Model Simulation of Ultrafine Particles inside a Road Tunnel

A contribution to subproject SATURN

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Summary

Various internationally published studies have found a relation between the concentration levels of suspended particulate matter (SPM) and health effects reflected in e g mortality rate, cardiovascular and respiratory deseases. In July 19 of 2001 a new Swedish regulation came into force, regulating the PM10 mass concentrations in ambient air. The most relevant physical parameter – among e g size, area, volume or composition - to characterize SPM effects on health is however under debate. Within heavily trafficed areas there is marked increase of the number of ultrafine (<100 nm) particles, typically with a maximum for a particle diameter of 20-30 nm, but there are also reports of a high peak also for particles <10nm close to roads (Harrison et al, 1999). Taking into account the potential health effect of those ultrafine particles and the fact that they do not contribute significantly to PM10 mass, it is important to investigate their generation, lifetime and general properties. The present work is an attempt to develop a modeling tool for studying the dynamics of different particles sizes in a heavily trafficked urban environment.

Aim of the research

Simulate the fate of vehicle emitted ultrafine particles inside a road tunnel and, through comparison with field measurements, conclude about their generation, mixing and transformation.

Activities during the year

A commercial CFD (*Computational Fluid Dynamics*) model package is used as a base for the calculations. The CFD model resolves the momentum, turbulence and transport equations, allowing the user to formulate source and sink terms. To the CFD model is coupled the MONO32 aerosol dynamical model, developed at the University of Helsinki (Pirjola and Kulmala, 2000). Particle size distribution for the tunnel application is treated by 5 size modes (Table 1), in which all particles are assumed to be of equal size and composition (internally mixed). The MONO32 model can handle nucleation, coagulation, condensation/evaporation and deposition.

Table 1. Particle mode classification for the Södertunneln application.

Mode	*Name*	*Diam. Range (nm)*	*Density (kg/m^3)*
1	Nucleation	1 – 10	1500
2	Aitken 1	10 – 25	1500
3	Aitken 2	25 – 100	1500
4	Accumulation	100 - 2500	1500
5	Coarse	>2500	1500

The Söderledstunnel is a 1,1 km long road tunnel in the center of Stockholm. A monitoring campaign was realized inside the tunnel during the winter of 1998-1999 (Johansson et al., 2001), measuring both particle mass (TEOM) as well as particle number size distribution (DMPS). Those measurements were taken at station North, close to the tunnel exit (Fig. 1), which leaves almost one km for the vehicle exhausts to accumulate before reaching the monitoring site.

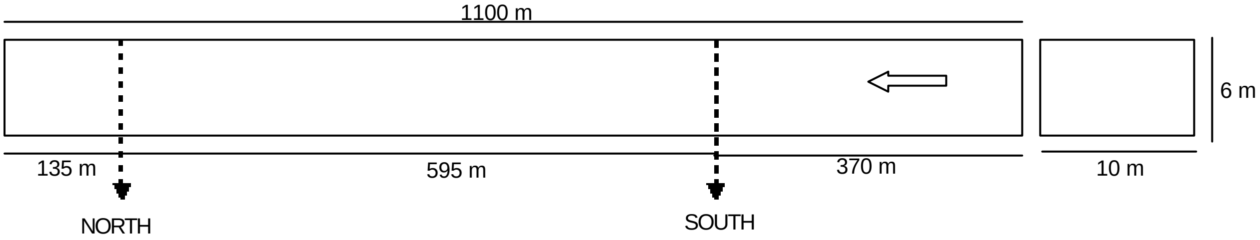

Figure 1. Principal drawing of the Söderledstunnel. The vehicles enter from the right, leaving the tunnel to the left.

There is a pronounced daily variation in mass and number concentrations, principally reflecting the traffic variation. The largest particles registered by the DMPS instrument (848 nm) has a daily variation similar to that of measured PM2.5 mass (Fig. 2a). Ultrafine particles of 52 nm size shows a pronounced peak at morning rush hours (between 8 to 9 am), while finer 12 nm particles has a clear minima during the morning rush hour (Fig. 2b).

