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Mapping of Airborne Particulate Matter Collected Using Two Sensors along US-Mexico Border

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Abstract

Particulate matter (PM) emissions from various sources can have significant effect on human health and environmental quality especially in the Chihuahuan Desert region along US-Mexico border. The objective of the study was to determine the effect of road dust texture and vehicular speed on airborne PM concentrations from different unpaved rural roads using two sampling techniques (DustTrak^R, and Sticky-tape). The surface soil textures of unpaved roads varied from silty clay to loam with less than 4% soil moisture content at the time of PM measurement. Sticky tape method in seven experiment sites showed that PM ranged from 0.529 to 3.054 mg m^{-3}, and DustTrak^R measurements showed that $PM_{2.5}$ concentration ranged from 1.11 to 37.1 mg m-3 at 1 m height. An exponential relationship was obtained between $PM_{2.5}$ by DustTrak^R and vehicle speeds with an average slope of -1.619 mg m^{-3}s^{-1}. The concentration of PM measured with the Sticky-tape decreased with increasing height of measurement. Both PM measurement techniques provided a good approximation of PM emissions at different vehicles speeds, unpaved roads and position of the instrument above ground level for a variety of unpaved roads. The low cost sticky tape method has the potential to further determine and abiotic (elemental composition) and biotic (fungus) particles in airborne PM.

Keywords: PM concentration; Unpaved roads; Vehicle speed; Dust-texture; $PM_{2.5}$

Introduction

Dispersion of particulate matter (PM) in the air is common in the Chihuahuan Desert region [1] classified as arid with low precipitation. The arid areas receive annual rainfall between 100 and 300 mm, but the precipitation is highly variable. The arid index, a ratio of precipitation and potential evapotranspiration, ranges from 0.03 to 0.20, according to the FAO conservation guide [2]. The low soil water content exacerbates dust emissions into the atmosphere, which could have an influence on human health, road safety, and soil conservation [3,4]. In the Chihuahuan Desert region, dust storms occur several times annually, mainly between February and April. Wind speeds can measure up to 80 km.h^{-1} for a few hours on a given day, and airborne PM can decrease visibility. Additionally, vehicular traffic on the unpaved roads and field operations on agricultural farms are reported to disperse large amounts of PM emissions into the air [5]. Low visibility during dust storms has been reported as the cause of some traffic accidents, while dust storms themselves are associated with soil erosion and are cited as the source of certain construction damage. Blowing dust from high winds is also reported to promote respiratory illness [6].

During a wind storm, organic and inorganic particles are ejected into the air. Particulates are also emitted into the air from the pulverization action of vehicles running on unpaved roads or from agricultural operations in a field. Commonly, unpaved roads are formed from soil material present at or near the road site and made of a graded and compacted roadbed [7]. On an unpaved road, dust dispersion starts with the force ejected by the rolling wheels of a vehicle. Fine soil particles get dislodged and become airborne. Additionally, turbulent vehicle wakes cause soil particles to be ejected into the atmosphere [8]. The vehicle size and speed have a strong influence on the magnitude of emissions from road surfaces. Other studies have reported that dust emission rates from unpaved roads are a function of the silt loadings or size distribution of particles [7,9,10], vehicle speed [5,3], size and weight of the vehicle [7], and moisture content of the road dust [9]. Dry conditions on unpaved roads in arid regions allow fine particles to become suspended in the air easily, even at low wind speeds, creating dust plumes. Dust emissions from dry, unpaved roads have been reported to be a direct function of particles <70 µm [11,10]. The potential for PM_{10} emissions of air-dried soils decreases with increasing sand content or increases with increasing silt and clay content [12,13]. For these reasons, surface soil properties, soil water content, weather conditions, and vehicle speeds are critical factors in explaining dust emissions from unpaved roads. In spite of all these research efforts, only limited amount of data are available on airborne PM.

PM measurement can be obtained using various devices including MET and DustTrack sensors. These sensors can provide continuous temporal estimation of PM emissions, but they also require a continuous power supply. Both are expensive and cannot be left in the field unattended. The number of units that can be installed in any given location is also severely restricted due to the high cost of these sensors. A low-cost sticky tape technique with rotorods is also available to measure PM concentrations [5]. The advantage of this technique is that it can be used to determine PM concentrations at different times and heights above the ground. A large number of devices can be installed in any given area to quantify the integrated airborne PM concentrations for given time intervals. The sticky tapes also can be used for determining the size of particles, elemental and morphological compositions, and organic and biological components of the particulate matter. For obtaining temporal data on PM concentration, sticky tapes must be replaced more frequently. There is an urgent need to quantify

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concentrations of airborne PM from different sources and to develop cheaper techniques of measurement.

The objectives of this study were to measure concentrations of airborne PM at field scale from several unpaved roads using two real-time point sampling techniques, DustTrak® and a low cost sticky-tape, for different vehicle speeds and at different heights above the ground in the Chihuahuan Desert region along the US-Mexico border. The second objective was to compare the techniques with respect to the PM concentrations under different vehicle speeds, heights, and locations in the Chihuahuan Desert. A prior knowledge of expected airborne PM concentration can help people plan their outdoor activities and travel, and take adequate precautions before leaving the house.

Materials and Methods

Experimental sites

Experiments were conducted from July to October 2011 in the state of Texas and New Mexico in the USA and state of Chihuahua in the Mexico along the USA-Mexico border. Four of the experimental locations, Anthony, Mesilla, Deming and Columbus, were in the USA, and three, Bolson, La Teja and Palomas were in the Mexico (Figure 1; Table 1). Unpaved roads selected for the study did not contain gravel or crushed rocks, which is typically added to well-constructed roads.

Measurement techniques

A low cost sticky-tape device [5], and the DustTrak® were used to simultaneously measure PM emissions due to vehicular traffic at each experimental site (Figure 2). The low cost sticky tape method consisted of two rotorods installed on a steel tower 1-inch in diameter. One of the rotorods was placed at 1 m and another at 2 m height above the ground surface. Each rotorod had two wings, and on each wing a transparent microscope glass slide and a double-sided sticky tape were attached.

Before the start of the experiments, each glass slide with and without the double sided sticky tape was weighed using an analytical balance with the precision of four decimal points. The glass slides were stored in a box for microscope glass to avoid dust contamination before their use for dust monitoring. To measure dust emissions, a rotorod attached to a 9 volt battery was installed on the tower. An already labeled glass slide with sticky tape was placed at each wing of the rotorod. Before turning on the rotorod, the adhesive tape was carefully peeled off and stored in a clean plastic zip lock bag for weighing. After 15 minutes, the rotorods were turned off; glass slides were removed carefully from the rotorod without touching the sticky tape area, each slide was weighed using the

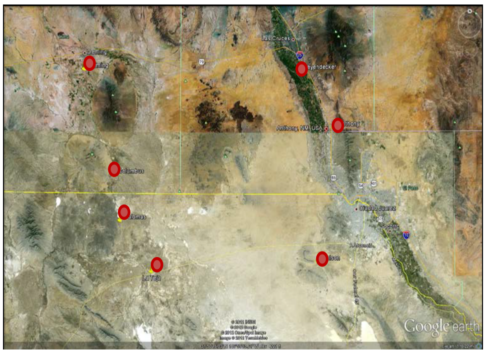

Figure 1: Experimental sites in the US (Anthony, Leyendecker (Mesilla), Deming, and Columbus, NM, and in Chihuahua, Mexico (Bolson, La Teja, and Palomas).

