1999) reference value of 0.6 $\text{m}^2 \text{g}^{-1}$ for the dry extinction efficiency of generic “coarse particles.” Inevitably, because PM_{10} concentrations are by definition numerically lower than TSP concentrations, the extinction efficiency of PM_{10} always exceeds that of TSP by a factor roughly equivalent to the TSP/ PM_{10} ratio, which typically ranges from 4.0 to 5.0 for agricultural aerosols (Parnell *et al.*, 2005). Importantly, we have not yet corrected the PM_{10} measurements for the design-imposed, upward, measurement bias (a. k. a., “oversampling bias”) inherent in federal reference method (FRM) PM monitors having inertial, size-selective inlets with cutpoint dimensions less than the mass-median diameter (MMD) of the ambient aerosol to be measured (Buser *et al.*, 2003). Were we to correct the PM_{10} data for oversampling bias, we would expect the apparent extinction efficiency of PM_{10} to increase by up to a factor of 2.

Coefficients of determination (R^2) for the regression models were generally excellent (>0.85) but suffered significantly when data sets were not filtered for low-quality measurements (e. g., zero photometer signal, out-of-sector wind direction, vehicle-related spikes of road dust). That effect can be seen clearly in Figure 5, in which a large number of zero photometer signals can be seen in the transmissometry data. In nearly all daily data sets, application of the objective data-filtering criteria increased R^2 .

In addition, our extinction measurements using the LPV represent the optical properties of feedyard aerosols as they exist in the environment (*in situ*), as contrasted with the extinction efficiencies published by Malm (1999) for *dry* aerosol particles. This distinction is particularly important for hygroscopic aerosols like feedyard dust, particles that absorb and desorb liquid water dynamically in response to changes in relative humidity (RH; Marek, 2006). Brooks *et al.* (2005) and Moon *et al.* (2005) have shown that some fractions of the feedyard aerosol exhibit pronounced deliquescence, which refers to a particle’s significant change in size and shape by water uptake as RH increases past a “deliquescence threshold,” which for feedyard dust appears to occur at $\text{RH}=72\%$. It appears likely that hygroscopicity and deliquescence are responsible, in part, for the variation in optical properties that shows up as an experimental variation in extinction efficiency. We plan additional research to determine if that is so.

Another possible source of variation in our estimates of extinction efficiency is the natural variation in $\text{PM}_{10}/\text{TSP}$ ratio – that is, the variation that occurs without regard to oversampling bias or other monitor-

specific phenomena. Parnell *et al.* (2005) showed that the particle-size distribution (PSD) of feedyard dust shifts dramatically after a precipitation event, reducing the MMD of the aerosol and increasing its PM_{10}/TSP ratio. Although we have not yet confirmed this, we suspect that moisture has a disproportionate effect on the mass of larger particles susceptible to mechanical shearing and emission as compared to finer particles.

One of the more obvious features of the scatter plots in Figures 5 and 6, which also illustrates one of the more obvious criticisms of our statistical approach, is the cyclical (“looping”) behavior of the concentration-extinction plots. We are plotting two time-series data sets against each other, which means that we have violated one of the major assumptions in linear regression: data points are assumed to be independent of one another. In this case, we say that the data are *autocorrelated* or *serially correlated*, which we plan to address with more powerful analytical techniques. For the time being, however, the predictive value of these regression models is beyond serious question; only the absolute values of the mean extinction efficiencies are likely to change as a result of the more rigorous analysis, not their orders of magnitude.

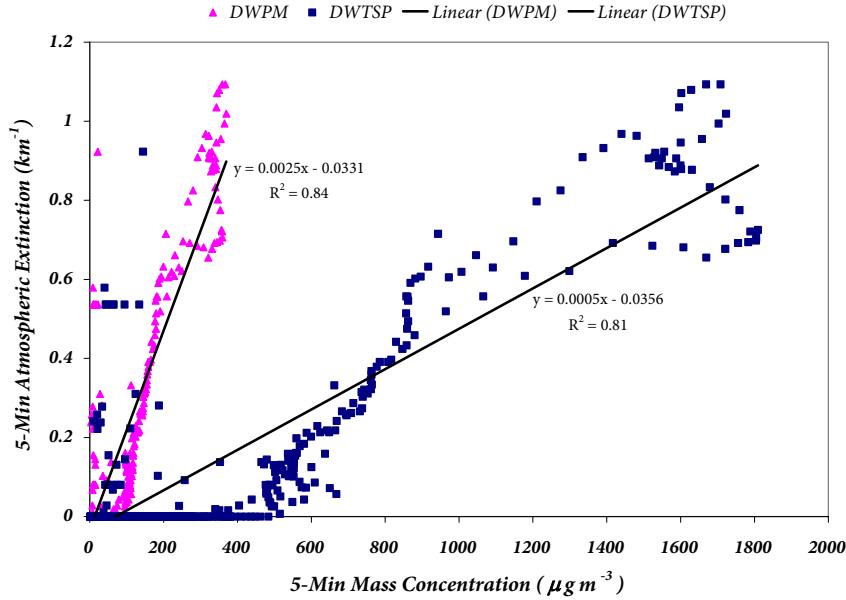


Figure 5. Scatter plots and linear regression of B_{ext} against mass concentrations of PM_{10} and TSP from November 1, 2005. Influence of zero photometer signal on the regression slope and coefficient of determination is evident in the TSP/ B_{ext} data; the same effect holds for the PM_{10} data but is obscured by the order in which the data markers were placed on the chart.

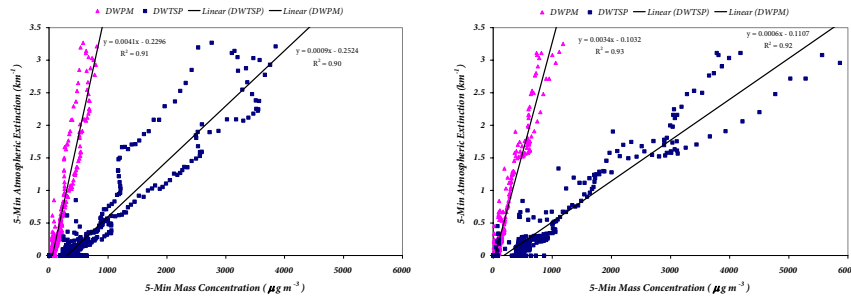


Figure 6. Linear regressions of B_{ext} against PM_{10} and TSP mass concentrations from November 10 (left) and November 13, 2005 (right). Although coefficients of determination are excellent (generally $R^2 > 0.85$), the influence of autocorrelation is evident from the looping behavior in the scatter plots.

Conclusions

Real-time, nearly instantaneous changes in the atmospheric extinction coefficient along the downwind perimeter of feedyard corrals appear reliably correlated with aerosol mass concentrations measured by TEOM. Mass concentration of PM₁₀ is a modestly more reliable predictor of B_{ext} than TSP concentration, and changes in PM₁₀ concentration have a significantly greater influence on B_{ext} than changes in TSP concentration. Our field techniques, which involve point measurement of mass concentration midway between the transmitter and receiver of a long-path visibility transmissometer, yield autocorrelated data, and we will need to refine our analytical technique to resolve the interpretive and predictive difficulties posed by that autocorrelation. Aside from those analytical weaknesses, our preliminary estimates of the extinction efficiency of feedyard dust are numerically close to Malm's (1999) reference value for generic, coarse dust. Relative humidity – specifically, its effect on particle size, shape and optical properties via hygroscopic adsorption and deliquescence behavior – is likely to be an important co-factor in exploiting the predictive relationships between extinction and mass concentration in the feedyard setting.

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