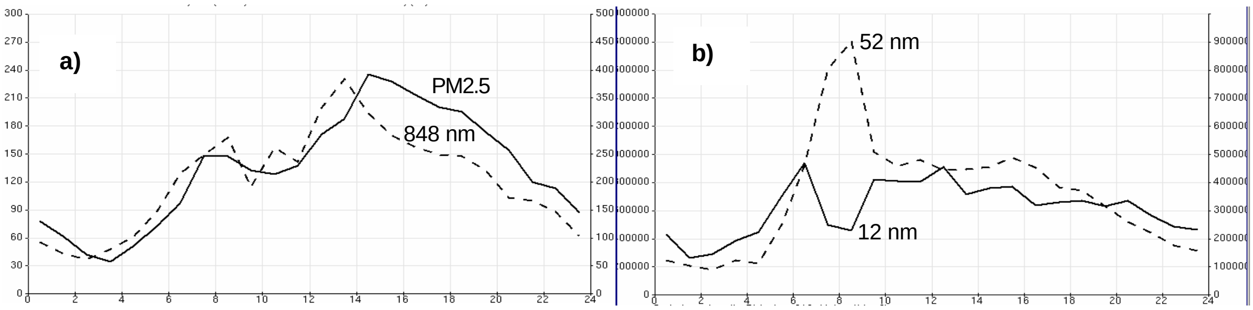

Figure 2. Daily variation pattern during workdays for PM2.5 mass and number concentrations of three different size modes (12, 52 and 848 nm). Monitor station "NORTH" (see Fig.1).

The differences in the daily variation patterns depicted in Fig. 2 can be attributed to emission variations, dispersion characteristics (principally the tunnel ventilation rate) and particle dynamics. The coupled CFD and MONO32 models are used to study the importance of those different mechanisms. The aerosol dynamical processes included in the study has so far been coagulation, self-coagulation and water uptake. The model results demonstrate the conditions under which coagulation is important for changing the ultrafine particle concentrations.

Principal results

The DMPS data together with traffic counts of LDV and HDV (light and heavy duty vehicles, respectively) were analyzed with multiple linear regression, resulting in emission factors according to Table 2. Those factors are used in model run I, for which the traffic intensity represents morning rush hour conditions (LDV=2286 and HDV=171 vehicles per hour, respectively).

Table 2. Particle radius and emission factors estimated from tunnel measurements (used for model simulation).

	Nucleation *3-10 nm*	***Aitken 1*** *10-25 nm*	***Aitken 2*** *25-100 nm*	***Accumulation*** *100-2500 nm*
Model (dry) radius (nm)	4,5	10,6	26,6	100
EF LDV in model (veh^{-1} km^{-1})	4,4 10^{13}	13,1 10^{13}	9,3 10^{13}	0,6 10^{13}
EF HDV in model (veh^{-1} km^{-1})	65,3 10^{13}	199,0 10^{13}	132,0 0^{13}	10,6 10^{13}

The particle number concentrations resulting from model run I are displayed in Fig. 3. The smallest particles (<10 nm) have maximum concentration about 650 m into the tunnel, with decreasing concentrations towards the tunnel end. This is due to coagulation with larger particle fractions, whose concentrations continue to increase all the way through the tunnel. A smaller curvature can also be seen for the Aitken 1 particle concentrations (size 10-25 nm). Fig. 4 illustrates the effect that coagulation has on the percentual composition of the emitted aerosols.