Country	Site	Latitude	Longitude	Elevation M
Mexico	Bolson	31o 32'15”	106o 39'01”	1249
Mexico	La Teja	31o29'53”	107o26'19”	1195
Mexico	Palomas	31o40'30”	107o 35'21”	1215
USA	Anthony	32o17'00”	106o45'24”	1307
USA	Columbus	31o50'01”	107o 37'11”	1275
USA	Deming	32o11' 59”	107o45'46”	1309
USA	Leyendecker	32o11' 59”	106o44' 14”	1175

Table 1: Geographic locations of experimental sites in the Mexico and the US.

precision analytical balance in the lab, and stored inside a box. The rpm of each rotorod was recorded with a tachometer at the beginning and at the end of the experiment. The volume of air sampled was calculated as follows:

$$TVA = \pi \times D \times L \times W \times RPM \times 2$$

Where total volume of air sampled (TVA) was the product of rpm of rotorods (RPM), circumference of the sampling area (π*D), and length (L), and width (W) of the sticky tape (2 tapes per rotorod) as indicated in the equation [14]. PM concentrations were calculated as the ratio of the known weight of PM on the sticky tape and the total volume of air sampled (TVA).

A DustTrak® instrument (Model 8535, TSI Inc., Shore view, MN) with optical particle sampler was used to determine $PM_{2.5}$ concentration in real time (Figure 2). At each experimental site, a 100 m stretch of straight unpaved road was selected for the running vehicle, which traveled at speeds of 32, 48, and 64 $km.h^{-1}$. Instruments were installed on one side of the road, the prevailing downwind side (Figure 2). Dust emissions were created by the vehicle traveling back and forth on the unpaved road for 10 passes during 15 minutes. Vehicles used were a Ford F-150 truck, 4-W drive, weighing approximately 2300 kg at the US sites, and a Chevy Silverado4-W truck weighing approximately 2100 kg at the Mexican sites.

Meteorological data

A porTable weather station (Davis instruments, model Vantage pro) was installed close to the experimental sites to record air temperature, relative humidity, wind speed, and wind direction for every one-minute interval. As shown in Figure 3, air temperature and relative humidity were relatively stable, but wind speed varied in short spans of time with a maximum of 15 $km.h^{-1}$ during some experiments.

Soil sampling and analysis

Composite soil samples were collected from the upper 3 cm layer of the soil on unpaved roads at each site. Soil samples were air-dried and passed through a 2 mm sieve. Analysis of soil consisted of determining particle size distribution using a hydrometer method [15]. Soil moisture was calculated as the ratio of the difference in in-situ weight and the weight after drying of the soil at 105oC in an oven and the dry soil weight. Soil pH was measured by a Pinchable Corning-340pH meter, and electrical conductivity (EC) was determined using an Orion 3 Star conductivity meter. Analyses of pH and EC were carried out from the soil saturation paste extracts [16].

Statistical analysis

Two-way analysis of variance (ANOVA) was conducted on the concentration of $PM_{2.5}$ detected with the DustTrak® device and on the mass of PM on the sticky tape technique. The analysis examined the effects of experiment site, vehicle speed, and height on dust emission. DustTrak readings for 10 passes of the vehicle at 1, 5, 10, 15, 20, 25,

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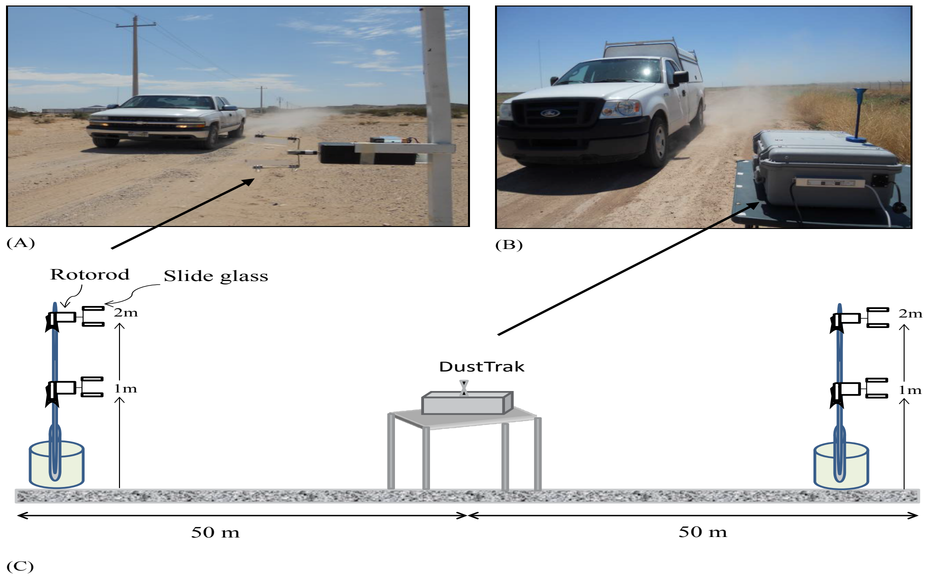

Figure 2: Rotorod with two glass slides taped on a tower at 1m height at Bolson, Mexico (A), the DustTrakR instrument on a table at 1 m height during the experiment at Columbus, NM, (B), and schematic diagram of the two towers with.

