Journal of Environmental Management 92 (2011) 2855–2859

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Simple estimates of vehicle-induced resuspension rates

A. Escrig [a,*], F. Amato [b], M. Pandolfi [b], E. Monfort [a], X. Querol [b], I. Celades [a], V. Sanfélix [a], A. Alastuey [b], J.A.G. Orza [c]

[a] *Instituto de Tecnología Cerámica-AICE, Universitat Jaume I, Campus Universitari Riu Sec, Avda. de Vicent Sos Baynat, 12006 Castelló, Spain*
[b] *Institute of Environmental Assessment and Water Research, IDAEA, Spanish Research Council (CSIC), C/ Jordi Girona 18-26, 08034 Barcelona, Spain*
[c] *SCOLAb, Departamento de Física Aplicada, Universidad Miguel Hernández, Avda. de la Universidad S/N, 03202 Elche, Spain*

A R T I C L E I N F O

Article history:
Received 26 July 2010
Received in revised form
8 June 2011
Accepted 21 June 2011
Available online 18 July 2011

Keywords:
Resuspension
Fugitive emissions
Emission factors
Paved roads

A B S T R A C T

Road dust emissions are considered to be a major source of airborne particulate matter (PM). This is particularly true for industrial environments, where there are high resuspension rates of deposited dust. The calculation of roads as PM emission sources has mostly focused on the *consequences* of this emission, viz. the increase in PM concentrations. That approach addresses the atmospheric transport of the emitted dust, and not its primary origin. In contrast, this paper examines the *causes* of the emission. The study is based on mass conservation of the dust deposited on the road surface. On the basis of this premise, estimates of emission rates were calculated from experimental data obtained in a road in a ceramic industrial area.

1. Introduction

Road dust emissions belong to everyday experience: it can be readily observed that dust is emitted when a vehicle travels on a dusty road. Road dust emission is often referred to as resuspension. This term contains the implicit information that it is not an actual source of airborne particulates, but a process that returns the deposited particles to the air. This is of course an ideal situation, since there is no a priori reason to restrict the origin of the road dust to atmospheric deposition. Newly generated particles can arise from brake, tyre, and road surface wear, for example in unpaved roads where the emitted particulates are part of the road itself.

The consequences of road dust resuspension from paved roads are inferred to be highly significant for urban air quality (Querol et al., 2004). Amato et al. (2009a) estimated that, in the city of Barcelona (Spain), resuspension had a similar impact on the levels of atmospheric particulate matter (PM) to that of exhaust emissions. Resuspension even prevailed over traffic-generated emissions in industrial areas where dusty raw materials were handled (Abu-Allaban et al., 2006).

Studies have been undertaken to calculate paved roadways as sources of PM, using techniques such as non-depositing tracers (Claiborn et al., 1995), or measuring vertical concentration gradients both upwind and downwind of a roadway (Cowherd and Englehart, 1984). These techniques evaluate overall emissions, including tailpipe emissions. There is also some doubt regarding the validity of such techniques, as Venkatram (2000) discussed in detail.

In the present study, road dust emission estimates were obtained by means of simple sampling instruments and interpretation models. To this end, the assumed properties of the system being studied were explicitly formulated. On the basis of these properties, tentative resuspension rates were calculated.

2. Theoretical considerations

Venkatram (2000) noted that if road dust emissions depend on the amount of dust deposited on the road surface, this dust loading must evolve with time until it is replenished at the same rate as it is removed. A simple mass balance helps to visualize this fact. Let M be the mass of road dust per unit area at a time t, and J the dust deposition flux. Accepting that road dust removal (i.e. emission flux) is a continuous process described by an unknown function of M, denoted by $f(M)$, the time evolution of M must obey:

$$\frac{dM}{dt} = J - f(M) \quad (1)$$

Two additional assumptions are made: (i) J is constant in time, and (ii) $f(M)$ increases monotonically with M. Indeed, these hypotheses are often tacitly assumed.

* Corresponding author. Tel.: +34 964342424; fax: +34 964342425.
E-mail address: aescrig@itc.uji.es (A. Escrig).

0301-4797/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2011.06.042

If it is assumed that, at a certain time, the value of M is such that $f(M) < J$, at the next (infinitely close) time, M will increase as will $f(M)$, so that the difference $J - f(M)$ will become smaller. In an infinite succession of such events, $f(M)$ will progressively augment as its magnitude balances with J, and $\mathrm{d}M/\mathrm{d}t$ approaches zero. As a result, in a sufficiently long time, an equilibrium value of M will be reached.