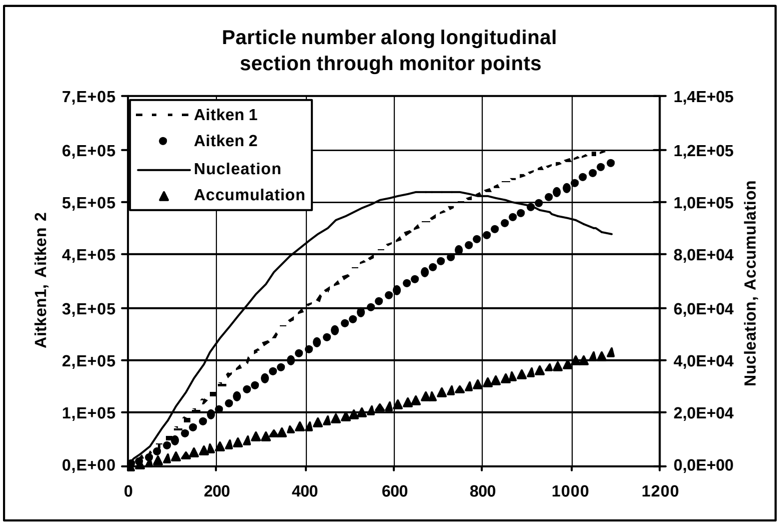

Figure 3. Particle number concentrations along a longitudinal transect through road tunnel (model run I)

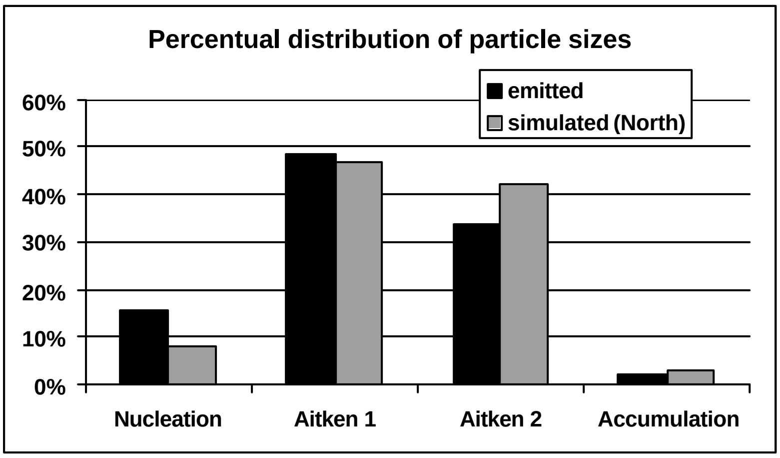

Figure 4. Redistribution of original (emitted) versus measured at station North) article number concentrations due to coagulation

In model run II the temporal variations are considered, noting that the traffic intensity of HDV is low during the morning rush hour (not shown). In order to compensate for the decrease of nucleation and Aitken 1 particles, the respective emission factors for HDV were increased and those for LDV decreased according to Table 3. The model results for model run II, using constant emission factors according to Table 3, is displayed in Fig. 5.

Table 3. Constant emission factors used in model run II

	***Nucleation* 3-10 nm**	***Aitken 1* 10-25 nm**	***Aitken 2* 25-100 nm**	***Accumulation* 100-2500 nm**
EF LDV in model (veh^{-1} km^{-1})	0,4 10^{13}	0,7 10^{13}	9,3 10^{13}	0,6 10^{13}
EF HDV in model (veh^{-1} km^{-1})	205,1 10^{13}	597,0 10^{13}	132,0 0^{13}	10,6 10^{13}

Fig. 5 shows that the model run II with constant emission factors works well for the two coarser modes, while it is not able to reproduce the decrease of Nucleation and Aitken 1 particle concentrations during the morning rush hour, neither it is able to keep the Nucleation particle concentrations high during the late afternoon and early night. According to Maricq et al. (1999) gasoline fuelled cars emit more particles at higher velocities. Velocities within the tunnel are rather constant, only markedly reduced during the morning rush hour. Such a velocity dependent emission may then be an explanation for the drop in particle number concentrations of the Nucleation mode. Consequently for the model run III, velocity dependent emission factors are introduced for the two finest particle modes:

