FUGITIVE DUST TRANSPORT UNDER ARID CONDITIONS: A FIELD AND MODELING STUDY IN DOÑA ANA COUNTY, NEW MEXICO

PROJECT NUMBER: A-00-7

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NARRATIVE SUMMARY
Soil dust is an air quality and health concern in many areas along the U.S.-Mexican border. This study focused specifically on wind-blown and vehicle-entrained dust in southern Doña Ana County, New Mexico. The county has experienced numerous exceedances of the 24-hour National Ambient Air Quality Standard (NAAQS) concentration limit for PM$_{10}$ of 150 micrograms per cubic meter ($\mu$g/m$^3$) and there is great interest in developing dust control measures that are effective under local conditions. One issue is to determine the relative importance of dust coming in from surrounding areas compared to dust generated by human activity within the developed areas where most people live.

Extensive studies of wind-blown and vehicle-generated dust have been conducted in central California, but much less research has been done along the U.S.-Mexican border. A goal of this study was to conduct experiments to determine whether conclusions based on the California research are also applicable for the soil conditions, weather patterns, and human activity patterns in southern Doña Ana County.

The main effort was a study to determine what happens to the dust that is initially suspended when a vehicle travels on an unpaved road. There are indications that the methods currently used to estimate dust emissions from unpaved roads overstate how much dust actually gets transported away from the road to cause regional effects on air quality. The goal was to determine for Doña Ana County conditions how much dust is redeposited near the road and how much is transported. The significance of knowing this is that it can help guide what dust control strategies are most effective in improving air quality where people live. If the dust travels only a short distance, then dust control on roads in developed areas will be effective even when the surrounding area is desert and grazing land.

The results obtained on the Jornada road northeast of Las Cruces suggest that for the light wind, midday conditions tested much of the dust is transported vertically and little of the PM$_{10}$ and PM$_{2.5}$ is redeposited near the road. Further experiments are planned to test the effect of different weather conditions on this initial conclusion.
This study provided site-specific data for the U.S.-Mexican border region in Doña Ana County that can be compared to published studies conducted in other parts of the United States. The study of horizontal and vertical dust concentration downwind of an unpaved road in Doña Ana County shows a decrease in concentration similar to that measured by Watson, et al. in California. However, comparison of the PM$_{10}$ and PM$_{2.5}$ concentrations and calculation of the horizontal dust flux suggest that, for the particular atmospheric conditions of this experiment, the decrease was due to dispersion and not redeposition. The limited measurements made during the Spring 2001 field suggest that time of day and atmospheric stability are important factors in the partitioning of road dust between near-source deposition and long-range transport. Future experiments are planned to better evaluate this tentative conclusion.

Based on studies in Nevada and in the San Joaquin Valley (SJV) (Watson and Chow 1996), it has been suggested that the relative contribution of nearby sources is greater than that of distant sources in moderate-wind dust events. Specifically, the San Joaquin Valley data show a large (<90%) decrease in dust concentration within 100 meters (m) of an unpaved road. As an explanation, the authors suggested that most of the dust that is initially suspended by vehicles is redeposited near the source when the wind hits brush, fences, and small terrain irregularities (Watson and Chow 1996; Watson, et al. 2000). This would suggest that the correct source contribution to regional PM inventories would be the fraction of dust that gets transported vertically above a certain height. If near-source redeposition is important in reducing dust transport, then it is reasonable to hypothesize that the majority of dust inhaled is generated locally and that dust control on roads near populated areas will be effective in reducing exposure.

Work by Watson and collaborators in Nevada and California also show that the threshold wind velocity for entrainment of dust is much lower in disturbed urban areas compared to open grazing land. Results of California studies suggest that, at least for moderate wind conditions; the dust coming from sources near the populated areas is more important than dust coming from areas miles away. The major exception would be during large-scale regional windstorms. The significance of these differences in threshold wind velocity for dust suspension is that it suggests that dust control in the developed areas can reduce exposure to the population, even when the area is surrounded by agricultural and arid grazing land.
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INTRODUCTION

Soil dust is an air quality and health concern in many areas along the U.S.-Mexican border; this study focused specifically on wind-blown and vehicle-entrained dust in southern Doña Ana County, New Mexico. Doña Ana County comprises 3,804 square miles in south central New Mexico, bordering on El-Paso County, Texas and the state of Chihuahua, Mexico to the south. It is the second most populated county in the state of New Mexico. The climate is generally mild and semi-arid, averaging 350 days of clear weather annually. Windstorms are common during the late winter and through the spring months. During these high velocity winds, Doña Ana County experiences particulate matter (PM) exceedances. The county has experienced numerous exceedances of the 24-hour National Ambient Air Quality Standard (NAAQS) concentration limit for PM$_{10}$ of 150 micrograms per cubic meter ($\mu$g/m$^3$) and is in violation of the PM$_{10}$ NAAQS (New Mexico Environmental Department 2000).

