Reconciling Fugitive Dust Emissions with Ambient Measurements: Along the Unpaved Road

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ABSTRACT

The discrepancy between PM_{10} emissions inventories for fugitive dust and the fraction of crustal material found on ambient filters remains a concern for the air quality community. This paper describes recently completed work that sheds light on some issues related to the transportable fraction vs. the deposited fraction of PM_{10} dust from an unpaved road.

There are at least three different dispersion and deposition regimes downwind of an unpaved road located in a rural area. In the first regime that extends a few meters in the downwind direction, the "impact zone", the dust plume is introduced to the surrounding landscape. Depending on the ground cover, the plume may be thinned when particles collect on available surfaces. This process more closely resembles filtration than dry deposition in the classic sense. In the second regime stretching hundreds of meters downwind, the "near-source" region, the plume is rapidly expanding in the vertical direction. The concentration of dust particles is reduced due to both dispersion and deposition. In the third regime, the "far downwind" region, the concentration profile is nearly invariant with height, except at the ground where particles continue to be removed by dry deposition.

These three regions are examined in the context of a recently completed field study, a Gaussian dispersion and deposition model, and a proposed Box Model. Field data indicate that the fraction of PM_{10} dust particles deposited in the "near-source" region may be small for conditions of the arid southwestern United States. Results are
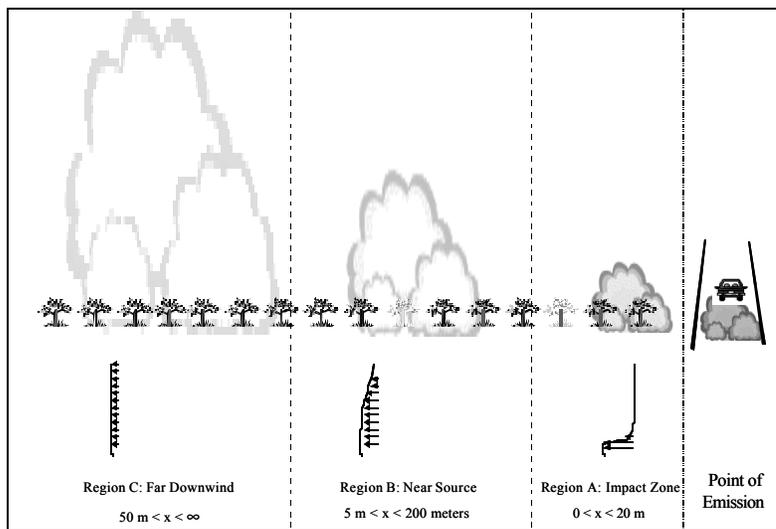
compared with other studies where measurable removal of PM_{10} was observed within a few hundred meters of the source.

INTRODUCTION

Fugitive dust is emitted from an unpaved road when a vehicle passes and disturbs the soil. A cloud of dust is raised behind the vehicle and begins to travel downwind. Initially, the dust cloud is very dense, sometimes to the point of being opaque, but with travel downwind, the cloud is dispersed by mechanical mixing at the ground and by buoyant eddies in the atmosphere. Particles suspended in the cloud can be removed by interaction with the vegetative cover in the downwind fetch of the unpaved road.

Figure 1 schematically illustrates the progression of a dust plume emitted behind a vehicle and advected downwind over a vegetative cover. In the region (A) where the dust cloud first meets the vegetation, dust particles may be removed by individual vegetation elements. Though possibly significant, none of the models or measurements discussed here is geared towards quantifying the extent of removal in this "impact zone". Some work in the area of particle removal by windbreaks may be applicable to this region[1] though the specific formulation would have to be adjusted for vegetative covers with a long fetch[2,3].

Figure 1. Development of a dust plume downwind of an unpaved road.

