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Short communication

Particulate dust emission factors from unpaved roads in the U.S.–Mexico border semi-arid region

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ABSTRACT

Unpaved road dust emissions in El Paso in Texas, Las Cruces in New Mexico and Ciudad Juárez in Mexico were measured using the Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER) system. PM_{10} (particles with diameter < 10 μm) emissions factors from unpaved roads in Ciudad Juárez, Mexico increased by a factor of five as compared to those measured in El Paso, TX and Las Cruces, NM. The highest emission factors were observed in spring. A strong exponential dependence of PM_{10} emissions factors on vehicle speed was observed in Ciudad Juárez, Mexico and El Paso, TX, whereas they remained constant in Las Cruces, NM reflecting differences in soil surface characteristics. The highest PM_{10} emissions in Las Cruces and Ciudad Juárez originated from the sideline tire, indicating the possible influence of accumulated loose soil and debris on the side of the unpaved roads. Overall, strong spatial and temporal variability of PM_{10} emission factors were computed in the Paso del Norte region, reflecting differences in road surface and vehicle traffic characteristics and further underscored the need for high spatiotemporal resolution of emission inventories to accurately identify the most susceptible unpaved roads and control their burden on particulate pollution.

Urban communities in the Paso del Norte region along the U.S.-Mexico border experience unhealthy levels of particulate matter with road dust from unpaved roads being the most important contributor. The Paso del Norte region is located within the Chihuahuan Desert and encompasses the cities of El Paso in Texas, Las Cruces in New Mexico, and Ciudad Juárez in Mexico. El Paso was designated by the U.S. Environmental Protection Agency (EPA) as a non-attainment (i.e. in violation) area for the National Ambient Air Quality Standards (NAAQS) for PM_{10} in 1990–2000 (TNRCC, 1999). In addition, portions of Doña Ana County exceed the NAAQS for PM_{10} since 1991. The Mexican ambient air quality standards (Norma Oficial Mexicana; NOM) for PM_{10} are also exceeded in Ciudad Juárez. Unpaved road dust is a critical issue since many roads in Ciudad Juárez are unpaved (~50%), and vehicle traffic in El Paso's and Las Cruces unpaved roads has rapidly increased due to expansion and growth (TNRCC, 1996; Gonzalez, 1998). Road dust from unpaved and paved roads constitutes the most important sources of PM_{10} in El Paso and Ciudad Juárez (~60% on average), followed by windblown dust (~27%) and tailpipe emissions (7%). Thus, controlling direct particulate matter emissions produced by vehicle traffic is essential in reducing particulate pollution in the region.

Dust particles from unpaved roads are lifted and dropped from the rolling wheels as the vehicle travels on an unpaved road (Dyck and Stukel, 1976). Factors that influence the magnitude of dust emissions include the condition of a road surface, the surface material silt and moisture content, the volume and speed of traffic and the vehicle weight. The U.S. EPA developed a methodology (i.e. AP-42) and emission factors for PM_{10} (particles with diameter < 10 μm) from unpaved road (EPA, 1995). The assumptions, limitations and silt-loading data collection requirements needed to utilize the methodology considerably diminish the accuracy of emissions inventories for road emissions as they assign a constant and temporally invariant emission factor for unpaved roads in large geographic areas. Recently, the Testing Re-entrained Aerosol Kinetic Emissions from Roads (TRAKER) vehicle-based system has been thoroughly field tested against the traditional AP-42 and an instrumented tower system to measure PM_{10} horizontal fluxes for

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the collection of paved and unpaved road dust as it is aerosolized by driving activities (Kuhns et al., 2001, 2003, 2005; Etyemezian et al., 2003a,b, Etyemezian and Kuhns, 2006). The mobile system correlated well with the tower measurements and comparable PM_{10} emission factors were obtained. AP-42 emission factors were, in general, lower than those estimated from the tower measurements and the TRAKER van.

