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Evaluation of the surface roughness effect on suspended particle deposition near unpaved roads

Dongzi Zhu [a,*], John A. Gillies [a], Vicken Etyemezian [b], George Nikolich [b], William J. Shaw [c]

[a] Desert Research Institute, 2215 Raggio Pkwy, Reno, NV 89512, USA
[b] Desert Research Institute, 755 E. Flamingo Road, Las Vegas, NV 89119, USA
[c] Pacific Northwest National Laboratory, 902 Battelle Blvd, Richland, WA 99354, USA

HIGHLIGHTS

- Measurement road dust PM10 concentration evolution during near-source transport.
- Study PM horizontal & vertical transport by array of real-time particle counters.
- Estimate impacts of the roughness/vegetation on PM deposition under 5 surfaces.
- Rougher surface induced increased turbulence, thus increased PM deposition.
- Dense grass site has highest reduction by enhanced particle impaction/interception.

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ABSTRACT

The downwind transport and deposition of suspended dust raised by a vehicle driving on unpaved roads was studied for four differently vegetated surfaces in the USA states of Kansas and Washington, and one barren surface in Nevada. A 10 m high tower adjacent to the source ($\approx$10 m downwind) and an array of multi-channel optical particle counters at three positions downwind of the source measured the flux of particles and the particle size distribution in the advecting dust plumes in the horizontal and vertical directions. Aerodynamic parameters such as friction velocity (u_*) and surface roughness length (z_0) were calculated from wind speed measurements made on the tower. Particle number concentration, PM_{10} mass exhibited an exponential decay along the direction of transport. Coarse particles accounted for $\approx$95% of the PM_{10} mass, at least to a downwind distance of 200 m from the source. PM_{10} removed by deposition was found to increase with increasing particle size and increasing surface roughness under similar moderate wind speed conditions. The surface of dense, long grass (1.2 m high and complete surface cover) had the greatest reduction of PM_{10} among the five surfaces tested due to deposition induced by turbulence effects created by the rougher surface and by enhanced particle impaction/interception effects to the grass blades.

1. Introduction

Unpaved roads are common in rural areas and large military and other installations in the U.S. Unpaved road dust due to surface disturbance by vehicle travel is the highest single emissions category within the non-point fugitive dust category, accounting for about one third of non-windblown fugitive dust emissions in the U.S.A (Pouliot et al., 2012). Williams et al. (2008) found that suspended dust collected at 1.5 m, 4 m and 6 m heights near an unpaved road spanned the size (diameter) range 0.05 μm–159 μm with 97.8%–99.6% of particles having diameters <50 μm. The fine part of suspended particulate matter with aerodynamic diameter ≤10 μm (PM_{10}) is regulated as a primary pollutant in the U.S. due to its potential to adversely affect human health. Fugitive dust raised by vehicles traveling on unpaved surfaces impacts regional and local air quality and visibility (Pinnick et al., 1985). Typically the impact of dust from unpaved roads on air quality is evaluated using emission factors to estimate the mass of particulates that are introduced into the atmosphere by vehicular travel (e.g., US EPA, 1995; Gillies et al., 2010), but what is lacking in this approach is

* Corresponding author.
E-mail address: zhu@dri.edu (D. Zhu).

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that all the mass that is estimated to have been ejected at the source is assumed to be available for near- and long-range transport. This neglects the effect of the interaction of the dust plume with the near field (<200 m) environment where it may be interacting with vegetation and roughness resulting in particle removal. Modeling particle deposition has concentrated on two types of flow environments: particle deposition in pipe flows and indoor environments, such as ventilation ducts, and from the atmosphere to the underlying surface. The latter is germane to the question of quantifying deposition of fugitive dust from unpaved roads. For supermicron size particles (diameter ≥1 μm), studies examining deposition and its variation with surface roughness and meteorological conditions are limited and highly uncertain due to the low concentration of particles detected in this size range in field studies (e.g., Nemitz et al., 2002), and it is typically examined within a framework of far-downwind transport where concentrations are relatively uniform with height and the surface is considered as a sink (e.g., Raupach et al., 2001). Dong et al. (2003) report that overprediction of coarse particles (2.5–10 μm diameter) concentrations of road dust contributions by as much as a factor of 1.7–11 in grid-based dispersion models is due to two factors: 1) the forced mixing of the plume to a minimum thickness of 20 m of height at the source, when it is known to be between 2 m and 6 m depending on vehicle height (Gillies et al., 2005), and 2) the dependency of coarse particle deposition on wind speed not being accounted for adequately. This lack of accounting for near source deposition is a shortcoming in evaluating the contributions of dust to the atmosphere for sources such as unpaved or off-road vehicle travel.

Field measurements of dust emissions created by vehicles traveling on unpaved roads are limited (e.g., Johnson et al., 1992; Gillies et al., 2005; Williams et al., 2008) and have typically focused on measuring the total mass flux of particles as a function of vehicle operating parameters and surface conditions to quantify vehicle emission factors. The subsequent transport and deposition of the entrained road dust along the downwind direction over relatively short distances has not been as well studied.