Region C: Far Downwind	Region B: Near Source	Region A: Impact Zone	Point of Emission
50 m < x < ∞	5 m < x < 200 meters	0 < x < 20 m	

Very far downwind (Region C in the figure), the dust plume approaches a steady concentration profile that does not change very much with transport downwind. In between the "impact zone" and the "Far downwind" region, the concentration profile of dust particles is changing with transport distance; specifically, the dust plume is expanding in the vertical direction. The models discussed here are most concerned with this region, where it is necessary to simulate the expansion of the dust plume in the vertical direction simultaneously with the removal of particles at the ground by the vegetative cover. These two processes are turbulent dispersion and dry deposition, respectively.

In this paper, we consider two preliminary attempts at modeling the deposition and dispersion of fugitive dust emitted from an unpaved road. The first approach relies

on the assumption of a Gaussian plume[4] while the second utilizes a simple box model[5]. The two models are compared to one another and to results from two field studies[6,7].

METHODS

Gaussian Model Approach

The ISC3 Short-Term dispersion model (ISC3 hereafter) is built on the approximation that a plume dispersing in the atmosphere assumes a shape similar to a Gaussian distribution[4]. The ISC3 utility allows for simulation of point, area, and volume sources with the aid of hourly meteorological data. Point and volume sources are treated in essentially the same way; volume sources are assumed to be point sources that originated at some distance upwind. Area sources are treated as multiple point sources. Line sources can be approximated by using multiple area or volume sources. The ISC3 also includes a number of optional parameters that can be used for adjusting the height of a plume (e.g. in the case of hot or high-speed stack gases), accounting for building downwash, and dispersion in complex terrain. For simulating a road dust plume generated by the movement of a vehicle on an unpaved road, the volume source approach is most directly applicable; accordingly, we will restrict the presentation of the ISC3 model to volume sources and omit material that is not directly applicable to unpaved road dust emissions.

The Gaussian representation of the concentration profile in the ISC3 model is actually a result of an approximate analytical solution to the Atmospheric Diffusion Equation under certain atmospheric conditions. It works best for sources that are high enough above ground that the dispersion parameter can be considered roughly constant. The applicability and limitations of Gaussian approaches to dispersion modeling have been considered by other investigators[8] and an in depth discussion is omitted here.

The basic equation that is solved for the ground-level concentration C ($\mu g/m^3$) downwind of a point source is

$$C = \left(1 \times 10^{-6}\right) \frac{QVD}{2\pi u_s s_y s_z} \exp\left[-0.5\left(\frac{y}{s_y}\right)^2\right]$$

Equation 1

where

Q = pollutant emission rate (g/s)

V = a vertical term that includes the effects of ground reflection, dry deposition, and vertical mixing

D = chemical decay term (assumed equal to 1 since road dust is non-reactive)

s_y, s_z = standard deviation of vertical and lateral concentration distribution

u_s = mean wind speed at release height.

For a continuous line source of non-reactive material (i.e. D=1); Equation 1 may be integrated over -∞ < y < +∞ to obtain

$$C = \left(1 \times 10^{-6}\right) \frac{\dot{Q}V}{\sqrt{2}\boldsymbol{p}u_s\boldsymbol{s}_z}$$

Equation 2

where the dot over the Q indicates that the source strength is expressed in terms of a unit crosswind distance (i.e. (g/s)/m). The most important parameter in the ISC3 model with regard to a continuous line source is the vertical standard deviation $\boldsymbol{s}_z$ which completely specifies the concentration distribution and therefore, also the vertical gradient. This is accomplished through the vertical term V in Equation 2 which, in the absence of deposition is specified as

$$V = \exp\left[-0.5\left(\frac{z_r - h}{\boldsymbol{s}_z}\right)^2\right] + \exp\left[-0.5\left(\frac{z_r + h}{\boldsymbol{s}_z}\right)^2\right] + [.....]$$

Equation 3

where z_r is the height at which the concentration is to be evaluated, and h is the initial height of the release. To account for the reflection of the plume at ground level, the first two terms on the RHS of the equation actually represent two sources, one located at h, and one at −h. For road dust, it may be assumed that the release height of the plume is the ground. The release height is different from the initial vertical depth of the plume (discussed below). The unspecified bracketed term on the far RHS of Equation 3 is used to account for multiple reflections between the ground and the mixing height. This term can be ignored for a ground-level release provided that the analysis does not proceed too far downwind (i.e. $\boldsymbol{s}_z$ <<mixing height).