The ability of the TRAKER mobile system to continuously measure PM_{10} emissions along the entire length of unpaved roads behind the two front wheels allows for the precise identification of unpaved roads segments that are most susceptible under typical driving conditions. This is critical in implementing targeted practices to control emissions from unpaved roads in an effective and cost-efficient manner. The objectives of the study were to estimate PM_{10} emission factors from existing unpaved roads in El Paso, TX, Ciudad Juárez, Mexico and Las Cruces, NM; assess the variability of emission factors over time; and determine the relative importance of emissions from the centerline and sideline of the unpaved roads.

Unpaved road PM_{10} emissions were measured for 138 and 149 km in April 2008 and June 2008, respectively, in the three urban areas. Table 1 shows the summary of the monitoring campaigns, including the number of segments of unpaved roads and the estimated distance of unpaved roads traveled. An observer (same for both surveys) rode and visually classified the road surfaces (gravel, native (fine) soil, rocks and hard surfaces, sandy soil or combination of them). The TRAKER is a cargo van that collects road dust as it is aerosolized on the road through inlets located behind the front tires (Etyemezian et al., 2003a,b, Etyemezian and Kuhns, 2006). Dust concentrations are continuously measured with a nephelometer-type DustTrak monitor (Model 8520, TSI Inc.) with a resolution time of 1-s. The designs of sampling and dilution systems, as well as the data collection system, are presented elsewhere (Etyemezian et al., 2003a,b, Etyemezian and Kuhns, 2006). The signal was transformed to emission factor (EF_{10}) (in g vkt^{-1} (vehicle kilometer traveled) by using the following equation (Langston et al., 2007)

$$EF_{10} = 0.92\cdot\left(\frac{1}{2}\cdot\left(\frac{PM_{10,r}\cdot V_{r,main} - PM_{10,back}\cdot V_{r,dil}}{V_{r,main} - V_{r,dil}} + \frac{PM_{10,l}\cdot V_{l,main} - PM_{10,back}\cdot V_{l,dil}}{V_{l,main} - V_{l,dil}}\right)\right) \tag{1}$$

where $PM_{10,r}$ and $PM_{10,l}$ were the PM_{10} mass concentrations measured behind the right and left tires (in mg m^{-3}); $PM_{10,back}$ was the background PM_{10} mass concentrations behind the passenger-side door (in mg m^{-3}); $V_{r,main}$ and $V_{l,main}$ were the flow rates at the right and left main inlets (in m s^{-1}); and $V_{r,dil}$ and $V_{l,dil}$ were the flow rates at the right and left dilution channels (in m s^{-1}).

Quality controls were conducted prior and after each of the two measurement periods. There were no problems associated with the performance of the PM_{10} DustTrak detectors; the monitors showed remarkable consistency and repeatability (slope of 0.96 and intercept of 9 μg m^{-3}). Audits and calibrations of the inlet flow rates were completed before each measurement period using a SPER Scientific Hotwire CFM anemometer. The instrument has been calibrated by the manufacturer. Given that the measurement systems are identical and that individual components of error are decoupled or shared between the two systems, the percent precision and relative bias were calculated. The precision and bias, 19.5% and −14.5%, respectively, were within the goals defined for this study. These results indicated that the readings between the instruments were comparable and consistent between each other. A set of validity criteria were applied to compensate for artifacts related to vehicle speed, acceleration and the surface characteristics of the unpaved road disturbed by the tires. The threshold values for vehicle speed (<1.5 m s^{-1}), acceleration (>0.5 m s^{-2}) and vehicle body ($>3°$) used in this study were similar to those used in earlier work (Veranth et al., 2003; Etyemezian et al., 2003; Kuhns et al., 2005).