$\mathrm{EF}_{\mathrm{LDV}}$ (Nucleation mode) = $(2{,}61 + (vel - 48)*0{,}392)\ 10^{13}$ $(veh^{-1}\ km^{-1})$

$\mathrm{EF}_{\mathrm{LDV}}$ (Aitken 1 mode) = $(1{,}18 + (vel - 48)*0{,}917)\ 10^{13}$ $(veh^{-1}\ km^{-1})$

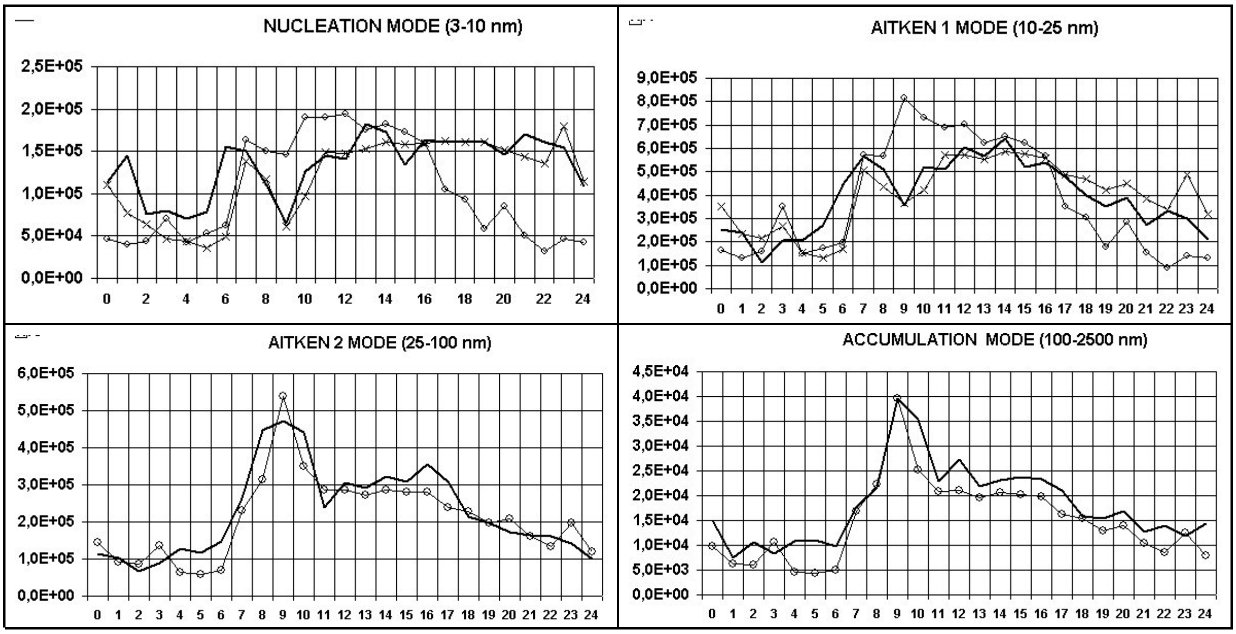

Figure 5. Particle number concentrations: Measured (solid line), constant emission factor (thin line, circles) and Velocity dependent emission factors (thin line, crosses)

With these emission factors, the model is able to reproduce the temporal variations in the particle number concentrations (Fig. 5) also for the two finer modes. Although qualitatively consistent with emission measurements like Maricq et al. (1999), the magnitude of the emission factors suggested for the Nucleation and Aitken 1 mode has so far not been able to be compared with published experiments (vehicle exhaust emission measurements rarely yield representative quantitative emission factors for particles smaller than 20-30 nm).

Main conclusions

The model application has demonstrated that coagulation influences notably the concentrations of particles smaller than 25 nm inside heavy trafficked road tunnels. A comparison between simulated and measured particle concentrations of those small particles suggests that their emission from the gasoline-fueled light duty vehicles increases with velocity.

References

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