The dispersion parameter $\boldsymbol{s}_z$ is dependent on the downwind distance x and is given by an equation of the form

$$\boldsymbol{s}_z = ax^b$$

Equation 4

The parameters a and b are determined by the atmospheric stability and the distance downwind of the source[9].

Using a modeled deposition velocity[4], dry deposition can be accounted for in the ISC3 by numerically integrating the removal rate over the distance downwind of the source. If the removal by deposition is slow compared to the rate of dispersion, then it is a reasonable approximation to apply the fractional removal at each time (distance) step to the entire concentration profile. In practice, this is only valid during neutral to unstable conditions, and even then, only when the deposition velocity is not too large. Other options are available for more accurate representation of the effect of deposition, and the ISC3 model accommodates their use. However, the computational cost of using them is not warranted for the present purpose.
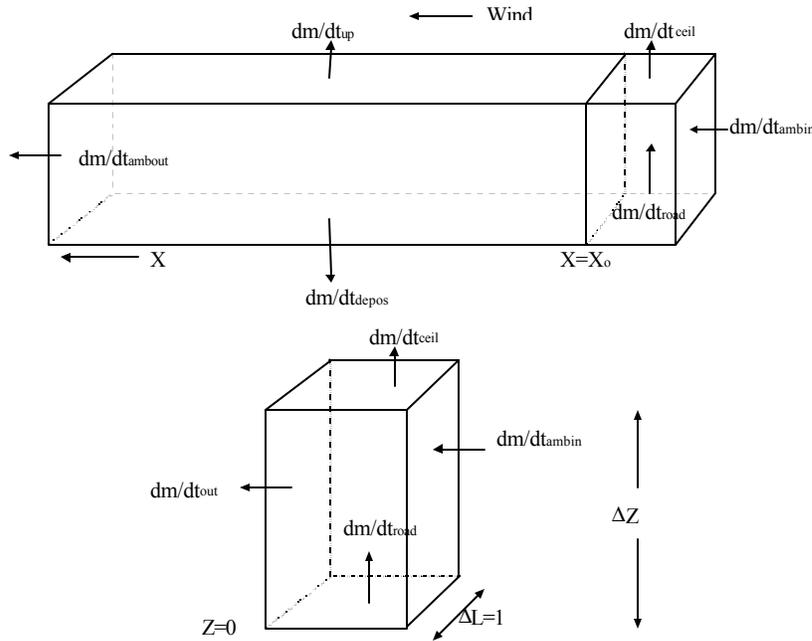
When a vehicle passes over a road, the plume generated behind the vehicle has a discrete depth in the vertical direction. This depth is a measure of the initial breadth of the plume and is different from the plume release height. To account for the fact that the

dust plume is initially dispersed by the turbulent wake of the vehicle, a "virtual" distance is added to the value of x in Equation 4. For example, the virtual distance x_0 is calculated by solving the equation for the initial value $\mathbf{s}_{z0}$. Since $\mathbf{s}_z$ is the standard deviation of the concentration in the vertical direction assuming a gaussian (Normal) distribution, then 95% of the plume is initially below the height $2\times\mathbf{s}_{z0}$. Therefore, we may approximately define $\mathbf{s}_{z0}$ as one half the "injection height" or the height of the influence of turbulence generated in the wake of a vehicle.

Box Model Approach

      Gillette[5] proposed a mass balance approach for estimating the transportable fraction of fugitive dust from an unpaved road using a simple box model such as the one shown in Figure 2. The ratio of the mass per unit time emitted through the ceiling of the CV downwind of the road (dm_{up}/dt) to the mass emitted from the road (dm_{road}/dt) can be considered the regionally "transportable fraction". This fraction Φ is given in Equation 5.