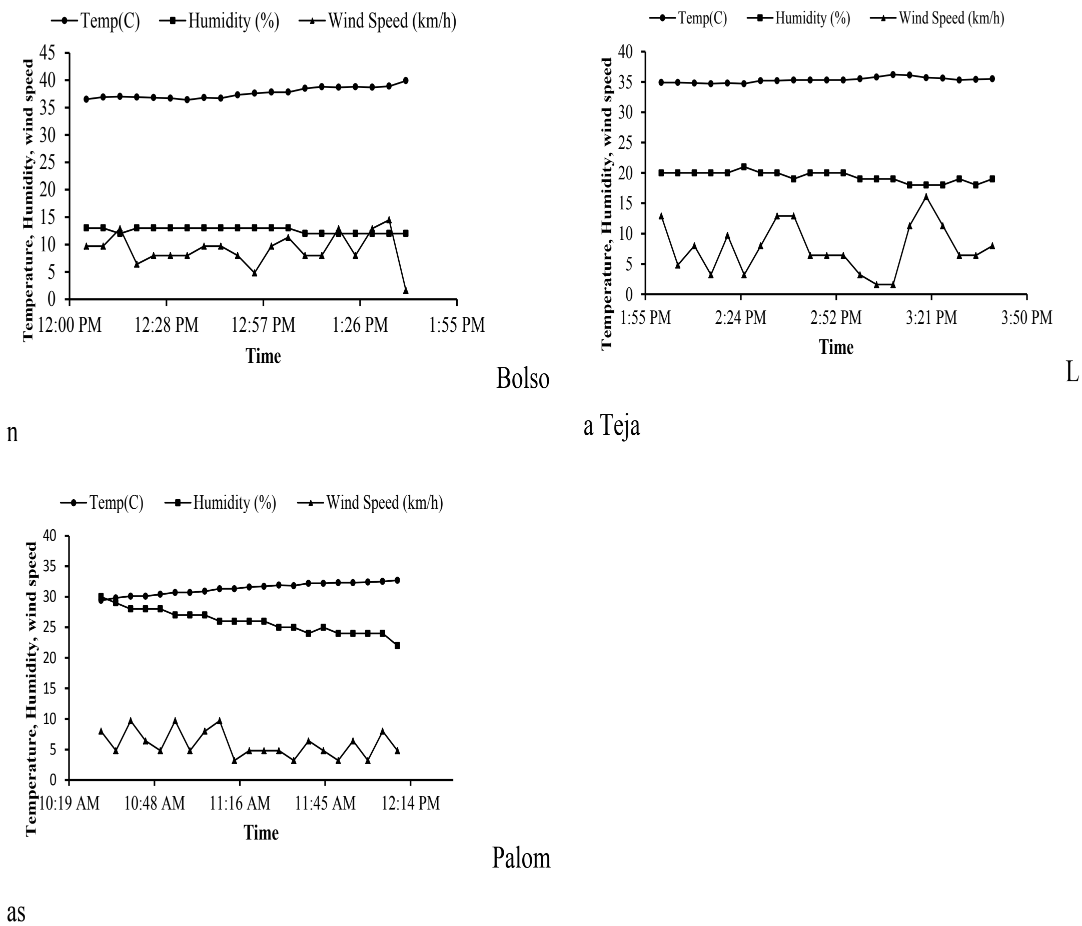

Figure 3: Average temperature, relative humidity, and wind speed during the experiments at Bolson, La Teja, and Palomas, Mexico.

and 30 seconds after the vehicle passed the instrument were also used. The data for one (1) second represents the peak concentration detected by the DustTrak®. The vehicle speeds at each experimental site were plotted as a function of $PM_{2.5}$ concentration and the best fit regression function was obtained for each speed and location, separately. The experimental design was treated as a randomized design with 10 replications, nested effects (speed×height inside site) and multiple pairwise comparisons were made using a Least Significant Difference (LSD) test at a probability level (α) of 0.05 with the statistical package SPSS version 19.0.

Results

Soil properties

The soil texture for these sites varied from sandy loam to loam. Table 2 shows that differences in the soil texture were greater for unpaved roads at the Mexican sites than at the US sites. The analysis of variance showed significant differences in particle size distribution of soil collected from unpaved roads ($p<0.01$). The highest percentages of sand were found at the Bolson and Anthony sites where roads were gravelly. These locations were in accord with the dominance of creosote bush (*Larreatridentata L.*) common to the Chihuahuan desert. In contrast, La Teja site had the lowest sand content, which could be explained by the accumulation of fine particles due to the wind erosion from desert areas (Table 2). For La Teja site, soil texture, according to the USDA classification, was silty clay. At the remaining sites, particle size distributions were nearly evenly distributed between coarse (sand) and fine (silt+clay) particles.

Moisture content of soils on the unpaved roads was always less than 4%, in accord with typically low precipitation in the area. For soils with higher amounts of clay and silt particles, soil moisture content was slightly higher than coarse textured soils. The dry soil was prone to become airborne due to wind and the vehicular traffic at each of the unpaved road.

Soil pH was about 7.5 for sites in Mexico and about 8.7 for sites in the US (Table 3). The electrical conductivity of (EC) soil ranged from 0.16 to 2.2 dS/m for 3 cm soil depth. The desert soils have typically high natural alkalinity and soil salinity varies with mineralogy, land use near the unpaved sites, and quality of wind deposited material.

Particulate matter recorded by DustTrak

The PM concentration was recorded by DustTrack once every two seconds and was averaged over 1 minute. Each peak of $PM_{2.5}$ concentration shown in Figure 4 corresponds to a time when the vehicle passed in front of the DustTrak, which was recording PM concentration in real-time. The maximum $PM_{2.5}$ concentrations for each vehicle speed and site are presented in Table 4. Except for the Deming site (readings of 32 and 48 $km.h^{-1}$ vehicle speed), the $PM_{2.5}$ concentration increased with increasing vehicle speed. The increase in $PM_{2.5}$ concentrations between 32 and 48 $km.h^{-1}$ and between 48 and 64 $km.h^{-1}$ vehicle speeds were similar for Bolson, La Teja, and Leyendecker sites and, on average, increases in $PM_{2.5}$ concentrations were 4.8, 6.2, and 0.53 $mg.m^{-3}$ for these sites, respectively.

The Palomas site produced the highest $PM_{2.5}$ concentration, and Leyendecker produced the least for all three vehicle speeds. At the Palomas site, maximum PM concentration increased by 1.2 when vehicle speed changed from 32 to 48 $km.h^{-1}$, and by 13.2 $mg.m^{-3}$ when speed increased from 48 to 64 $km.h^{-1}$. The Anthony and Columbus sites showed the lowest changes in maximum $PM_{2.5}$ concentration of 0.5 to 2.66, and 0.51 to 3.15 mg m-3 when speed increased from 32 to 48 and from 48 to 64 $km.h^{-1}$, respectively (Table 4).

The average $PM_{2.5}$ concentrations are presented in Figure 5 for the Leyendecker site, as an example. The first peak in Figure 5 was denoted as T1 because it was the peak concentration after the vehicle passed in front of the DustTrak. Subsequent times were selected as T5, T10, T15, T20, T25, and T30 to indicate times 5, 10, 15, 20, 25, and 30 seconds after the peak concentration. The $PM_{2.5}$ concentrations and time elapsed displayed an inverse relationship and were best represented by a power function for all three vehicle speeds, separately (Table 5). The slope of the concentration time curve varied from 0.94 to 1.04 for the three vehicle speeds with coefficient of determinations above 0.87.

Country	Site	pH	EC dS/m
Mexico	Bolson	7.63 ± 0.56†	0.6 ± 0.099†
Mexico	La Teja	7.51 ± 0.04	2.244 ± 0.061
Mexico	Palomas	7.71 ± 0.01	1.166 ± 0.014
USA	Anthony	8.97 ± 0.03	0.167 ± 0.011
USA	Columbus	9.36 ± 0.17	0.647 ± 0.122
USA	Deming	8.71 ± 0.06	0.387 ± 0.07
USA	Leyendecker	8.26 ± 0.18	1.137 ± 0.416

†Average and standard deviation; EC = electrical conductivity

Table 3: Soil alkalinity and soil salinity at experiment sites.

Country	Site	-------------- PM2.5 (mg m-3) ----------------		
		32 $km\ h^{-1}$	48km h^{-1}	64km h^{-1}
Mexico	Bolson1	8.40z	12.4	18.0
Mexico	La Teja2	5.37	12.4	17.8
Mexico	Palomas3	22.7	23.9	37.1
USA	Anthony4	1.87	2.37	5.03
USA	Columbus5	3.05	3.56	6.71
USA	Deming6	13.9	13.1	23.3
USA	Leyendecker7	1.11	1.66	2.17

[z]n=300, difference between vehicle speeds: [1](e.g., 12.4-8.4 = 4; 4, 5.6); [2](7.03, 5.4); [3](1.2, 13.2), [4](0.5, 2.66); [5](0.51, 3.15), [6](-0.8,10.2), and [7](0.55, 0.51)

Table 4: Maximum concentrations of PM2.5 detected by the DustTrak for different vehicle speeds at seven experiment sites in the US and Mexico.

