Atmospheric Environment 79 (2013) 590–598

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Effects of a shelterbelt on road dust dispersion

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HIGHLIGHTS

- Studied impact of a two-row tree shelterbelt on dust plumes off a gravel road during windy conditions.
- Shelterbelt did not reduce the aerial concentration of PM_{10} particles.
- Reasonable agreement of measured and simulated transects of mean wind speed.
- Disagreement between measured and modelled dust plumes.
- Higher fidelity treatment of one or more aspects of the problem needed.

ARTICLE INFO

Article history:
Received 24 November 2012
Received in revised form
3 July 2013
Accepted 5 July 2013

Keywords:
Air quality
Airborne particulate
Dust control
Environment
PM_{10}
Road dust
Shelterbelts
Windbreaks

ABSTRACT

The impact of a roadside shelterbelt on the downwind concentration of road dust raised by a passing vehicle was investigated experimentally, and by numerical modelling. With or without the shelterbelt, the gravel dust plume, as measured some 60 m or more downwind from the road, was dominated by small particles (most frequent diameter ≈ 6 μm) whose gravitational settling velocity was negligible compared to the turbulent velocity scale (i.e. friction velocity). The time-averaged concentration of these small particles was not lower in the lee of the shelterbelt than in a nearby, unsheltered area downwind of the road. Standard formulae for spheres in an airstream negotiating obstacles suggest such fine particles may pass through the shelterbelt on the bleed flow with little likelihood of interception and entrapment, because their small inertial time constant mandates that they accelerate with the wind, deviating around foliage. Numerical simulations of the experiment are consistent in some respects with what was observed, and suggest that the shelterbelt may increase the fraction of fine particles remaining airborne one minute after their injection at the road.

1. Introduction

Dust raised from unpaved rural roads represents a nuisance and potentially a pulmonary health risk for those regularly inhaling a fine fraction liable to enter and remain in their lungs. Factors affecting the amount of dust raised off an unpaved road include vehicle type, weight and speed, and the condition and composition of the road surface. Spraying rural roads with water, oil or other dust suppressants (e.g. Gillies et al., 1999) is a common intervention to control dust, but it would be useful to establish more definitively the potential effectiveness of roadside vegetation in scrubbing dust from the airstream, and/or enhancing the rate of plume dilution and deposition. Earlier studies have quantified the dust emission factor (mass per vehicle kilometre travelled, kg VKT^{-1}) under normal or controlled traffic conditions, by using artificial tracer techniques or by adopting an atmospheric dispersion model that allows a relation to be obtained between a measured dust concentration and an (implied) emission rate (Claiborn et al., 1995; Kantamaneni et al., 1996). Other work has used the integrated horizontal flux (IHF) method to investigate the downwind fate of a road dust cloud. Working over an open desert surface (roughness length $z_0 = 0.005$ m) Etyemezian et al. (2004) determined that the loss of PM_{10} particles (diameter $d \leq 10$ μm) between the unpaved road and a point 100 m downwind was less than 9.5%, while in contrast Veranth et al. (2003) found that over 85% of PM_{10} dust particles had vanished from the airstream over a comparable fetch of much rougher surface (specifically an artificial "urban canopy," composed of shipping containers).

A slow rate of loss of PM_{10} aerosols from an airstream on open ground might be expected, given the small terminal velocity w_g of

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http://dx.doi.org/10.1016/j.atmosenv.2013.07.015

Table 1
Particle terminal velocity w_g, particle inertial time constant $\tau \equiv g^{-1} w_g$, and normalized impaction conductance g_p/U versus particle diameter d. Impaction conductance is given for two values of the air speed U around foliage. Assumptions: air pressure 93 kPa and temperature 25 °C; characteristic dimension of foliage $d_e = 0.05$ m; kinematic viscosity of air $\nu = 1.55 \times 10^{-5}$ m^2 s^{-1}; dust particle density $\rho_p = 1522$ kg m^{-3} (Note: in LS simulations the Stokes number St was evaluated with U given by the instantaneous particle speed).

d, μm	w_g, m s^{-1}	τ, s	g_p/U, $U = 1$ m s^{-1}	g_p/U, $U = 5$ m s^{-1}
1	4.9e-5	5.0e-6	6.3e-8	1.6e-6
2	1.97e-4	2.0e-5	1.1e-6	2.3e-5
6	0.0018	1.8e-4	8.0e-5	1.9e-3
10	0.0049	5.0e-4	6.0e-4	0.012
20	0.020	2.0e-3	8.3e-3	0.11
50	0.12	1.2e-2	0.15	0.58
100	0.49	5.0e-2	0.51	0.86

PM_{10} particles (Table 1 gives theoretical values of w_g), but the character of the downwind surface and its vegetation must play a role by virtue of their control over the near ground profiles of mean wind speed and turbulence, potentially multiplying the opportunities for particles to come in close contact with and deposit onto surfaces (the ground, or foliage), and delaying the rate of advection of dust downwind. Pardyjak et al. (2008) have developed a model to compute the fate of a particulate plume rising from a road and encountering a *uniform* canopy of vegetation. The present paper focuses on the efficacy of shelterbelts, i.e. narrow roadside belts of trees, which have been considered a possible means of abating the problem of nuisance road dust (Steffens et al., 2012). We shall describe an experiment and related numerical modelling that, taken together, suggest shelterbelts (of the type and in the configuration studied) may not substantially ameliorate the problem of wind-borne road dust in the PM_{10} category.

