AN ESTIMATION OF PRESENT AND PROJECTED DIESEL PARTICLE EVOLUTION OVER CHICAGO

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Abstract. The impact of a potential increase in vehicular diesel emissions on atmospheric particle concentrations and size distributions in a large urban area (Chicago) is investigated numerically, for idealized meteorological conditions. Results indicate that the projected increase in diesel emissions would affect mainly the concentrations of particles with diameters smaller than 1 μm; larger particles would not be affected significantly. The particle concentrations in the accumulation mode (diameter near 0.2 μm) would be increased by about a factor of ten, while the concentration of particles of the Aitken nuclei mode (diameter near 0.02 μm) would be reduced significantly. The area in which the annual average air quality particulate standard is exceeded is quite small for the reference case based on emissions in 1983, but would increase to cover almost the entire urban area for the projected increase in diesel emissions in 2000.

1. Introduction

The use of diesel automobiles has attracted considerable attention because they consume approximately 25% less fuel by volume than gasoline engines of the same power (e.g., Paul, 1979). The potential impact upon the environment, however, is not clear. In comparison with gasoline engines, diesel engines produce less CO and total hydrocarbons, but generate a new spectrum of hazardous, potentially carcinogenic, pollutants (e.g., Santodonato et al., 1978). The most obvious emission increase from diesel engines is substantially more particulate matter. In addition, more than 90% of the mass of diesel emissions is in the form of particles of diameters less than 1 μm. These sizes are generally considered respirable as they are capable of passing into the pulmonary alveoli without significant impaction and removal in the upper respiratory track.

In a study by Paul (1979) on the impact of future diesel emissions on the air quality of large cities, an empirical relationship between transportation emissions and ambient levels of total suspended particle was used with projected emission data to predict future atmospheric concentrations of total suspended particles at a selected location. However, the particle size distribution, which is one of the most important components in studies of health effects and particle transport, was not addressed. In the present study, a numerical model capable of predicting particle size distributions is used to simulate dispersion of vehicular particle emission over a large urban area, and to examine the potential impact of future diesel emissions.
2. Description of the Model

The numerical model used here is similar to the earlier work by Sheih (1977), but some improvements have been made in the numerical scheme, and the treatment of surface dry deposition has been changed. The transport equation used for each particle size considered is

\[ \frac{\partial n_j}{\partial t} + u_j \frac{\partial n_j}{\partial x_j} = v_g \frac{\partial n_j}{\partial z} + \frac{\partial (K_j \frac{\partial n_j}{\partial x_j})}{\partial x_j} + Q + S, \]  

(1)

where \( n_j \) is the particle number concentration density of diameter \( D_j \) such that \( n_j \Delta D_j \) is the number concentration of particles with diameters between \( D_j - \Delta D_j / 2 \) and \( D_j + \Delta D_j / 2 \), and \( x_j \) is a coordinate component, \( z \) is the vertical coordinate, and \( u_j \) and \( K_j \) are the components of mean wind velocity and eddy diffusivity, respectively. For each particle size interval, \( v_g \) is gravitational settling velocity, \( Q \) is the pollutant emission rate, and \( S \) is the coagulation term. The repeated subscripts in the terms of Equation (1) indicate summation.

The gravitational settling velocity and coagulation rate are computed from the formulae given by Fuchs (1964) as follows,

\[ v_g(r) = \frac{2gr^2}{9v} \left[ 1 + \frac{Al}{r} + \frac{gl}{r} \exp \left( -\frac{\beta r}{l} \right) \right], \]  

(2)

\[ S(r, t) = \frac{1}{2} \int_{r_a}^{2^{1/3}r} P(\eta, \xi) n(\eta, t) n(\xi, t) \left( \frac{r}{\xi} \right)^2 d\xi \]

\[ -n(r, t) \int_{r_a}^{r_b} P(r, \xi) n(\xi, t) d\xi, \]  

(3)

with \( n = (r^3 + \xi^3)^{1/3} \). In these equations, \( r \) is the particle radius, \( g \) is the gravitational acceleration, \( v \) is the kinematic viscosity of the air, and \( r_a \) and \( r_b \) are the lower and the upper limits of the range of particle sizes present. The quantities \( A, l, \beta, \) and \( q \) are constants, and \( P(\eta, \xi) \) is the probability of coagulation of two particles with radii of \( \eta \) and \( \xi \).

Since the primary objective of the present study is to investigate the relative impact of a projected increase in diesel emissions with respect to a base case, the meteorological conditions assumed will be very simple. The atmosphere is assumed to have a neutral stability, a 1000-m inversion height, and a wind velocity of 10 m s \(^{-1}\) from southwest at the inversion. Wind velocities for other levels below the inversion height are obtained by interpolation with the \( 1/7 \)-power law. The vertical eddy diffusivities are computed from the formula for neutral stability used by Shir and Shieh (1974) as follows,

\[ K_z = k^2 uz \left[ \ln (z/z_0) \exp (4z/H) \right]^{-1}, \]  

(4)