Although Doña Ana County has experienced exceedances of the 24-hr PM$_{10}$ standard, the EPA Natural Events Policy allows the discretion to not designate an area as non-attainment for a criteria pollutant if it can be shown that certain exceedances were caused by uncontrollable natural events. However, control measures are still required for significant human-caused sources. To be effective, a plan for Doña County must consider the unique local conditions, including the arid climate, the developments and agriculture in the river valley, and the transport of particulates across the international border.

Ambient particulate matter is regulated by the U.S. Clean Air Act (1990) because particles are a concern for public health (EPA 1996) and for regional visibility (Grand Canyon Visibility Transport Commission 1996). Current regulations are based on the mass of particles less than a specified cut size as measured by Federal Reference Methods (Code of Federal Regulations 1998). The existing NAAQS were based on protecting public health with an adequate margin of safety. Recent epidemiological studies (Samet, et al. 1998; American Thoracic Society 2000; HEI 2001) continue to show a statistical correlation between increased ambient particle concentration and adverse health effects. Review of many studies suggests that an increase of 10
micrometers per cubic meter (µm/m$^3$) of particles is associated with a 0.5 percent to 1.0 percent increase in the death rate (HEI 2001).

The mass measurements used for current regulations do not distinguish between the different particulate matter components: soil minerals, elemental carbon, organic carbon, sulfate, and nitrate. A few health effects studies have considered the composition of the particles (Dockery, et al. 1993). There is some evidence that the health effects are less strongly associated with soil dust and are more associated with other particle components (Pope, et al. 1999; Schwartz, et al. 1999) but results are inconclusive and the toxicology of particles is an active area of research.

High levels of soil dust are a nuisance that degrades the quality of life. Even if soil dust is less damaging to health than other components of ambient particulates, soil dust will remain a concern to air quality officials on the U.S.-Mexican border and elsewhere. While dust is common in the undeveloped areas, it becomes much more prevalent where natural soils have been disturbed by human activities. This is because natural soils have a tendency to form a mineral and organic crust—a desert pavement—that is resistant to erosion by wind. Human activities can remove or break this crust, thus allowing the dust to be entrained more easily by the wind. Even sparse desert vegetation provides protection to the soil surface by serving as an organic binder. When human activities remove vegetation, the soil is more susceptible to wind. Scraping and tilling are used locally for weed control, which results in large areas of unvegetated soil. Construction sites and unpaved roads are additional, human-caused areas of disturbed soil.

While very little can be done to decrease windblown dust from the open desert areas during high wind periods, there are a lot of things that one can do to decrease the dust caused by human activities. Reducing the amount of dust in the air requires understanding where the dust comes from. One needs to know how much of the dust in residential areas comes from nearby roads, disturbed land in developed areas, unpaved roads, agriculture, and undeveloped grazing land. Developing accurate apportionment of the sources contributing to the dust arriving at a receptor site requires an understanding of the behavior of airborne particles, including initial suspension, atmospheric transformation, transport, and removal.

The fundamentals of atmospheric aerosol behavior are described in standard texts that provide detailed citations to the original literature (Seinfeld and Pandis 1998; Friedlander 2000). Extensive reviews of the literature on fugitive dust from roads and wind entrainment are also available (Chow and Watson 1982; Watson, et al. 2000).

Air quality officials in the southwest are not satisfied with the current inventory and dispersion modeling methods for predicting airborne dust. A workshop reviewed reconciling discrepancies between source inventories and receptor sample apportionment measurements of atmospheric particulates (Watson, et al., 1999; Watson and Chow 1996). There is increasing evidence that current inventory
methods overstate the regional impact of soil dust, but there has been limited research to test specific hypotheses related to the sources of the overestimate.

Based on studies in Nevada and in the San Joaquin Valley (SJV) (Watson and Chow 1996), it has been suggested that the relative contribution of nearby sources is greater than that of distant sources in moderate-wind dust events. Specifically, the San Joaquin Valley data show a large (<90%) decrease in dust concentration within 100 meters (m) of an unpaved road. As an explanation, the authors suggested that most of the dust that is initially suspended by vehicles is redeposited near the source when the wind hits brush, fences, and small terrain irregularities (Watson and Chow 1996; Watson, et al. 2000). This would suggest that the correct source contribution to regional PM inventories would be the fraction of dust that gets transported vertically above a certain height. If near-source redeposition is important in reducing dust transport, then it is reasonable to hypothesize that the majority of dust inhaled is generated locally and that dust control on roads near populated areas will be effective in reducing exposure.

Work by Watson and collaborators in Nevada and California also show that the threshold wind velocity for entrainment of dust is much lower in disturbed urban areas compared to open grazing land. Results of California studies suggest that, at least for moderate wind conditions; the dust coming from sources near the populated areas is more important than dust coming from areas miles away. The major exception would be during large-scale regional windstorms. The significance of these differences in threshold wind velocity for dust suspension is that it suggests that dust control in the developed areas can reduce exposure to the population, even when the area is surrounded by agricultural and arid grazing land.