Figure 2. Control Volume for Box Model.

Wind

dm/dt_{up} dm/dt_{ceil}

dm/dt_{ambin}

dm/dt_{ambout}

dm/dt_{road}

X $X=X_o$

dm/dt_{depos}

dm/dt_{ceil}

dm/dt_{ambin}

dm/dt_{out}

dm/dt_{road}

ΔZ

$Z=0$ $\Delta L=1$

$$\Phi = \frac{\dfrac{dm_{up}}{dt}}{\dfrac{dm_{road}}{dt}} = \left[1 - \frac{V_d}{(V_d + K)}\right] = \frac{K}{(V_d + K)}$$

Equation 5

where

$$K = Au_*$$

Equation 6

The deposition velocity, V_d, depends on a number of parameters including the friction velocity (u_*) and the particle size[10]. The value of A was derived by using data of Porch and Gillette[11] (1977) and Gillette[12] (1974). Porch and Gillette[11] (1977) provided data on fast-response concentrations of diffusing dust simultaneously taken with fluctuation vertical wind speeds at the same location. Analysis of the high-speed data showed that the aerosol flux could be expressed approximately as $0.04u_*[C]$ where $[C]$ is the mean mass concentration. Analysis of gradients of dust concentration in wind-eroding fields[12] showed that the aerosol flux could be expressed as approximately $0.07u_*[C]$. The mean of the coefficients gives a value of 0.06 for A.

Using Equation 5 with K equal to $0.06\ u_*$, yields the "transportable fraction" of fugitive dust emitted from the road. Practical application of Equation 5 can use values of V_d chosen to represent particle size and environmental conditions, for example, those of Slinn[10] (1982). Values of u_* are chosen by the user to represent the environmental conditions of interest.

RESULTS

The fraction of particles removed is shown for multiple downwind distances in Figure 3 a-e. One interesting result is that when the friction velocity is 0.1 m/s, the removal of particles is greater than when it is 0.3 m/s; however, as u_* continues to increase, the removal of particles also increases. The key to understanding this behavior is that the deposition velocity for particles also increases with friction velocity. For values of u_* that are higher than a certain threshold (near 0.3 m/s for the conditions of Figure 3) the greater mixing that occurs is more than offset by the greater deposition rate, resulting in a net increase in particle removal. The opposite is true for values of u_* that are less than the threshold.

The ISC3 model indicates that under neutral to unstable conditions, the fraction of particles remaining in suspension for values of $u_* \leq 0.5$ m/s is greater than 78% at a downwind distance of 1 km and greater than 59% at a downwind distances of 10 km. Even for a very high friction velocity ($u_*=1.2$ m/s) the fraction of particles remaining in suspension 1 km downwind is greater than 50%. Note that in arid regions, very high values of u_* initiate wind blown dust storms, which can dwarf the emissions of dust from an unpaved road. The degree of particle removal is greater under stable conditions than neutral and unstable conditions. This is intuitive, since in the absence of buoyant mixing, particles are likely to remain closer to the ground where they can be removed by impaction and gravitational settling. Stable conditions cannot exist when the friction velocity is high because mechanical mixing does not allow for stratification to occur to any appreciable extent (there is always a small stable layer near the ground at night, though it may only be a few centimeters in depth when wind speeds are high). Therefore, conservatively assuming that u_* does not exceed 0.5 m/s when conditions are stable, the removal of particles 1 km downwind of the unpaved road is not likely to be greater than about 50%. There is an exception to this result that occurs when the friction velocity is nearly zero (i.e. very little vertical mixing and downwind transport) and particles settle to

the ground under the influence of gravity. In this case, the dispersion models presented here are not applicable, and the fraction of particles remaining in suspension decreases linearly with time since emission (e.g. Figure 4). It seems unlikely that there would be a significant amount of motor vehicle traffic on unpaved roads during nighttime stable conditions. Thus, though removal of particles under stable conditions is considered for completeness, we note that for most emissions from unpaved roads, conditions are probably neutral to unstable.