This result is, however, not new. Several empirical models have been devised to fit the time variation of M after a runoff episode (Alley and Smith, 1981; Grottker, 1987). These empirical formulae can be derived from Equation (1), assigning a first-order kinetics to $f(M)$. In this case, Equation (1) becomes:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = J - k \cdot M \tag{2}$$

If the road dust mass at time $t = 0$ is designated by M_0, the analytical solution of Equation (2) is:

$$M = \frac{J}{k} + \left(M_0 - \frac{J}{k}\right)\exp(-k \cdot t), \tag{3}$$

which is formally analogous to the model proposed by Alley and Smith (1981). The predicted equilibrium value for M is thus:

$$M_\infty = \frac{J}{k} \tag{4}$$

The US EPA AP-42 model for $f(M)$ (Cowherd and Englehart, 1984) is of the form:

$$f(M) = V \cdot a \cdot M^b \tag{5}$$

where V is the traffic flow rate, and a and b are empirical constants. The equilibrium value predicted by this model can be obtained by substituting Equation (5) into the mass balance (1):

$$M_\infty = \left(\frac{J}{V \cdot a}\right)^{1/b} \tag{6}$$

Nevertheless, there is a fundamental problem in considering $f(M)$ to be directly proportional to V. This important observation was made by Nicholson (2001): "unless the input of material on to the road surface is directly related to traffic density, then the amount resuspended cannot be proportional to the number of vehicles passing a given point". In other words, if an equilibrium between deposition and resuspension is reached, then the resuspension rates will be independent of the traffic flow rate unless the vehicles themselves contribute to road dust deposition.

A further point of criticism is the assumption that $f(M)$ depends *only* on M. It has been shown that a number of other factors influence this emission rate (Nicholson et al., 1989; Nicholson and Branson, 1990). Vehicle speed seems to play a particularly important role. The second version of the AP-42 model included a dependence on vehicle weight. However, traffic speed was found to be correlated with road dust loading and it was preferred to use dust loading as an independent variable for introducing seasonal variability, since vehicle speed does not vary substantially during the year (US EPA, 1993).

Independently of the above caveats, the asymptotic behaviour predicted by the models of the form of Equation (1) was experimentally observed (Pitt, 1969; Grottker, 1987), which suggested that they provided at least a rough description of the system under study (though not necessarily of another road with different characteristics). The equilibrium itself and an increase in emissions with dust loading seem to be typical properties. If this identification is equivocal, roads will accumulate unlimited dust (unless the dust is externally removed), which is not the observed behaviour. The existence of this balance was, in fact, recognized in the AP-42 document (US EPA, 1993).

3. Methods

3.1. Study site

The study site was located on an industrial estate at L'Alcora (eastern Spain). This area is characterized by a high concentration of ceramic tile manufacturing facilities. The selected paved road is the main access to an important spray-dried granule producer. Spray-dried granules are raw materials used in ceramic tile manufacture and are produced as follows: the raw materials making up the tile body composition are wet milled, yielding an aqueous slurry that is then sprayed in a stream of hot air, producing highly uniform, more or less spherical, hollow granules. This form of powder has high flowability, facilitating accurate filling of the press dies for subsequent pressing of quite large tiles.

The selected paved road was about 1 km long and 5 m wide. There was a narrow (less than 1 m wide) pedestrian pavement between the roadway and the walls of the industrial facilities surrounding this transect. More than 500 dump trucks used this road everyday, most of which transported clay or spray-dried granules. As a result, appreciable quantities of mineral dust were deposited on to the road surface, and the resuspension of dust in this road was an observable fact.

During the study campaign, periods with street cleaning practices were alternated with non-cleaning periods. The street cleaning activities consisted basically of manual sweeping followed by washing with pressurized water. These activities were performed every night during the periods summarized in Fig. 1. The starting time was either 12 p.m. or 4 a.m., in an alternating sequence. The effect of these measures on the particulate pollutant concentrations will be described in a forthcoming paper.

3.2. Road dust sampling

Samples of road dust were collected using a sampling instrument introduced by Amato et al. (2009b). An area of the active lane of the road was vacuumed with this sampler, traffic being detoured

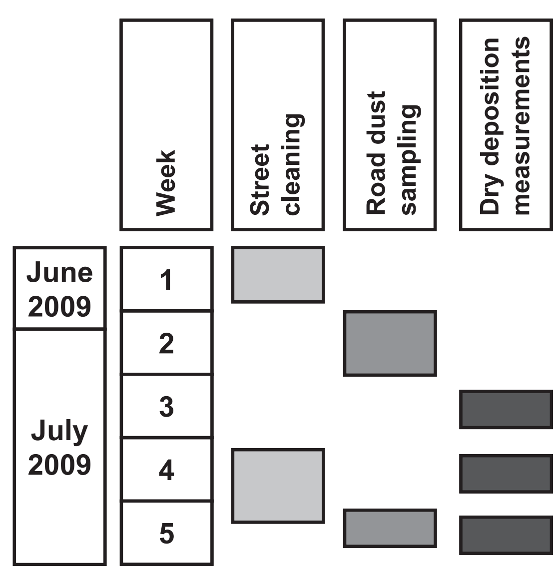

Fig. 1. Sampling calendar.