RESEARCH OBJECTIVES
This study investigates whether conclusions based on published studies of fugitive dust in the San Joaquin Valley and other areas in central California also apply for the soil conditions, dust particle size distributions, human activity patterns, and terrain in southern Doña Ana County, New Mexico. Extensive studies of fugitive dust in the Central Valley of California have been funded by the U.S. Environmental Protection Agency (EPA) and by the California Air Resources Board (CARB) and provide a base of methods and data for designing similar studies in the U.S.-Mexican border region (Watson, et al. 1998a; Watson, et al. 1998b; Watson, et al. 2000).

The study consisted of three subprojects. Taking measurements in Doña Ana County of:

- Dust particle size and concentration for source profiles and instrument calibration
- Dust concentration as a function of wind speed at various sites along the U.S.-Mexican border
- Dust suspension and transport from unpaved roads; the road dust measurements were taken at various distances from the edge of the road and at various heights above the ground
RESEARCH METHODOLOGY/APPROACHES
This section describes the study location, the locations of the monitoring sites on the road, the instrumentation used to measure ambient PM$_{10}$ concentrations and the test surface characteristics.

Field Sites
The selected sites were the New Mexico Environmental Department (NMED) air monitoring stations in Sunland Park City Yard, Desert View Elementary School, Jornada Road, and the Santa Teresa border crossing, an undeveloped site on state land about five miles west of Santa Teresa, all are in Doña Ana County. Topographic and soil maps (U.S. Department of Agriculture 1984) were obtained to document the test sites. The Jornada Road site was excellent for characterization of the horizontal and vertical transport of dust from vehicle travel on unpaved roads. The Sunland Park, Desert View, Santa Teresa, and West sites range from developed river valley to rural undeveloped mesa top conditions and were all within three miles of the Mexican border.

Road Selection
The road selected for the vehicle-entrained dust field experiments was the Jornada Road site northeast of Las Cruces. This road is an unpaved road with sparse traffic and state-owned land on both sides. For the selected site the number of car trips past the sampling station was reasonably controlled and there was access to set up the sampling towers as needed. It is flat land, thus the sampling was not affected in any way by the topography of the land. In addition, the vegetation on both sides of the road mainly consisted of mesquite, which had been disturbed by the grazing of cattle. This made the soil loose and susceptible to being lifted up by high winds. The wind was predominantly from west to east. The road runs north to south.

PM$_{10}$ Sampling
DustTraks (Model 8520 DustTrak TM, TSI Incorporated, Shoreview, Minn.) were used to measure PM$_{10}$ concentration upwind and downwind of the test section. Three DustTraks were used in sampling. The DustTrak uses a battery pack with four C batteries or AC power to power a pump that draws ambient air through an inlet at a flow rate of 1.7 liters per minute (l/min). The aerosol size cut point is achieved by a single-stage impactor. PM$_{2.5}$ and PM$_{1.0}$ configurations are available, but these inlets come with a greased impaction plate. Quality checks for the DustTraks included:

- Daily inspection of the impactor inlets, with cleaning whenever particle deposits were observed
- Filter checks for zero readings were done first thing in the morning and after every run
- Flow rate checks first thing in the morning and after every run
- Collocation of the DustTraks daily to check for precision between the instruments
- Factory calibration using a standard test dust prior to shipment to verify the accuracy of the conversion from light scattering to calculated PM$_{10}$ mass
• Collocation of DustTrak and NMED-Tapered Element Oscillating Microbalance (TEOM) to check mass accuracy under local conditions

The sampling date, start time, stop time, sampler ID, sampler position, and flow rate were recorded in the lab notebook. At the end of each sampling interval, the flow rate was recorded to account for any drift.

Meteorological Instrumentation
A Davis Monitor - II weather station (Product number 7440) was fixed at 2m above ground level (agl) on the closest station to the source (3m away from the edge of the road). It consisted of a wind vane to monitor the wind direction and a four-cup anemometer to record the wind speed. Data was recorded once each minute. This data was used mainly to obtain the average wind speed and wind direction for the test site.

Sampling and Characterization of Surface Material
Soil samples were taken from the test site. A whiskbroom and dustpan were used to remove the loose surface material from the hard road base making sure that the base of the road was not abraded during sweeping. An approximate amount of 400 grams (1 pound) was collected for silt analysis. The material was analyzed for silt fraction by standard sieving methods.

Vehicle Type and Traffic Monitoring
The test vehicle was a VW Westfalia van weighing approximately 2.5 tons with four wheels. The vehicle was driven at approximately 40 miles per hour (mph) and was logged every time it passed the nearest sampling location. The test vehicle was driven at constant speed, for approximately 1/8 mile in each direction from the monitoring station. The distance between the vehicle turnaround points was 1/2 mile. All extra traffic on the road was logged with the vehicle type (passenger car, pick-up truck, etc). Trips with the van were skipped when another vehicle passed the sampling station to keep the number of trips per sample constant.

Sampling Pattern
The best results were obtained with a controlled sampling pattern where four car trips occurred while each DustTrak was at a fixed location. The sampling and the averaging time were set at 15 seconds so that the DustTrak would be able to capture the dust peak.