2. Experiment

Dust samplers and cup anemometers were arranged on (geographic) east–west transects perpendicular to a long, straight, rural gravel road, parallel to which and 60 m downwind (eastward) ran a two-row shelterbelt (see Figs. 1 and 2). “Shelter” transects ran through (or above) and downwind of the shelterbelt, while “reference” transects 100 m away traversed an open (*nominally* unsheltered) area at the south end of the shelterbelt. The objective was to measure and interpret *differences* between the dust distributions in the open and in the lee of the shelterbelt. To this end during suitable meteorological conditions — a strong westerly wind, a dry road — dust was raised by making repeated passes of a 3/4 ton truck, driven at about 80 km h^{-1} and in as consistent a manner as could be managed. The interval between consecutive passes (S–N, N–S, S–N…) was two minutes, and each experiment consisted of twenty such passes over 40 min. Five experiments were executed on five different days, but here the discussion is restricted to two experiments performed during strong winds and (consequently) weak thermal stratification[1] (see Table 2).

The shelterbelt, located at (a constant) longitude −103.99237° and spanning latitude range 50.58810°–50.59335° (i.e. 583 m oriented north–south geographic), consisted of a row of green ash (*Fraxinus pennsylvanica* Marsh.) on the western side and a row of Scots pine (*Pinus sylvestris* L.). The overall cross-section of the shelterbelt was $W \approx 4.7$ m, and the mean height $H \approx 10$ m. In the discussion to follow the origin of the east–west (i.e. x or x/H) coordinate is taken to lie at the centre of the shelterbelt such that the road is centred at $x = -60$ m ($x/H = -6$), and the north–south coordinate y runs parallel to the road with its origin $y = 0$ at the south end of the shelterbelt. Upwind of the shelterbelt stretched a crop of peas whose continuity was interrupted by the road with shallow ditches on either side, while downwind of the shelterbelt ($x > 0$) stood a crop of flax. Both upwind and downwind, the canopy height was $h_c \approx 0.4$ m. The reference transects were located at $y = -25$ m ($y/H = -2.5$), that is, 25 m south of the south end of the shelterbelt, and they bisected a cut break (of about 50 m width) that spanned from the south end of the shelterbelt to an abandoned farmyard (still farther south, and not represented on Fig. 1) growing scrub and short trees of irregular height. This small separation (2.5H) between the south end of the shelterbelt and the reference transects implies that with increasing downwind distance x/H the broadening wakes of the shelterbelt and the farmyard scrub must have impinged on (and modified) the airstream carrying dust plumes downwind along the reference transect. Measured mean wind speeds (shown later, Fig. 3) confirm this disturbance.

The transects were instrumented (see Fig. 1) at three east–west locations $x/H = (0.75,5,10)$ and two heights $z/H = (0.2,1.2)$. Rotorod-type spore counters (viz. 2 mm square-section rods, rotating at 2400 RPM on a 2 cm radius) provided size-discriminated 40 min mean concentrations $\bar{c}_k(x,y,z)$, where k labels particle diameter bins of width 1 μm and spanning 1 μm $\leq d \leq$ 100 μm; a size-dependent collection efficiency was assumed in converting from the Rotorod particle count, performed automatically using Image Pro software (Media Cybernetics, Inc., Rockville, Maryland), to the implied aerial concentration. Co-located Casella Microdust Pro sensors (Model 176000A, Casella CEL, Buffalo, New York) provided 40 min time series of size-aggregated dust mass concentration $c(x,y,z,t)$ spanning 20 vehicle passes, and from those twenty realizations it was possible to approximate for each Casella sensor an ensemble mean concentration transient $\langle c \rangle$. Individual correction factors for the Casella instruments were assigned on the basis of an intercomparison with all instruments exposed close together during test passes of the vehicle.

Table 2 gives the micrometeorological conditions during the two experiments discussed here. A three-dimensional sonic anemometer at height $z_s = 2$ m and standing at $x/H = -3$ on the reference transect provided the mean wind vector $\overline{u}_i \equiv (\overline{u}, \overline{v}, \overline{w})$, the mean kinematic sensible heat flux density vector $\overline{u_i' T'}$ and all components of the Reynolds stress tensor $\overline{u_i' u_j'}$. From that information the friction velocity (u_*) and Obukhov length (L) were computed as

$$u_* = \sqrt[4]{\overline{u'w'}^2 + \overline{v'w'}^2}, \tag{1}$$

$$L = \frac{-u_*^3 T_0}{g k_v \overline{w'T'}}, \tag{2}$$

where $k_v = 0.4$ is the von Karman constant, g is gravitational acceleration and T_0 is the mean Kelvin temperature. Roughness length was inferred by best-fitting the Paulson (1970) mean wind profile, using the Monin–Obukhov universal functions recommended by Dyer and Bradley (1982), to the mean wind speed, friction velocity and heat flux density provided by the sonic anemometer. The reference wind speed $U_r = \overline{u}(12\ \text{m})$ cited in Table 2 was computed by extrapolation using the resulting mean wind profile.

3. Numerical simulations

A preliminary analysis of the experiments established that such data as it had been possible to gather would not suffice to

[1] In this respect (and several others) the present work differs from that of Steffens et al. (2012), whose focus was the fate of sub-micron particles raised by ambient traffic on a paved urban motorway during a period of *very light* winds (mean wind speed $\overline{u} = 0.57$ m s^{-1} at $z = 3$ m).