Figure 3f. shows the fraction remaining in suspension according to the box model for various values of the parameter A in Equation 6. The deposition velocity for the box model was computed assuming a height of 1 meter and neutral stability. Note that the box model gives a result that is independent of distance downwind of the source. For all values of A, the box model captures the general behavior of particle deposition to a surface; the greater the dispersion rate (as characterized by A and u_*), the smaller the fraction of particles that deposit. However, comparison of Figure 3f. with the other five panels in the figure (ISC3 model results) underscores the basic difficulty of using the box model: Though in its derivation the box model does not depend on the height of the box or the downwind distance, the parameter A used in the model depends on both. A also depends on atmospheric stability.

Gillies et al.[6,13] (2002) measured the removal of PM_{10} dust emitted from an unpaved road at 50 m and 100 m downwind. There results, obtained for unstable conditions over sparsely vegetated terrain, indicated that there was no measurable removal of PM_{10} at 100 m downwind of the source. That is, nearly all of the PM_{10} emitted from the unpaved road is regionally transportable. This appears to be in good agreement with the predictions from the ISC3 model (Figure 3d). In contrast, Veranth et al.[7] (2003) performed similar measurements during nighttime stable conditions over very rough terrain. They measured an 85% removal (15% remaining) of PM_{10} over the first 95 m downwind of the unpaved road. The Gaussian model (Figure 3a) appears to substantially over predict the transportable fraction of PM_{10} under those conditions. This indicates that the model requires additional tuning prior to widespread use.

Finally, the removal of dust in the area near a source is often assumed to be significant because concentrations of particles downwind of a source rapidly attenuate to the background. This is an erroneous deduction. Watson and Chow[14] (2000) and Countess[15] (2001) both cite an earlier study[16] where the concentration of PM_{10} dust was found to decrease by 90% only 50 m downwind from the source. The concentration of particles may decrease rapidly with downwind distance, but it is incorrect to assume that the decrease is due solely to deposition. This concept is illustrated in Figure 5. The figure clearly shows that while concentrations decrease rapidly downwind of the source, the actual fraction of particles remaining in suspension may be quite high. For example, according to the ISC3 model, under neutral conditions, the concentration at a height of 1 meter 200 meters downwind of the road is 6% of its value near the road (within a few meters). However, 90% of the particles are still in suspension at the same downwind distance. Clearly, the decrease in concentration can be due primarily to the vertical mixing of particles and is not necessarily due to deposition.

Figure 3. Fraction of particles remaining in suspension for a given downwind distance. Panels a through e correspond to numerical solutions to the ISC3 with z_0=0.01 m, D_p=8 ▬▬m. under various conditions of atmospheric stability. The downwind distance is estimated based on the wind speed at 10 m assuming a logarithmic profile and z_0 = 0.01 m. Panel f shows the fraction remaining according to the box model for various assumed values of A. Under unstable and very unstable conditions, the algorithm of the ISC3 cannot be used past 5,000 m and 1,000 m, respectively.

a. very stable (L=10 m)

b. stable (L=1,000 m)

c. neutral |L|>100,000

d. unstable (L=-1,000 m)

e. very unstable (L=-10 m)