Horizontal Profile
A motivating hypothesis is that not all dust suspended by the wind is transported long distances. There is published data showing that about 90% of the dust suspended 2m above ground level from an unpaved road is redeposited within 50m of its source (Watson et al. 1996). One of the objectives of the field experiment was to provide data from Doña Ana County measurements on the near source redeposition of fugitive dust over distances of 3m to 100m.
The test road was considered a line source for fugitive dust. The test vehicle traveled up and down on this road at 40mph creating dust emissions. The reference DustTrak was kept nearest to the source at 3m to collect every activity occurring on the source. Most importantly, it was used to record the initial size of the dust cloud generated by the moving vehicle. The reference DustTrak was not moved throughout the entire experiment. The reference DustTrak was initially kept at 2m above ground level and then was changed to 1m above ground level, which recorded the initial dust cloud concentration better. An upwind sample was taken before each run. Another DustTrak was used to measure the upwind PM$_{10}$ concentration and this DustTrak was kept far away from the source so as not to be affected by any vehicle traveling on the road. The sampling locations were at 3m, 10m, 20m, 30m, 50m, 100m and 200m downwind of the road (perpendicular to the road). Another DustTrak was used for sampling at these locations. The sampling time was approximately five minutes at every location. This DustTrak was kept at either 1m above ground level or 2m above ground level depending on the experiment being conducted that day. Between three and four replicate sets of car trips were taken at every location. The wind data was recorded every minute of the experiment. This experiment was done for both PM$_{10}$ and for PM$_{2.5}$ at 1m above ground level and 2m above ground level.

**Vertical Profile**

The vertical concentration profile of the dust cloud was measured to evaluate the vertical dispersion/vertical mixing of dust and gain more insight into whether the settling of PM$_{10}$ with distance is purely due to gravitational settling or whether vertical mixing and dilution explains the concentration decrease.

The Jornada Road side was again considered the line source for dust emissions. A vertical tower of 9m was placed 10m downwind from the source. The reference DustTrak was again placed 3m away from the source. A pulley was used for the 10m pole to lift the DustTrak that was being used for the vertical profile to different heights above ground level. Sampling was done at heights of 1m, 2m, 4m, 6m, and 9m above ground level. The entire experiment was also repeated by keeping the vertical tower at 30m away from the source. In addition, a mini-vertical profile was conducted at 3m away from the source. In this case, the sampling was done at 0.5m, 1m, and 2m above ground level. The experiments were both for PM$_{10}$ and for PM$_{2.5}$.

**Collocation of the Three DustTraks with the TEOM and the OPC**

The accuracy of the field instruments was tested under field conditions by collocating the three DustTrak monitors and a Lasair Model 310 optical particle counter (OPC) at the NMED Sunland Park City Yard monitoring site. The three DustTraks and the OPC were placed adjacent to the TEOM of the air monitoring station. The basic goal was to collocate the DustTraks with the OPC and the TEOM and to see how the three different instruments varied in their PM$_{10}$ values. The three instruments were left running overnight and the results were noted.
**Gravimetric Measurement of PM**$_{10}$

A portable PM$_{10}$ MiniVol® sampler (Airmetrics, Inc.) was used to obtain the gravimetric measurement of PM$_{10}$ at the test site. The MiniVol uses a rechargeable battery pack to power a pump that draws air through a single filter pack at a flow rate of 5l/min. The MiniVol ran the entire time of sampling on a particular day, usually for about six hours. This experiment was conducted on two days. We used polycarbonate filter (Millipore polycarbonate membrane filter, 47mm diameter, 0.2mm GTTP) on one day and a Whatman filter (Whatman® GF/A 47mm diameter) on the other day. The filters were both tared and weighed on a microbalance in the climate-controlled weighing room in the Civil Engineering Department at University of Texas at El Paso.

**Microscopy of the Dust Particles**

The PM$_{10}$ MiniVol samplers were used to obtain four samples for electron microscopy to study the shape of the fugitive dust particles. The MiniVols were placed 22 feet (ft) downwind from the road. The samples were based on the number of car trips. A Teflon filter (Gelman Teflo™ 47 millimeter [mm] diameter, 2mm) was used for sampling in each case. The filters were then studied under a Scanning Electron Microscope in the Material Science Department at University of Utah to view the shape of the particles.

**Horizontal Flux Calculations**

The horizontal flux mentioned above simply indicates the amount or mass of dust leaving the road per length of road when a vehicle passes by on an unpaved road. The horizontal flux measures the total mass of dust being transported. If the flux decreases with distance from the source, then it is an indication that the dust is settling and not spreading out vertically. It is thus very important to find out this value.