When dust particles are suspended by vehicles, they are transported downwind and dispersed by turbulent diffusion. Wilson (2000) using data from Hage (1961) and Walker (1965) demonstrated that particles >50 μm diameter released into the wind quickly settle out in a few hundred meters. When particles in suspension collide with surface roughness elements such as grass, rocks, or buildings, they can deposit (Pardyjak et al., 2008). Particles are brought to these depositional surfaces by Brownian diffusion, impaction, interception, sedimentation, or combinations of these processes. For submicron particles, diffusion dominates; as particle size increases, deposition by sedimentation (i.e., gravity force) and impaction become more important removal processes relative to Brownian diffusion and interception (Friedlander, 2000). Particle deposition depends not only on the particle diameter, but also on parameters like surface roughness and canopy morphology, wind friction velocity (u_*), and atmospheric stability (Fowler et al., 2009). Field testing and direct measurement of dust-sized particle (<30 μm diameter) deposition rates is difficult and only a limited number of studies have been reported. Johnson et al. (1992) used light detection and ranging (LIDAR) instrumentation to measure the backscatter coefficient of a depositing dust plume over a relatively smooth surface (an unpaved road) and reported the deposition flux was proportional to the plume concentration as would be expected by the linearity of the advection diffusion equation.

Johnson et al. (1992) observed that particles >10 μm almost completely settled out by the time their measured plumes traveled 250 m from the source, and the reduction of the initial mass scaled through time as e^{-1}, which under the conditions present during their study accounted for a reduction of initial mass to 36% in 10–40 s Etyemezian et al. (2004) reported that they could not measure depositional losses in vehicle-generated dust plumes traveling 100 m over a surface of sparse vegetation cover at Ft. Bliss near El Paso, TX, for a range of atmospheric stability conditions. Veranth et al. (2003), however, reported quite high removal rates (≈85%) of fugitive dust at 95 m downwind of an array of 2.5 m high containers simulating an urban setting. Cowherd et al. (2006) reported different PM_{10} loss ratios (from <10% to 67%) at 20 m downwind for various vegetation types (cedar trees, tall grass) bordering unpaved road sources. Zhu et al. (2011) reported an exponential decay of PM_{10} as a function of downwind distance from a paved road source with leafless deciduous birch trees acting as a vegetation barrier under winter conditions. Mao et al. (2013) reported 51% of 20 μm and 61% of 50 μm suspended particles deposited within 60 m downwind of an unpaved road with the plume traveling over a surface composed of the agricultural crop peas and a passing through a shelterbelt of trees approximately 10 m high. These various studies do not reveal a consistent pattern to explain the range of observations of dust deposition that have been reported. Movement of dust laden wind into a vegetated canopy where the flows are generally characterized by strong flow heterogeneity, intermittency, and non-Gaussian flow statistics limits the applicability of simplified modeling approaches (Poggi et al., 2006). This also can create complex vertical profiles of PM that are not easily defined or well-predicted by models.

Due to lack of experimental data to distinguish PM loss either from sedimentation or impaction with vegetation downwind, some researchers assume the PM transportable fraction (TF, the fraction of particles not captured by the surrounding land cover) can be used as an index to characterize the magnitude of particle removal from a plume. For example, a plume advecting over short distances could have a TF value of 1 (i.e., no discernable loss) for flat surfaces barren of macro-roughness elements (i.e., no vegetation or large solid elements). Pace (2005) proposed the following TFs for various surface types to improve emission inventory processing: 0.05 for forests, 0.5 for urban, 0.75 for grass, and 1 for bare surfaces. Pace's (2005) assumed TF values for different surfaces have not been validated by field experimentation. Therefore, there is a need to clarify near source dust deposition flux under different vegetative roughness configurations to quantify the deposition losses during the initial transport phase of fugitive dust. Better quantification of the magnitude of the near field depositional flux will improve regional air quality modeling using an emission inventory approach as well as dispersion-modeling approaches that quantify the spatial distribution and magnitude of PM at identified receptor sites.

To contribute to improved understanding of the near field deposition process, a series of field measurement campaigns were undertaken to measure in real-time the change in suspended particulate matter (PM) concentration and size distribution in dust plumes advecting downwind following emission from unpaved road sources to infer particle loss downwind and close to the source (<200 m). The measurements were carried out over one non-vegetated and four differently vegetated surfaces and under a restricted range of wind speeds and atmospheric stability conditions. Use of near real-time instruments (sampling interval 1 Hz) allowed for the characterization of multiple, individual, transient dust plumes at each study location. These data can be aggregated into ensemble mean values with associated uncertainties (e.g., mean normalized PM_{10} and associated standard deviation) for further analyses. The objective of these field studies was to quantify the TF for PM_{10} as a function of downwind distance for different surface roughness and vegetation types (long grass, short grass, sagebrush, steppe grass, and no vegetation) to evaluate the attenuation of emissions by near-field deposition processes. With dust number concentration as a function of particle (aerodynamic)