The descriptive statistics of the estimated EF_{10} for each segment of unpaved roads for the two monitoring efforts (April and June 2008) are presented in Table 1. In April 2008, EF_{10} in unpaved roads in Las Cruces, NM varied from 5 g vkt^{-1} up to 36.82 kg vkt^{-1} with median (mean) emissions from 67 (97) g vkt^{-1} in segment#8 to 138 (229) mg vkt^{-1} in segment#6. In El Paso, TX, EF_{10} measured in segment#9 were as high as 13.6 kg vkt^{-1} with a median (mean) of 193 (306) g vkt^{-1}. Mean EF_{10} in segments#10 and #11 were 30 (37) and 36 (39) g vkt^{-1}, respectively. The highest instantaneous EF_{10} values were recorded in Ciudad Juárez, Mexico (up to 169.8 kg vkt^{-1}), with a median (mean) value of 114 (606) g vkt^{-1}. In June 2008, median (mean) EF_{10} in Las Cruces, NM were from 66 (105) g vkt^{-1} in segment#2 up to 151 (202) g vkt^{-1} in segment#7. In El Paso, TX, the highest EF_{10} was 826 g vkt^{-1} in segment#10a, with median (mean) values ranging from 40 (56) g vkt^{-1} for segment#10 to 107 (123) g vkt^{-1} for segment#10a. The maximum instantaneous EF_{10} in the two segments at Ciudad Juárez were 1.5 kg vkt^{-1} for segment#12 and 0.9 kg vkt^{-1} for segment#12 with median (mean) of 75 (108) and 125 (150) g vkt^{-1}, respectively. These estimated were compared to those reported at the Fort Bliss Military Base

Table 1

Description of unpaved roads, distance traveled and mean, median and standard deviation (σ) of measured PM10 emission factor (in g vkt^{-1}) in April and June 2008.

Segment	Description	April				June			
		Distance	Mean	Median	σ	Distance	Mean	Median	σ
Las Cruces, New Mexico									
1	Hornada Rd, Gravel	27 km	210	97	895	24 km	180	99	1034
2	Hornada Rd, Gravel	6 km	144	97	201	7 km	105	66	122
3	Residential, native soil	8 km	119	74	212	4 km	422	126	2335
4	Residential, native soil	6 km	197	136	255	3 km	205	121	257
5	Residential, Gravel	9 km	167	131	361	–	–	–	–
6	Residential, rocks and hard surfaces	5 km	229	138	361	7 km	246	147	397
7	Residential, native fine soil	33 km	149	112	168	29 km	202	151	201
8	Residential and farming, sandy soil	4 km	97	67	170	15 km	166	137	129
El Paso, Texas									
9	Park, gravel	6 km	306	193	630	6 km	56	40	49
10	Open land, gravel and native soil	1 km	37	30	23	5 km	49	43	35
10a	Residential native soil	–	–	–	–	2 km	123	107	99
11	Residential native fine soil	9 km	39	36	26	17 km	61	57	30
Ciudad Juárez, Mexico									
12	Residential, native soil	23 km	606	114	7218	24 km	108	75	125
13	Residential, native soil	–	–	–	–	9 km	150	125	107

located north of El Paso, TX in 2001 and 2002 using TRAKER (Kuhns et al., 2005) and in European unpaved roads using an approach similar to the TRAKER mobile van (Mathissen et al., 2012). In a previous study, Williams et al. (2008) estimated PM_{10} emissions factors from 10147 g km^{-1} at 48 km h^{-1} and 11062 g km^{-1} at 64 km h^{-1} speed.

The estimated EF_{10} were comparable for Las Cruces, NM and El Paso, TX in April 2008 but about five times lower than that was computed for Ciudad Juárez. On the other hand, in June 2008, the highest EF_{10} was measured in Las Cruces, NM and was three times higher than that measured in El Paso, TX. The mean emissions factors between the two monitoring periods varied from 16% in Las Cruces, NM up to 80% in Ciudad Juárez, Mexico. The differences among the three areas and the measurement periods demonstrated spatial and temporal variations of emissions from unpaved roads. To further examine whether these differences are significant (at a confidence level of >99%), the null hypothesis was tested using univariate analysis on variance (ANOVA):