The system described in this section is discussed in terms of shell mass balance. A control volume (shell), the surface of which is normal to the direction of wind, is considered as shown below. An unsteady state law of conservation of mass is applied to calculate the horizontal flux in the control volume.

\[
\text{Mass In} - \text{Mass Out} + \text{Source} - \text{Sink} = \text{Accumulation}
\]

In the schematic diagram, the coordinates are defined as follows:
- x coordinate = horizontal distance perpendicular to the road with the positive x denoting the downwind direction
- y coordinate = parallel to the direction of travel along the road
- z coordinate = height above ground level
Mathematically, the horizontal flux of dust leaving the unpaved road is defined as

\[
\text{Flux} = \int C(y, z, t) V(z, t) dy dz dt \text{ mg/VMT} \quad (1)
\]

We can simplify the above equation by assuming the following: The velocity of the wind varies with time and altitude but is assumed constant with respect to the x and y coordinates of the control volume \((V = f(z, t))\). The concentration gradient is considered constant with the y-coordinate \((C = f(x, z, t))\). This assumption is justified because the vehicle traveling on a road approximates a line source; the vehicle turnaround is every 400m nominal in each direction from the sampling location compared to the measurements taken to about 100m in the x direction. As a further simplification, time average measurement values are substituted for the instantaneous values of the time varying variables.

Due to equipment limitations, the wind speed at the test site was measured only at one height (2m above ground level). To calculate the horizontal flux, the wind profile was calculated by making two different reasonable assumptions: 1) The wind profile was assumed constant with height; and 2) the wind profile was assumed to be varying with height according to the logarithmic wind profile given by (Panofsky and Dutton 1984).

\[
u = \frac{u_*}{k_a} \ln \left( \frac{z}{z_0} \right) \text{ m/s} \quad (2)
\]

where,
\(Z \geq z_0\)
\(z_0 = \text{roughness length. It is a measure of surface roughness.}
\(= 0.2 \text{ for pasture land (table 6.2 Panofsky and Dutton 1984)}
\(k_a = \text{Von Karman constant} = 0.4\)
The ratio of (2) applied at the two heights $z_2$ and $z_1$ is

$$\frac{u_2}{u_1} = \frac{\ln \frac{z_2}{z_0}}{\ln \frac{z_1}{z_0}}$$

where,

$z_1 = 2 \text{ m}$

$u_1 = \text{measured wind speed at 2 m}$

Evaluating the integral also requires having a relationship for the dust concentration as a function of height. The steady-state dust profile in the atmosphere occurs when the net upward movement of dust due to turbulent fluctuations in vertical velocity equals the net downward movement due to gravitational settling. Theory predicts that the dust concentration at steady state will decrease exponentially. Gillies (Watson, et al., 1996) provides a derivation.

Vertical dust profiles were measured at three different distances (3m, 10m, 30m) away from the source. DustTrak measurements were made at six different heights ranging from a height of 0.5m above ground level to 9m above ground level. The data at fixed heights were used to calculate the constants for an exponential dust profile at the three distances by the least squares fit of the log-transformed data to the equation parameters.

Different methods were used to evaluate the horizontal flux integral:
Analytical integration was used to evaluate the combination of an exponential dust profile with a constant wind speed.

$$Flux = \int_0^C z V_z dz$$  (4)

$$Flux = dm = \int_0^{C_0 e^k z} \int_0^V z V_z dz$$  (5)

The appeal of using an analytical expression for the profile is that the integral converges so it allows us to extrapolate above the highest measurement point.

An analytical solution does not exist for the integral when using a logarithmic wind profile from equation 3.

$$Flux = dm = \int_0^{C_0 e^k z} \int_0^V \frac{u_1}{k} \ln \frac{z}{z_0} dz$$  (5A)

However, the above equation can be solved numerically. Thus at a particular height interval $Dz$, the flux is given by:
\[
\left[\text{Flux}_n\right] = \frac{C(z) + C(z + 1)}{2} \left[ u(z) + u(z + 1) \right] \frac{z - (z + 1)}{2}\right) \quad (6)
\]

These terms are summed up over discrete intervals of height to get a total flux at a particular distance away from the source.

\[
\text{TotalFlux} = \sum_0^n \text{Flux} \quad (7)
\]

The disadvantage of this method is that the flux can be calculated only to a certain height above the ground level determined by the highest value for which data are available. There is an additional method that can be used in future experiments to calculate the horizontal flux leaving a road. In this method, the flux is calculated as a combination of a discrete sum in the height interval where discrete measurements are made, plus a converging integral for a residual term above the highest measurements.

\[
\sum_0^n \text{Flux} = \sum_0^n V_i C_i + \text{Residual Term} \quad (8)
\]

**PROBLEMS/ISSUES ENCOUNTERED**

The intended study of threshold wind velocity for dust entrainment was not completed as there was only one brief period of high winds while the sampling team was in the field. Likewise, some of the road dust studies were confounded by weak fluctuating winds at a time of year when strong wind from the West is the normal pattern.

**RESULTS**

The study produced new data for fugitive dust that is specific to U.S.-Mexican border conditions in Doña Ana County.