f. Box model for various values of the parameter A
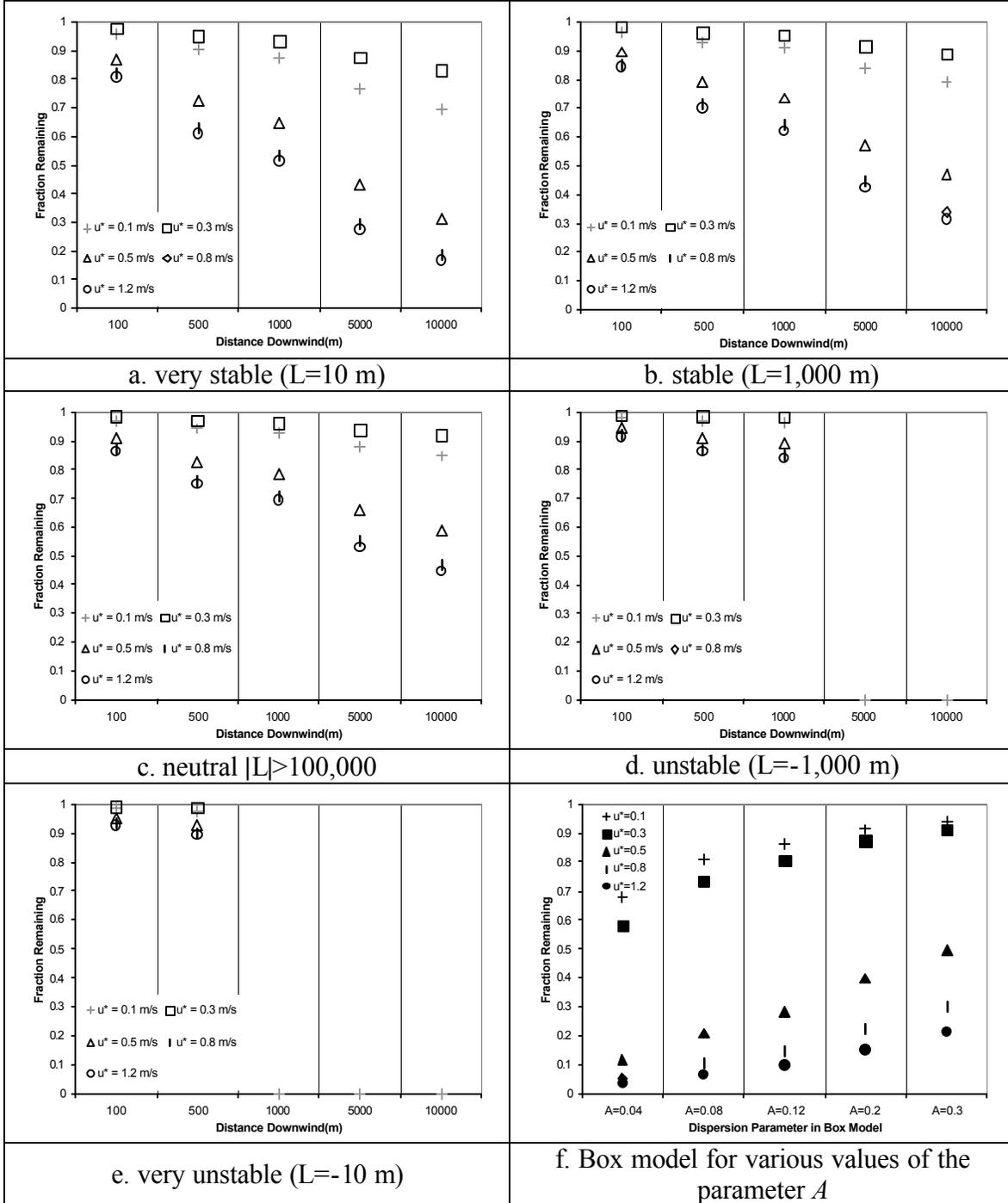
Figure 4. Fraction of particles remaining in suspension vs. time since emission for 8 ▮m particles falling under the influence of gravity in the absence of any dispersion (u∗=0).
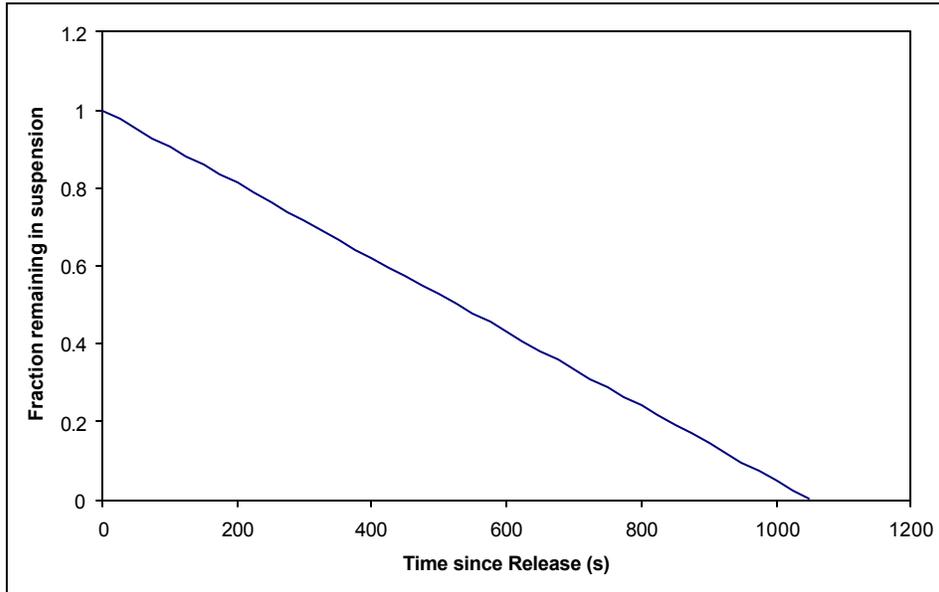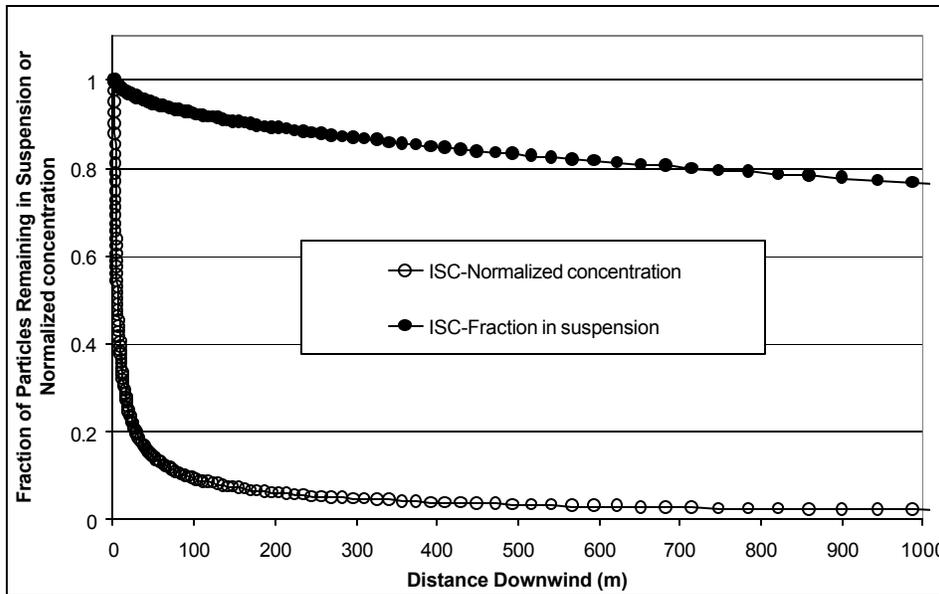

Figure 5. The fraction of particles remaining in suspension and the Concentration at a height of 1 meter above ground level vs. time for neutral atmospheric conditions according to the ISC3 model. z_0=0.01 m, D_p=8 ▮m, u_* = 0.3 m/s in all cases.

CONCLUSIONS

For unpaved road dust emissions, the Box Model provides an order of magnitude estimate of the dust particle removal due to deposition. For a more accurate assessment, a model that accounts for changes in the concentration profile with downwind distance is required. The algorithm of the ISC3 is reasonably well-suited for simulating near-source

dispersion. However, comparison with field studies indicate that the model needs substantial modification and verification prior to widespread use.

KEYWORDS

Emission Inventory

Fugitive Dust

Deposition

Dispersion

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