Country	Experiment site	Soil Particle Size			Soil Moisture	Soil Texture
		Clay	Silt	Sand		
		- - - - - - - - - - - - - - - - - - - -	%	- - - - - - - - - - - - - - - -		
Mexico	Bolson	3.60 ± 0.01	5.44 ± 2.0	90.96 ± 2.0	0.59 ± 0.003	Sandy
Mexico	La Teja	49.89 ± 1.15	41.81 ± 1.98	8.29 ± 3.14	3.62 ± 0.32	Silty clay
Mexico	Palomas	23.89 ± 3.85	16.72 ± 4.1	59.38 ± 1.41	1.87 ± 0.17	Sandy clay loam
USA	Anthony	1.39 ± 1.81	2.85 ± 2.13	95.95 ± 1.15	0.22 ± 0.08	Sandy
USA	Columbus	17.20 ± 5.17	31.95 ± 8.71	50.85 ± 11.37	1.55 ± 0.25	Loam
USA	Deming	14.02 ± 9.72	36.25 ± 2.61	49.73 ± 11.38	2.07 ± 0.32	Loam
USA	Leyendecker	16.94 ± 7.15	21.93 ± 10.48	61.12 ± 10.18	0.47 ± 0.001	Sandy loam

Table 2: Soil particle size distribution and soil moisture for each experimental site.

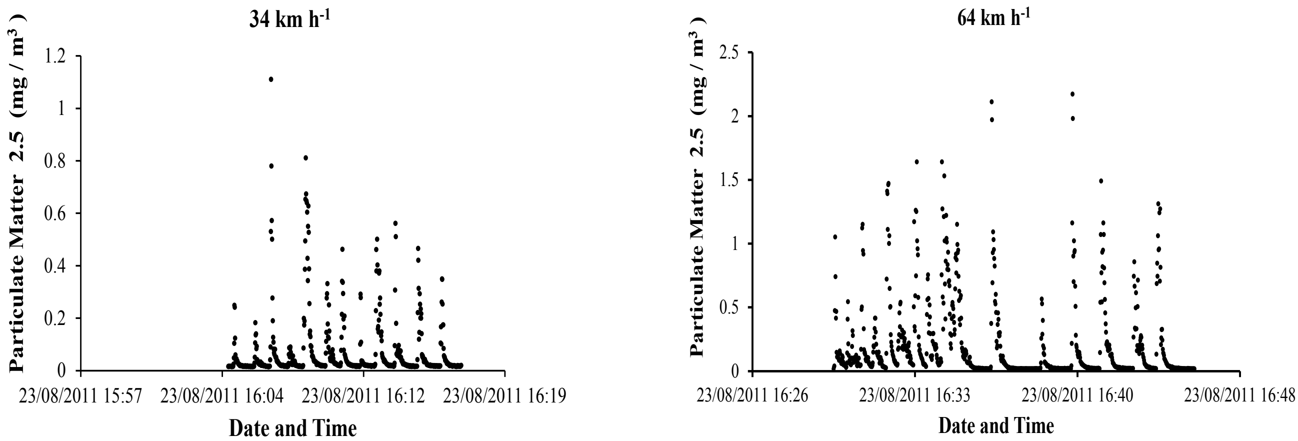

Figure 4: PM $_{2.5}$ concentrations in the DustTrak after 15 minutes for vehicle speeds of 34 and 64 km/h at Leyendecker, NM.

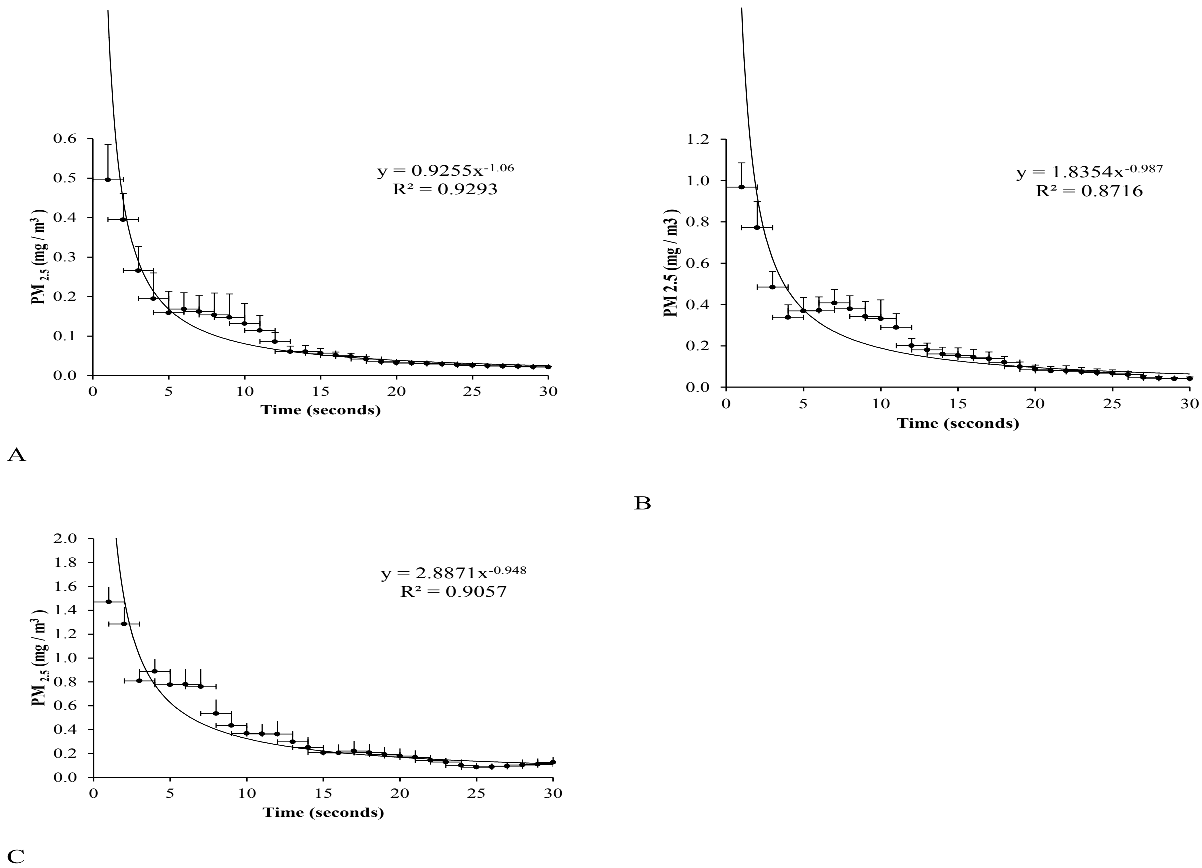

Figure 5: Average trend of PM2.5 from the highest emission detected after the vehicle passed the DustTrak during 10 vehicle passes at 32 (a), 48 (b), and 64 (c) km h^{-1} at Leyendecker, NM.

The highest intercept values were observed for Palomas site, which agreed with the large values of $PM_{2.5}$ concentrations presented in Table 4. The $PM_{2.5}$ concentrations followed a decreasing order of Palomas>La Teja>Deming>Bolson>Anthony>Columbus>Leyendecker (Table 5). Average slope of the concentration time curves was -1.619 ± 92 mg $PM_{2.5}$ $m^{-3}s^{-1}$ for the best fit power model, and average R^2 was 0.927 ± 0.065, excluding the Bolson site. The slope value indicated that $PM_{2.5}$ particles are moving in the downwind direction after the vehicle passed in front of the DustTrak.