**Typical Data**

Figures 1 and 2 illustrate typical dust concentration versus time measurements. Note that for visual clarity, the data for each horizontal distance from the road has been offset by a constant and that the values for the farther stations have been multiplied by a factor of 10. The car trips are indicated by the triangle symbols. The numbers adjacent to each trend line are the x and z coordinates (downwind direction and height) of the DustTrak location. Figure 2 shows what was considered a good sampling period when favorable wind perpendicular to the road and well-spaced car trips allowed resolving the travel of the dust cloud from each vehicle pass.
Horizontal Variation in Dust Concentration
The concentration change in PM$_{10}$ at 2m above ground level with horizontal distance from the source was measured and found to decrease rapidly with downwind distance. The results, which are consistent with the work by Watson and Chow, showed an almost 90% decrease in the dust concentration within 100m of the source. An exponential curve was fit to the data. This is an empirical fit and the functional form was not based on prior theoretical analysis. The result is shown in Figure 3. In Figure 3, the solid line is the curve fit to the Doña Ana data and the dashed line is the curve calculated by Watson from California studies. The symbols indicate the measurements from three different days, March 13, 19, and 21 for the circle, diamond, and triangles respectively. The experiment for PM$_{10}$ was carried out at 1m above ground level.

The horizontal concentration profile was also determined for PM$_{2.5}$ at 1m and 2m above ground level, and the results were compared with each other in Figure 4. The heavy line shows the PM$_{10}$ concentration and the lighter lines are the PM$_{2.5}$ concentration. The PM$_{2.5}$ concentration was much lower than that of PM$_{2.5}$ but the data presented are normalized to the value at the closest measurement station to allow direct comparison. If the decrease were due to inertial deposition, one would expect a flatter profile for PM$_{2.5}$ compared to PM$_{10}$. The results indicated a steeper decay for PM$_{2.5}$, which suggests that the observed concentration decrease is principally due to dispersion of the dust cloud (dilution due to mixing with clean air).

Vertical Variation in Dust Concentration
The effect of vertical mixing of PM$_{10}$ was studied at 1m, 2m, 4m, 6m and 9m above ground level and at three different distances from the source—3m, 10m, and 30m—and the results were recorded. Figure 5 shows the scatter in the data and the exponential equations fit to the data at each location. The justification for assuming the exponential form for the vertical concentration is discussed above. Note that the exponential decay is much faster at 3m versus 30m and that the curves cross. The large scatter in the data is typical of outdoor measurements and reflects the effects of variation in the dust entrainment and wind transport with each car trip.

Horizontal Flux
The relative importance of redeposition and dilution in causing the observed decrease in concentration with horizontal distance can be evaluated by calculating the horizontal flux through planes at an increasing distance from the road. The horizontal flux was calculated from the vertical profile data at 3m, 10m, and 30m away from the source of dust. The road dust field measurements were made under unstable atmospheric conditions with strong vertical mixing. The vertical wind speed profile over the range of interest (1m to 10m) was not determined in the field. Two different methods were adopted to calculate the horizontal flux: 1) analytical integration assuming that the wind speed was constant with height, and 2) numerical integration assuming that the wind varied logarithmically with height. The logarithmic profile was estimated using published typical values for $z_o$ (Panofsky and Dutton 1984).
The calculations of horizontal flux are explained in detail in the Research Methodology section. The results are shown in Table 4. If the decrease is due to settling, the horizontal flux would decrease with distance from the source. But, the calculations show approximately a constant horizontal flux within the uncertainty of the measurements. This suggests that the decrease in concentration shown in Figures 3 and 4 is due to dispersion of the dust cloud and not due to particle deposition.

**Mass Concentration Measured by Collocated Instruments**

Collocated measurements from the three DustTraks, the OPC, and the NMED TEOM are shown in Figure 6. The TEOM is certified as an equivalent to the Federal Reference Method and TEOM results are used by air quality agencies for compliance reporting. Very good agreement was obtained considering that these instruments operated on different principles. The relative readings showed similar trends and the largest differences occurred during spikes in the ambient PM concentration. The absolute values of mass read by the DustTrak are a good approximation of the TEOM readings under Doña Ana conditions.

**Gravimetric Measurement**

Gravimetric measurement of PM$_{10}$ was made at the Jornada Road test site using PM$_{10}$ MiniVol samplers. Both polycarbonate filter paper and a Whatman filter paper were tested. The MiniVol ran for between five and six hours on both days. On the polycarbonate filter, a weight of 1.139mg of PM$_{10}$ for six hours of sampling at 5lpm, which gives a time-average mass concentration of 7.8µg/m$^3$. This is higher than would be expected from the DustTrak readings, which gave peak concentrations of 5mg/m$^3$ to 10mg/m$^3$ for 15 seconds at five-minute intervals. The Whatman filter paper gave inconclusive results since the tare weight was higher than the final weight. A minimum time needed to get a good sample weight on the MiniVol located 3m horizontal and 1m vertical from a road was found to be at least eight hours to 10 hours with the level of vehicle activity used in the Jornada Road experiments.

**Microscopy**

The passive collection samples for SEM were exposed to the dust clouds from one, two, four, and 20 car trips. The one and two car trips sample was so lightly loaded that nothing much could be seen on it. The 20 car trips sample was too heavily loaded and particles overlapped. We however did get some interesting SEM pictures from the four car trips sample. Both the pictures in Figures 7 and 8 belong to the same sample. The first (Figure 7) was taken at 300x magnification and the next (Figure 8) at 3000x magnification. The pictures suggest that the road dust particles are irregular, which is consistent with particles formed from crystalline minerals by mechanical processes. Some particles appear to be aggregates and not individual particles. The particle morphology is important information since most instruments and post-experiment calculations use the default assumption of individual spherical particles for conversion of particle size and number concentration into equivalent particle volume and mass.
**Silt Fraction**
The silt fraction (material less than 200 mesh) for the soil comprising the Jornada Road site was 10% of the original mass collected by sweeping.