$$H_o : \mu_1 = \mu_2 = \mu_3 = \ldots..\mu_\nu \tag{2}$$

that assumes that the means (μ_1, μ_2,μ_3, … μ_v) were all estimates of the same population. The null hypothesis is further defined as: (i) Spatial variation: there was no difference among EF_{10} from the segments of unpaved roads (at a significance level of 99%) for a given measurement effort; and (ii) Temporal variation: there was no difference among EF_{10} measured during the two measurement efforts (at a significance level of 99%) for a given segment of unpaved roads. The credibility of the null hypothesis was tested by using the F-ratio, which was defined as the squared ratio of the variance within groups (s_{wg}) to the variance between groups (s_g). Values of F-ratio equal or lower than 1 confirm the null hypothesis, while F ratios higher than unity indicate the rejection of the null hypothesis at significance level $p < 0.001$. The high F-ratios suggested that the differences of EF_{10} among the segments of unpaved roads were statistically significant. With respect to the seasonal variation of EF_{10}, unpaved roads in El Paso, TX and Ciudad Juárez, Mexico exhibited high F-ratios indicative of significant differences between the two measurement efforts. On the other hand, a seasonal difference was only observed for segments #2, #3, #7 and #8 in Las Cruces, NM, while EF_{10} for segments#1, #4 and #5 were comparable for the two measurement efforts.

Fig. 1 shows the dependence of EF_{10} on the speed of the TRAKER van for the three urban areas. Note that average EF_{10} for each TRAKER speed was computed for all sites within each of the three localities with these sites being representative of different types of soils. This categorization scheme was selected based on previous studies, to present the findings in a manner that is consistent and usable by local entities on a county/region level and to obtain an estimate of associations for a range of vehicle speeds. In all cases, despite the variability of soils the standard error of average EF_{10} values was very low. A strong dependence of EF_{10} on vehicle travel speed was observed in El Paso, TX and Cuidad Juárez, rising exponentially from 4 to 8 m s^{-1}, corresponding to 16–32 km h^{-1}. The lowest and the highest EF_{10} value for vehicle travel speeds of less than 5 m s^{-1}, were measured in El Paso, TX and Las Cruces, NM. The EF_{10} values remained unchanged for different vehicle travel speeds in Las Cruces, NM, but they were lower than those computed in El Paso, TX. On the other hand, EF_{10} values in Ciudad Juárez exceeded those measured in the US locations for vehicle travel speeds higher than 7 m s^{-1}, reaching a maximum of 415 mg vkt^{-1} at 8.3 m s^{-1}. The PM_{10} measurements exceeded the upper limit of the instruments for higher vehicle speeds in Ciudad Juárez. These differences suggest substantial variability of unpaved roads surface characteristics, including the size and availability of dust particles. For example, unpaved roads in Las Cruces were typically outside the urban grid and characterized by limited supplies of fine soil particles on solid soil surfaces (or gravel). The presence of fine soil material on hard unpaved road surfaces may be due to wind and water erosion from nearby deserts. Although unpaved roads in Ciudad Juárez were mostly of native soil, the intense and heavy traffic in unpaved roads in Ciudad Juárez (constitute about 50% of the network) may yield an unlimited supply of fine particles.

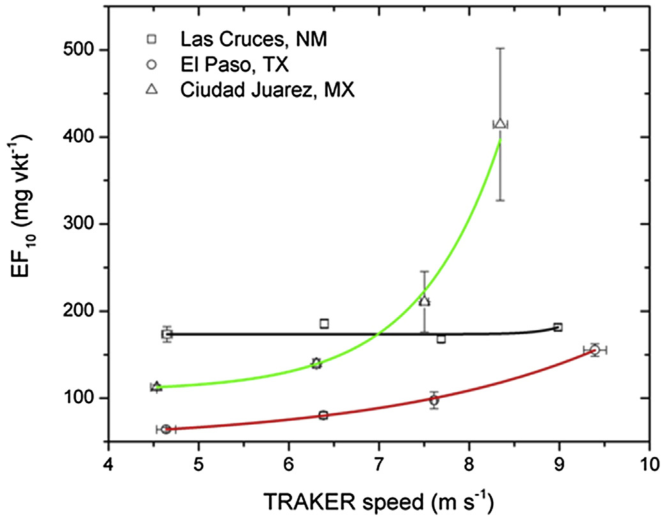

Fig. 1. Emission factors as a function of TRAKER speed. Error bars represent three times the standard error of the mean emission factor and TRAKER speed.