The ANOVA for site, speed, and "speed (site)" as main effects showed significant differences for $PM_{2.5}$ concentrations (p<0.001) detected

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by the DustTrak device for sites at different times and for total $PM_{2.5}$ concentration (Table 6). For vehicle speeds, significant differences were detected only for times T1 and T5 and the total $PM_{2.5}$ concentration, while speed (site) showed a significant effect for T1 only. The coefficient of variation for $PM_{2.5}$ concentrations increased with increasing time. This might be expected because particle size distributions can change rapidly with time. Coarser particles tend to fall back more quickly than finer particles. Also experimental sites showed different particle size distributions.

The LSD test showed that, on an average, $PM_{2.5}$ concentrations recorded by the DustTrak for all times, including the total, were highest from the Palomas site followed by La Teja, and Deming during the first 5 seconds after the vehicle passed in front of the instrument (Table 7), although La Teja unpaved road contained higher amounts of clay and silt particles than roads at the Palomas and Deming sites. It seems the high moisture content of soil on La Teja unpaved road could have inhibited PM emission in spite of the high silt and clay contents. The $PM_{2.5}$ concentrations from T10 to T30 were not significantly different for rest of the experimental sites (Table 6).

Country	Site	Vehicle Speed (km h)	Equation[z]	R^2
Mexico	Bolson	32	$y = 448.34x^{-2.785}$	0.9093
Mexico	Bolson	48	$y = 102.63x^{-1.76}$	0.9358
Mexico	Bolson	64	$y = 3538.3x^{-3.459}$	0.9417
Mexico	La Teja	32	$y = 130.2x^{-1.892}$	0.7086
Mexico	La Teja	48	$y = 127.19x^{-1.796}$	0.8909
Mexico	La Teja	64	$y = 1406.7x^{-2.723}$	0.9304
Mexico	Palomas	32	$y = 8E+06x^{-4.425}$	0.9767
Mexico	Palomas	48	$y = 36667x^{-2.701}$	0.8236
Mexico	Palomas	64	$y = 7E+06x^{-0.4042}$	0.9738
USA	Anthony	32	$y = 1.0644x^{-0.847}$	0.9568
USA	Anthony	48	$y = 2.0482x^{-0.951}$	0.9544
USA	Anthony	64	$y = 4.7164x^{-1.219}$	0.9778
USA	Columbus	32	$y = 0.864x^{-1.137}$	0.9464
USA	Columbus	48	$y = 1.0093x^{-1.139}$	0.9678
USA	Columbus	64	$y = 1.7845x^{-1.249}$	0.9605
USA	Deming	32	$y = 10.495x^{-1.303}$	0.9500
USA	Deming	48	$y = 21.506x^{-1.512}$	0.9106
USA	Deming	64	$y = 24.672x^{-1.629}$	0.9725
USA	Leyendecker	32	$y = 0.9255x^{-1.06}$	0.9293
USA	Leyendecker	48	$y = 1.8354x^{-0.987}$	0.8716
USA	Leyendecker	64	$y = 2.8871x^{-0.948}$	0.9057

[z]y = mg $PM_{2.5}$ /m^3, and x = time (seconds)

Table 5: The best fit power functions for the observed $PM_{2.5}$ concentrations and times at each of three vehicle speeds for the seven experimental sites.

ANOVA for vehicle speed at different experimental sites, separately, showed that $PM_{2.5}$ concentrations during T1 were significantly higher at 64 km.h^{-1} vehicle speed than at the speeds of 32 and 48 km.h^{-1} (Table 8). Similar results were also observed for the total $PM_{2.5}$ concentrations. On an average, when vehicle speed increased from 32 to 48 km.h and from 48 to 64 km.h^{-1}, the concentration of $PM_{2.5}$ for T1 increased by 0.76 and 1.42 mg.m^{-3}, respectively, for sandy soils of the Anthony and Bolson sites (Figure 6a). Thus, $PM_{2.5}$ emission increased by 0.7 mg.m^{-3} for each 16 km.h^{-1} increase in vehicle speed for soils with 93% (average) sand content in the unpaved roads with soil moisture less than 4%. A relationship between particle size and PM concentration showed that the $PM_{2.5}$ concentration increased as sand content of the soil decreased. When vehicle speed increased from 32 to 48 and 48 to 64 km.h^{-1}, the average $PM_{2.5}$ concentration was 1.65, and 4.07 mg.m^{-3}, respectively (Figure 6a), for soils with less than 60% sand and soil texture ranging from sandy clay loam to silty clay (Palomas, Columbus, Deming, and La Teja).

Average $PM_{2.5}$ concentration for the combination of site and speed, analyzed as the nested effect of speed, are shown in Figure 6a-6c for T1, T5, and the total. Clearly, the Palomas site had the highest $PM_{2.5}$ concentration, and demonstrated how $PM_{2.5}$ emission increased with vehicle speed at most of the experiment sites (Figure 6).

Particulate matter recorded by sticky tapes

The PM collected on the sticky tapes included not only the $PM_{2.5}$ particles but other larger particles. Figure 7 presents the electron microscope images of the PM collected on sticky tapes and shows

Source of Variation	d.f.	T1	T5	T10	T15	T20	T25	T30	Sum
Site	6	0.0001**z	0.0001**	0.0001**	0.0001**	0.0001**	0.0001**	0.5349	0.0001**
Speed	2	0.0001**	0.0010**	0.1301	0.4990	0.5505	0.3388	0.3006	0.0001**
Speed (site)	12	0.0040**	0.1562	0.2658	0.5586	0.6980	0.3507	0.3678	0.1486
C.V. (%)		56.4	113.8	198.4	266.1	354.32	410.8	678.1	84.8
Mean (mg/m^3)		5.864	3.417	1.294	0.643	0.433	0.271	0.08	11.96

[z]Observed level of significance (Pr > F: **) at 0.01 is considered highly significant effect, C.V.=coefficient of variation . d.f.=degree of freedom, T1 to T30 are times readings at 1 to 30 sec

Table 6: Analysis of variance for the $PM_{2.5}$ detected by the DustTrak instrument at different time intervals when a vehicle was running at three speeds at several sites in Mexico and US.

Variable	Experiment Site						
	Leyendecker	Columbus	Deming	Anthony	Bolson	La Teja	Palomas
$PM_{2.5}$ T1	0.978d[z]	2.195d	8.329b	1.768d	5.584c	7.617b	15.615a
$PM_{2.5}$ T5	0.435de	0.124e	2.373cd	0.506de	4.499b	4.27bc	12.189a
$PM_{2.5}$ T10	0.277b	0.073b	0.848b	0.250b	1.041b	0.744b	6.063a
$PM_{2.5}$ T15	0.139b	0.047b	0.346b	0.154b	0.269b	0.459b	3.215a
$PM_{2.5}$ T20	0.099b	0.033b	0.201b	0.103b	0.125b	0.549b	1.998a
$PM_{2.5}$ T25	0.059b	0.026b	0.123b	0.074b	0.124b	0.275b	1.265a
$PM_{2.5}$ T30	0.063a	0.023a	0.085a	0.069a	0.058a	0.264a	0.00 a
$PM_{2.5}$ Total	2.052 c	2.522c	12.31b	1.925c	11.7 b	13.86b	40.34a

[z]Means with the same letter are not significantly different (LSD mean) at the 0.05 level of significance

Table 7: Average particulate matter ($PM_{2.5}$) (mg/m3) detected by the DustTrak at 1 to 30 seconds after 10 passes of the vehicle in front of the instrument.