**CONCLUSIONS**
This study provided site specific data for the U.S.-Mexican border region in Doña Ana County that can be compared to published studies conducted in other parts of the United States. The study of horizontal and vertical dust concentration downwind of an unpaved road in Doña Ana County shows a decrease in concentration similar to that measured by Watson, et al. in California. However, comparison of the PM$_{10}$ and PM$_{2.5}$ concentrations and calculation of the horizontal dust flux suggest that, for the particular atmospheric conditions of this experiment, the decrease was due to dispersion and not redeposition. The limited measurements made during the Spring 2001 field suggest that time of day and atmospheric stability are important factors in the partitioning of road dust between near-source deposition and long-range transport. Future experiments are planned to better evaluate this tentative conclusion.

The default calibration of the DustTrak was shown to agree with the time average PM$_{10}$ mass measurements of a TEOM for a specific springtime period in Doña Ana County. Further measurements are needed to generalize this conclusion and, as always, a site-specific calibration at the time of the measurements is needed if accurate absolute dust concentration values are needed.

No conclusions were reached on threshold wind speed for dust entrainment since weather conditions were unfavorable and very limited data was collected.

**Recommendations for Further Research**
Field experiments are time consuming, labor intensive, and dependent on the weather. Additional studies of this type will strengthen conclusions. The threshold wind velocity experiment needs to be reattempted until a good data set is collected under springtime high-wind conditions. Data on threshold velocity dust pickup for a range of sites in Doña Ana County will be valuable for air quality planning.

The road dust partitioning between redeposition and transport measurements need to be repeated with improved methods based on lessons learned from the initial field study.

**Simultaneous Horizontal and Vertical Sampling Preferred**
The plan for future studies is to sample the PM$_{10}$ concentration using a simultaneous horizontal and vertical grid. This provides more data, saves time, and allows two experiments to be conducted simultaneously. However, this requires more instruments than the three available in Doña Ana County.
Measuring the Vertical Wind Profile at Least Two Heights Above Ground Level

Having detained wind profile data on both the scale of 0m to 5m at the test site and the regional atmospheric wind profile are important for calculating the horizontal flux and for interpreting the data.

Other Recommendations

1. Structured sampling patterns with specified numbers of vehicle trips give the best results for data interpretation. Allowing more time between individual car trips will make it possible to better distinguish the dust clouds from each other. In addition, the concentration peaks at each sampling station can then be associated with a particular dust cloud. Sampling should continue until the visible dust cloud has passed the farthest station.

2. A much better synchronization of the various instrument and data recording clocks is necessary.

3. Do the experiment at different times of the day to get different atmospheric stability conditions. In the early morning, there is maximum atmospheric stability whereas in the late afternoons the atmosphere becomes highly unstable.

4. Try to do the experiments over different vegetations to find out how the vegetation affects the fugitive dust.

5. Do direct SEM measurements of dust depositions on horizontal and vertical surfaces.

Research Benefits

This study provided the New Mexico Department of Environmental Quality’s Division of Air Quality with local data on fugitive dust in the U.S.-Mexican border region that can be compared to published studies from other geographical areas. This will aid air quality planning and modeling efforts by providing site-specific experimental justification for various assumptions.

A poster presentation on this work was accepted for the fall 2002 American Association for Aerosol Research conference. A publication in a peer-reviewed journal is expected to result from this study.

This project has supported the research of one graduate student and has facilitated technical meetings of university faculty with state air quality staff in the planning and modeling groups.

Local capacity-building occurred through involvement in the research of faculty from Universidad Autónoma de Ciudad Juarez. Also, two engineering undergraduates from University of Texas at El Paso received practical hands-on experience in field air quality studies.

Acknowledgements

Drs. JoAnn Lighty, Henk Meuzelaar, Dean Lillquist, and Dale Stevenson of the University of Utah for the loan of equipment for the field study; Adel Sarofim for
technical consultation; Sriram Satya and James Campbell for help with electron microscopy; Dana Overacker, Ben Nelson, Mark Eddings, Brian Zufeld, and Dave Wagner of the University of Utah for help in equipment fabrication and setup; Dave Dubois and Brad Musick of the New Mexico Department of Environmental Quality for technical consultation and help in site selection and access; New Mexico State Land Office for permission to set up the test on their property; Dr. John Walton and students Brian Bain and Thomas Grijalva for help in conducting the field experiments; Dr. Wen-Whai Li of the University of Texas at El Paso for sample weighing; Dr. Adrian Vazquez of the Universidad Autónoma de Ciudad Juarez for technical consultation on Mexican-specific conditions.

REFERENCES
1990. Clean Air Act Section 109 (b)(1).