Fig. 2a and b presents the PM_{10} emissions at the centerline and sideline of the unpaved roads for each measurement period. In April 2008, PM_{10} emissions measured behind the left tire of the TRAKER were substantially higher than those measured behind the right tire in Las Cruces, NM and El Paso, TX, whereas in Ciudad Juárez the opposite pattern was observed. A different profile was observed in the summer (June 2008). For El Paso, TX, PM_{10} emissions on the centerline of the unpaved road were still higher than those measured on the sideline, whereas for both locations in Ciudad Juárez, right-side measurements accounted for the vast majority of PM_{10} emissions. On the other hand, in Las Cruces, NM,

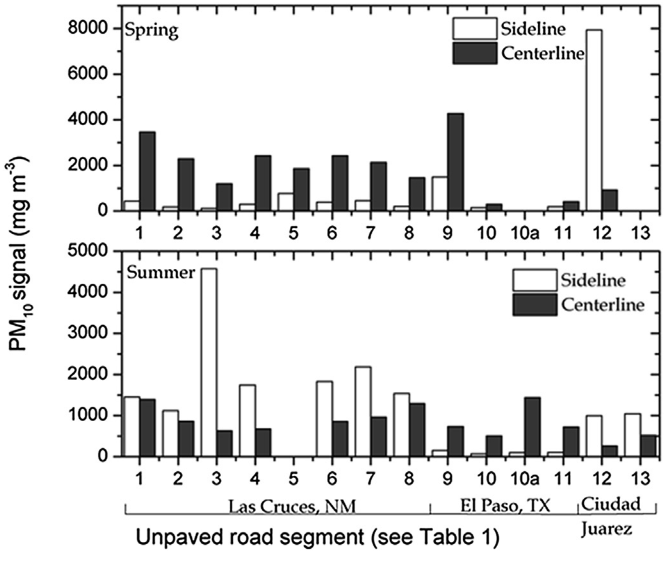

Fig. 2. TRAKER PM_{10} emissions from the center (left tire) and side (right tire) of the unpaved roads in each segment on April 2008 (up) and June 2008 (bottom).

sideline PM_{10} emissions were higher than those measured in the middle-of-the-road (Chiou and Tsai, 2001). High sideline emissions may be explained by larger quantities of loose soil and debris that accumulate at the curb site. On the other hand, high PM_{10} emissions from the middle of the roads may be associated with driving patterns (driving in the middle of the road). Conclusively, emissions of PM_{10} dust particles were continuously measured using state-of-the-art mobile technology. A total of fourteen segments of unpaved roads were identified in the Paso del Norte region (eight locations in New Mexico; four locations in El Paso, TX; and two locations in Ciudad Juárez, Mexico). Average EF_{10} ranged from 37 g vkt^{-1} at Segment#10 in El Paso, TX to 606 g vkt^{-1} at Segment#12 in Ciudad Juárez on April 2008, and from 49 g vkt^{-1} at Segment#10 in El Paso, TX to 422 g vkt^{-1} at Segment#3 in Las Cruces, NM. The differences in EFs among the segments of unpaved roads were statistically significant, indicating that there was a strong spatial variation of emissions from unpaved roads. This may reflect differences in the quality of unpaved roads, the type of soil, and driving conditions (frequency, type of vehicle, speed). Estimated EFs in Ciudad Juárez were five times higher than those measured for unpaved roads in Texas and New Mexico in April 2008. In contrast, significantly lower EFs were measured in June 2008 in all regions. Comparison of PM_{10} emissions behind the right and left tires of the TRAKER van for the two monitoring periods showed that the accumulation of loose soil and debris on the side of the unpaved roads resulted in higher PM_{10} emissions in Mexico (for both monitoring periods) and New Mexico (only for June 2008). On the other hand, PM_{10} emissions from the left tire were higher than those measured behind the right tire for unpaved roads in El Paso. TX.

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