Citation: Flores-Márgez JP, Shukla MK, Deb S (2014) Mapping of Airborne Particulate Matter Collected Using Two Sensors along US-Mexico Border. J Environ Anal Toxicol 4: 206. doi: 10.4172/2161-0525.1000206

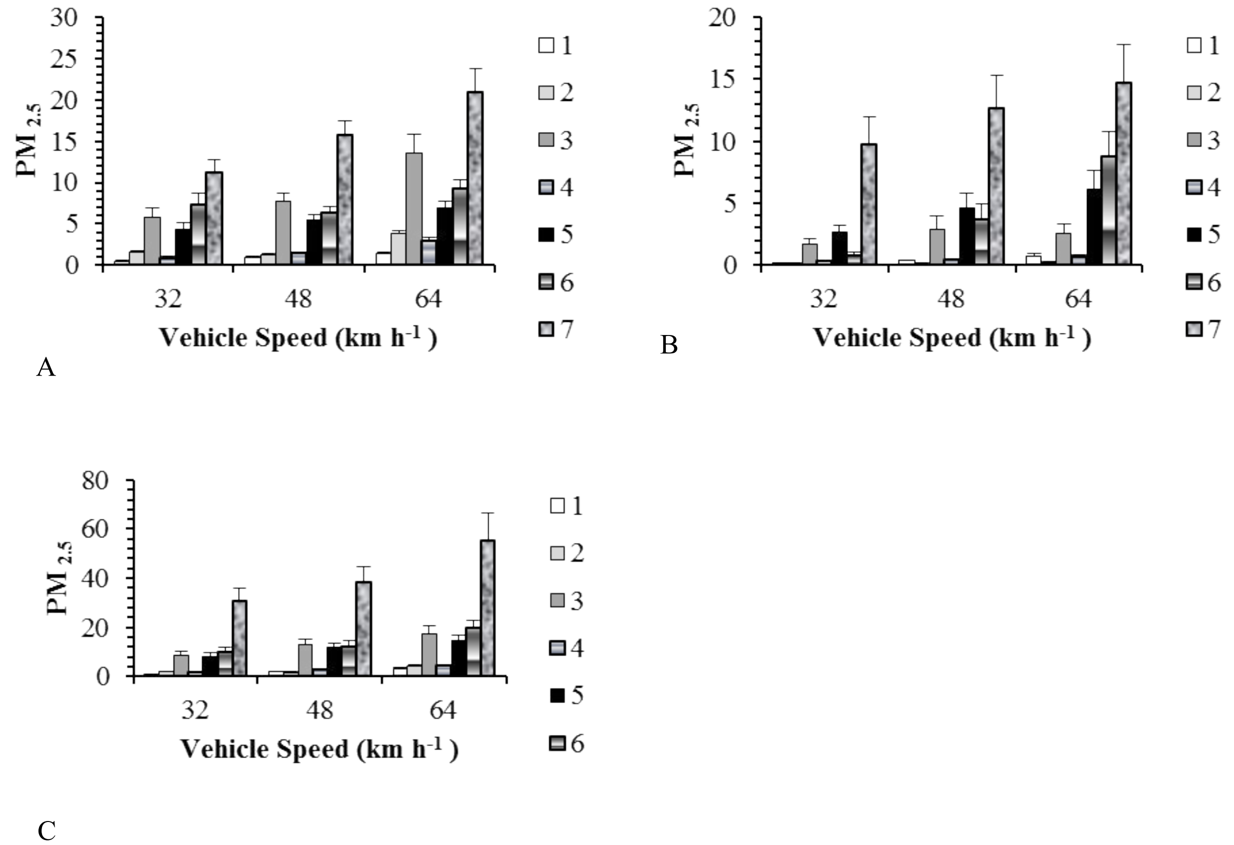

Figure 6: Average instantaneous particulate matter ($PM_{2.5}$; mg/m^3) detected by the DustTrak^R instrument at the first second-T1 (a), five seconds-T5 (b), and the sum of seven readings (c) as a function of vehicle speed for experiment sites in Mexico and the US. Small bars represent standard error. 1=Leyendecker, 2=Columbus, 3=Deming, 4=Anthony, 5=Bolson, 6=La Teja, 7=Palomas.

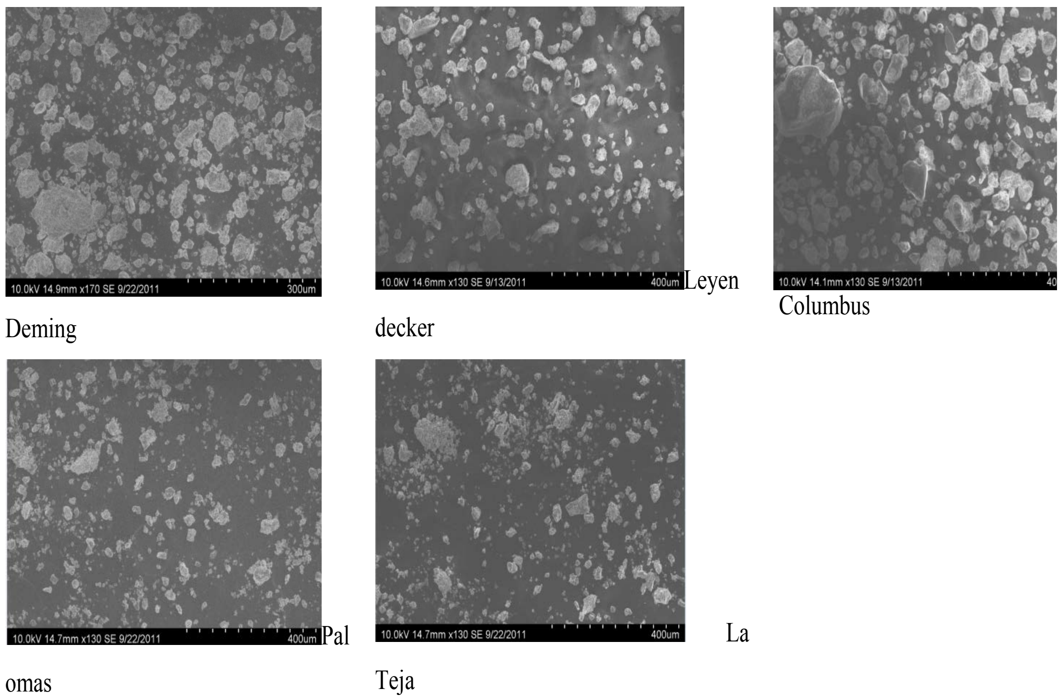

Figure 7: Raw image generated by the electron microscope showing the dust particles on the sticky tapes.

larger amounts of PM on sticky tapes from Deming, Leyendecker, and Columbus sites than at the Palomas and La Teja sites. This occurs as larger size particles are retained on sticky tapes from the former sites than at the last two sites. Such variation is consistent with the particle size distribution for these sites. The statistical analysis of total PM retained on sticky tapes showed significant differences ($p<0.001$) between sites, vehicle speed, height, and the speed×height interaction in site as nested effect ($p<0.01$) (Tables 9 and 10).

On an average, the highest PM concentration on the sticky tapes was obtained from the Anthony site and the lowest from La Teja (Table 10). On an average, PM on sticky tapes also decreased with increasing sand, plus silt content, of soil (Figure 8) and produced a polynomial relationship with coefficient of determination of 0.82. This trend was clearer with $PM_{2.5}$ concentration detected with the DustTrak instrument. The emission of PM_{10} is reported to decrease with increasing sand content or decreasing silt and clay content by others also [12,13].