Figure 1. Typical Data, Unfavorable Conditions
Figure 2. Typical Data, Favorable Conditions
Figure 3. Comparison of Doña Ana and San Joaquin Valley Data

\[ y = 0.9403 \exp^{-0.0461x} \]
\[ R^2 = 0.89 \]

\[ y = \exp^{-0.0199x} \]
\[ R^2 = 0.41 \]
Table 1. Data to go with Figure 3

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<td></td>
<td></td>
<td></td>
<td>Avg of entire population</td>
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Figure 4. Comparison of PM$_{10}$ and PM$_{2.5}$ Horizontal Profile
Table 2. Data to go with Figure 4

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<tr>
<th>PM&lt;sub&gt;10&lt;/sub&gt;Horz @2m agl normalized by 3,2</th>
<th>Distance&gt;</th>
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<th>10</th>
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<th>100</th>
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<td>1.400</td>
<td>0.452</td>
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<th>Distance&gt;</th>
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<tbody>
<tr>
<td>2H213</td>
<td>Avg</td>
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<td>0.014</td>
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<td>Stdev</td>
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<td>0.121</td>
<td>0.045</td>
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<td>0.014</td>
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</table>

<table>
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<th>PM&lt;sub&gt;2.5&lt;/sub&gt;Horz normalized by 3,1</th>
<th>Distance&gt;</th>
<th>3</th>
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<th>100</th>
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<td>2H121</td>
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Note: The data plotted in Figure 4 are the absolute dust concentrations shown in this table normalized by the value at 3m, which is shown in bold for that row.
Figure 5. Vertical Dust Concentration Profile
Table 3. Data to go with Figure 5

<table>
<thead>
<tr>
<th></th>
<th>3m x h–agl (m)</th>
<th>1.000</th>
<th>1.000</th>
<th>2.000</th>
<th>Avg</th>
<th>1.211</th>
<th>0.813</th>
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<th>1.429</th>
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<th>Max</th>
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<th>0.004</th>
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<th>Count</th>
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<td></td>
<td>10m x h–agl (m)</td>
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<td>9.000</td>
<td>Avg</td>
<td>0.438</td>
<td>0.213</td>
<td>0.168</td>
<td>0.147</td>
<td>0.056</td>
<td>Max</td>
<td>3.535</td>
<td>2.145</td>
<td>2.926</td>
<td>1.608</td>
<td>1.008</td>
<td>0.014</td>
<td>0.004</td>
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<td>68</td>
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<tr>
<td></td>
<td>30m x h–agl (m)</td>
<td>1.000</td>
<td>2.000</td>
<td>4.000</td>
<td>6.000</td>
<td>9.000</td>
<td>Avg</td>
<td>0.237</td>
<td>0.305</td>
<td>0.154</td>
<td>0.097</td>
<td>0.082</td>
<td>Max</td>
<td>1.878</td>
<td>1.672</td>
<td>0.734</td>
<td>0.807</td>
<td>0.511</td>
<td>Min</td>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.001</td>
</tr>
</tbody>
</table>
Figure 6. Collocated PM Instruments
Figure 7. 300X SEM Image of Road Dust
Figure 8. 3000X SEM Image of Road Dust
Table 4. Horizontal Flux Values

<table>
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<th>Distance away from the source (m): -</th>
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<th>30</th>
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</thead>
<tbody>
<tr>
<td>Numerical (varying wind) analysis (mg/m³)</td>
<td>7.133</td>
<td>6.747</td>
<td>7.272</td>
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<tr>
<td>Normalized by 3m</td>
<td>1.000</td>
<td>0.946</td>
<td>1.019</td>
</tr>
<tr>
<td>Analytical (constant wind) analysis (mg/m³)</td>
<td>2.911</td>
<td>1.994</td>
<td>1.942</td>
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<tr>
<td>Normalized by 3m</td>
<td>1.000</td>
<td>0.685</td>
<td>0.667</td>
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</table>
SAMPLE CALCULATION:

1) Numerical integration: A varying wind profile is assumed. In this case, i.e. we take into account that the wind is varying with height. Since we had measured the wind only at 2 m agl, we used equation (4.3) to find the wind speed at various heights.

At 3.3 (3 m away from source and at 3 m agl):
C(z) = 1.4713e^{-0.5055z} (got from figure 5.5 for 3 m x)
=> C(3) = 1.4713e^{-0.5055\cdot3} = 0.323

\( z_0 = 0.2 \) for pasture land (refer chapter 4)
\( z_1 = 2 \) m
\( u_1 = 3 \) m/s

=> \[ u(3) = 3 \ln \left( \frac{3}{0.2} \right) \ln \left( \frac{3}{0.2} \right) = 3.53 \text{ m/s} \]

=> \[ \frac{C(3) + C(2)}{2} \frac{u(3) + u(2)}{2} (3 - 2) = 1.4 \]

2) Analytical Integration: Here we have assumed a constant wind profile and integrated the concentration over the entire height.

At 3 m x;

\[ \text{Flux} = \int_0^3 C(z)dz \]

\[ = \frac{1.4713}{0.5055} = 2.91 \]