As vehicle speed increased, the amount of dust retained on sticky tapes also increased for all sites in the US (Table 11). Two of the three sites in Mexico also showed a similar trend (Figure 9) while others did not maily due to the changing wind direction during the experiments. On an average, PM concentration on sticky tapes increased by 0.49 $mg.m^{-3}$ when vehicle speed increased from 32 to 48 $km.h^{-1}$ and by 0.80 $mg.m^{-3}$ when speed increased from 48 to 64 $km.h^{-1}$. The PM concentration on sticky tapes also decreased with increasing height of

Variable	--------------------Vehicle Speed (km h-1)--------------		
	32	48	64
$PM_{2.5}$ T1 1	4.5191bz	5.5914b	7.6613a
$PM_{2.5}$ T5 2	2.2379b	3.5369ab	4.5953a
$PM_{2.5}$ T10 3	1.0883a	1.0868a	1.7526a
$PM_{2.5}$ T154	0.5603a	0.5873a	0.7987a
$PM_{2.5}$ T205	0.2998a	0.4736a	0.5363a
$PM_{2.5}$ T256	0.1334a	0.3170a	0.3747a
$PM_{2.5}$ T307	0.03214a	0.04767a	0.16937a
$PM_{2.5}$ Sum8	8.872b	11.641b	15.740a

[z]Means with the same letter are not significantly different (LSD mean) at 0.05 level of significance
Difference between vehicle speeds on average: [1](1.07, 2.07); [2](1.3, 1.06); [3](0, 0.66); [4](0.03, 0.21); [5](0.17, 0.06), [6](0.18,0.06), [7](0.01, 0.12), and [8](2.77, 4.1)

Table 8: Average particulate matter ($PM_{2.5}$) (mg/m^3) detected by the DustTrak for three vehicle speeds 1 to 30 seconds after the vehicle passed in front of the instrument.

Source of Variation	d.f.	Pr > F	F value
Site	6	0.0001*z	21.57
Speed (Site)	7	0.0001**	5.22
Height (Site)	7	0.0001**	16.58
Speed*Height (Site)	7	0.0168*	2.51
C.V. (%)		80.89	
Mean (mg/m^3)		1.035	

[z]Observed level of significance (Pr > F: *, **) at 0.05, and 0.01 significant effect, C.V.=coefficient of variation, d.f.=degree of freedom

Table 9: Analysis of variance for the PM measured with sticky tape technique at different time intervals when a vehicle was running at three speeds at sites in Mexico and the US.

	Experimental Sites						
Variable	Bolson	La Teja	Palomas	Anthony	Colum-bus	Deming	Leyen-decker
PM ($mg\ m^{-3}$)	0.877c[z]	0.529c	1.008c	3.054a	2.752ab	2.381b	1.124c
Sand+Silt (%)	96.4	50.1	76.1	98.8	82.8	85.9	83.0

[z]Means with the same letter are not significantly different at 0.05 level of significance. LSD mean test

Table 10: Average PM measured with sticky tape technique for all sites.

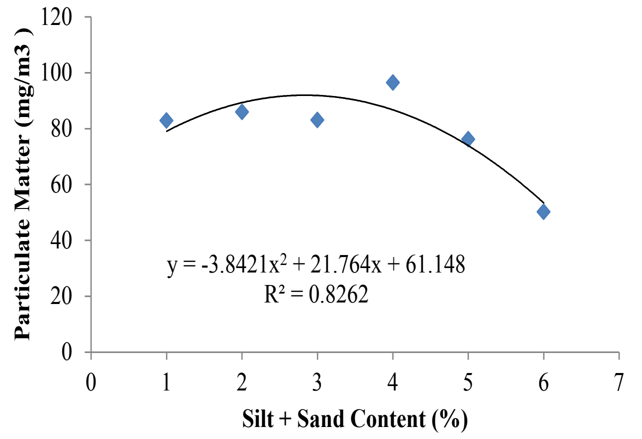

Figure 8: Dust particle concentration on sticky tapes as a function of the content of the large size particles from unpaved roads at six experiment sites in Mexico and the US.

Variable	Vehicle Speed (km h^{-1})			
	32	48	64	
PM	0.5932 ± 0.2475c	1.0874 ± 0.0905b	1.888 ± 0.0656a	
	Rotorod Height (m)			
	0.6	1.2	1.8	2.4
PM	4.2063 ± 0.762a	1.3264 ± 0.092b	0.6393 ± 0.109b	0.519 ± 0.302b

[z]Means with the same letter are not significantly different (using Fisher's LSD mean) at 0.05 level of significance. Bol=Bolson, Tej=La Teja, Pal=Palomas, Ant=Anthony, Col=Columbus, Dem

Table 11: Average PM measured by sticky tapes (mg/m^3) for US sites at different vehicle speeds and at different heights using rotorods.

the rotorods above the soil surface (Table 11; Figure 9). The highest concentration was obtained at 0.6 m and decreased sharply with height above the ground.

The rotorods were placed at 1 and 2 m above the ground at Mexican sites. The effect of rotorod height on PM concentration followed the same trend as with the US sites. An average PM concentration of 1.24 and 0.31 $mg.m^{-3}$ was detected at 1 and 2 m height, respectively. The analysis of PM retained on the sticky tapes indicated that concentration of PM increased with vehicle speed only at the Bolson site, and this increase was 0.74 $mg.m^{-3}$ when vehicle speed increased from 32 to 48 $km.h^{-1}$ and 0.57 $mg.m^{-3}$ when vehicle speed increased from 48 to 64 $km.h^{-1}$ (Figure 9). The effect of vehicle speed was not clear at sites in Palomas and La Teja because wind direction changed during the experiments.

Comparing measurement techniques

The two techniques, low cost rotorod with sticky tapes and DustTrack, use different mechanisms to record PM concentrations from the unpaved roads. The DustTrack method can be set to record continuous diurnal changes in $PM_{2.5}$, PM_{10} and total PM at any given time interval, while the low cost sticky tape method records only total PM for a specific time interval. Figure 10 show that both methods, although significantly different, demonstrate relatively similar results for the Deming, Anthony, and Bolson sites. Out of seven sites where simultaneous measurements of PM concentrations were made, low cost sticky tape method recorded higher concentrations of PM than the DustTrack method. However, for the Palomas and La Teja sites DustTrack concentrations were higher than those by sticky tapes. As

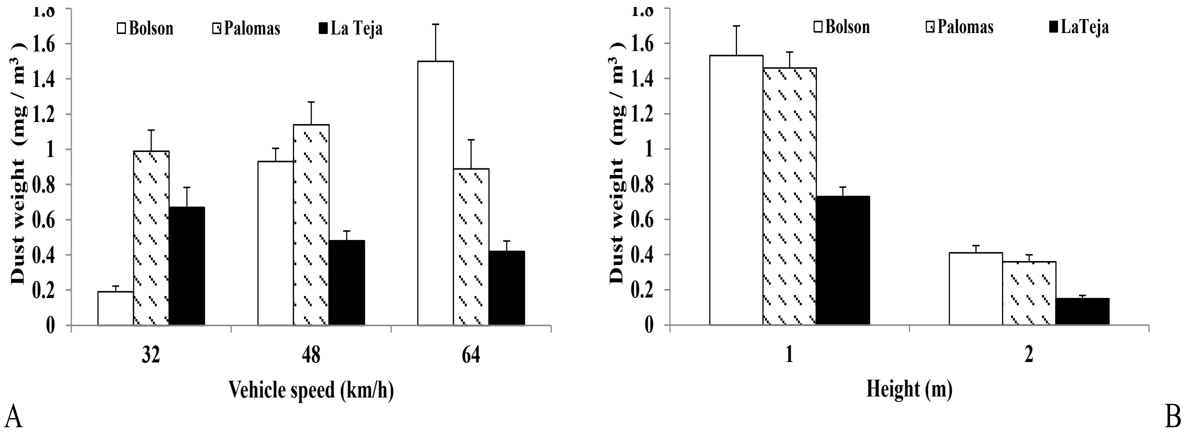

Figure 9: Average dust weight measured with sticky tapes as a function of vehicle speed (A) and height of the rotorods (B) at sites in Mexico. Small bars represent standard error.

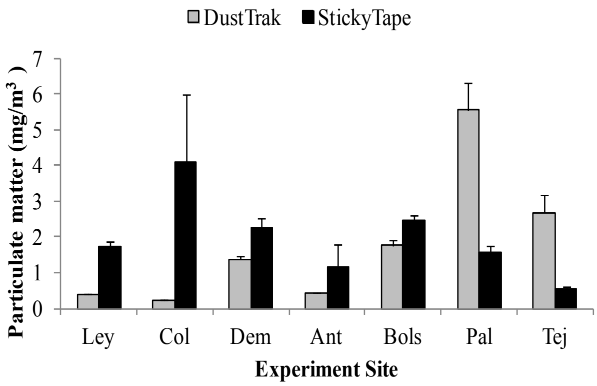

Figure 10: Average dust weight (sticky tape) and $PM_{2.5}$ readings (DustTrak) at 1 m height on the ground measured for vehicle speeds of 64 km h-1 Ley=Leyendecker, Col=Columbus, Dem=Deming, Ant=Anthony, Bol=Bolson, Pal=Palomas, Tej=La Teja Small bars represent standard errors.

pointed out earlier, these two sites did not follow the generally accepted trend of increase in PM concentration with increasing vehicle speeds due to the change in wind direction during the measurement.

Discussion

This study was conducted to determine the concentration of airborne PM at field scale due to natural winds and vehicular traffic on unpaved roads. The PM emissions were quantified at different vehicle speeds and on different unpaved roads characterized by differences in texture and soil water content using two real-time point sampling techniques. One technique used the DustTrak instrument, which although expensive, is capable of real-time continuous measurement of PM concentration. The second technique rotorods with sticky-tape is an inexpensive method to determine total PM concentration at a specified time interval. It can also be used to determine size distribution, elemental and mineralogical composition of airborne PM as well as fungal spores. The study was conducted at various locations in the Chihuahuan Desert region along US-Mexico border.

Both real-time point sampling techniques (DustTrak and Sticky-Tape) showed an increase in PM concentration with increasing vehicle speed at most sites. A similar trend was reported by Flores et al. [14] who used a MET^{-1} sampler and found that PM increased by 0.07 $mg.m^{-3}$ at 32 $km.h^{-1}$, and 0.12 mg m^{-3} at 48 $km.h^{-1}$. However, in this study the DustTrak detected an increase of 1.07 $mg.m^{-3}$ when vehicle speed increased from 32 to 48 $km.h^{-1}$.

Soil particle size and moisture are important factors affecting PM emissions on unpaved roads [7,9,10]. The current study covered a wide spectrum of soil textures from loam to sand with very low moisture content (< 4%). The detection range of $PM_{2.5}$ concentration for all sites was 1.11 to 37.10 $mg.m^{-3}$ with the DustTrak® instrument, and the variation of PM concentration showed a consistent inverse relationship with time best described by an exponential function with an average slope of -1.62 $mg.m^{-3}.s^{-1}$. This value reflects how particles move away from an emission source; follow a downwind direction, and how heavy particles settle on the unpaved road. Also, this value could be valuable for soil erosion studies or the impact of PM emissions on human respiration for people living near unpaved roads.

The sticky tape technique showed significant effect for site, speed, and height of rotorods on the PM concentration. The PM concentration on sticky tapes decreased with increasing height of the rotorods. This was evident from the smaller-sized PM particles detected on the sticky tape at 2 m height as compared to the 1 m. similar observations were reported by Williams et al. [5] and Flores et al. [3]. In the US, PM concentrations ranged from 1.1 to 37.0 $mg.m^{-3}$ from DustTrak and from 0.15 to 1.53 $mg.m^{-3}$ for sticky-tape technique for a 45 minutes measurement period. These measurements are higher than values reported for the region by the US Environmental Protection Agency [17]. In Mexico, the highest PM emissions were measured between May and June on unpaved roads in Ciudad Juarez and ranged from 0.13 to 0.356 $mg.m^{-3}$, above the National Mexican Standard for Air Quality (NOM-025-SSA1-1993) of 0.12 $mg.m^{-3}$. Another study to monitor dust emission used a large rotating barrel dust generator and reported that for the sandy clay loam and sandy clay soils dust emissions were from 400 to 500 $mg.m^{-3}$ in area of Lubbock, TX [12].

Although several devices are available to measure real-time PM concentrations [17] use of a low-cost sensor for airborne PM concentration determination will augment the much needed database on PM concentration. Although our data find an approximation between results from both techniques for different heights, vehicles speeds, and on different unpaved roads from two countries, a valuable contribution of this study was to confirm that sticky tape, a low-cost technique, has the potential to be used under different atmospheric conditions and can provide good information on trends of airborne PM. The study found that results from the sticky tape technique were similar to results from the expensive techniques such as the commercially available point sensors devices.

Conclusions

The unpaved roads of this study had a wide variation in soil textures ranging from sand to silty clay with less than 4% soil moisture content. The two techniques, DustTrak and inexpensive rotorod with sticky-tape, were evaluated to record airborne PM and produced good approximation of PM concentrations under different vehicles speeds and from a variety of unpaved roads. The DustTrak recorded a $PM_{2.5}$ concentration range of 1.11 to 37.10 mg.m^{-3} at 1 m height in seven experiment sites. The regression between $PM_{2.5}$ concentration and time generated a power function with a slope averaged -1.62 mg.m^{-3}.s^{-1} for vehicle speeds of 32, 48, and 64 km.h^{-1}. Both methods showed that PM concentration increased with increasing vehicle speed. The sticky tape technique displayed an inverse association between soil particle size (sand + silt) and PM concentration. The PM concentration recorded by the sticky tape method also decreased with increasing height of the rotorods above soil surface.

Data on airborne PM and the abiotic factors causing the PM emission are still limited in the Chihuahuan desert region. Low cost techniques that can simultaneously measure PM concentration as well as collect PM sample for further physical, chemical or microbial analyses over a large area are needed. The data on quantity and diversity of funguses and other microorganisms in the air are also scant. Future attempts should be aimed at measuring the abiotic factors causing PM emission, for example soil types, soil moisture contents and wind velocities, and biotic factors, for example funguses, simultaneously. There is a need to develop a forecast model for predicting PM concentrations and associated air-quality parameters. Such a model would be useful for the health and welfare of the people living in this area and could improve the quality of life along the Chihuahuan desert region.

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