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On-road measurements of ultrafine particle concentration profiles and their size distributions inside the longest highway tunnel in Southeast Asia

Yu-Hsiang Cheng [a,*], Zhen-Shu Liu [a], Chih-Chieh Chen [b]

[a] Department of Safety, Health and Environmental Engineering, Ming Chi University of Technology, 84 Gungjuan Road Taishan, Taipei 24301, Taiwan
[b] Institute of Occupational Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Taipei, Taiwan

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ABSTRACT

This study measured ultrafine particle (UFP) levels and their size distributions in the Hsuehshan tunnel from August 12 to 19, 2009, using a Fast Mobility Particle Sizer. Measurement results demonstrate that traffic volume, the slope of the tunnel (downhill or uphill) and the ventilation system affected UFP levels inside the tunnel. Average UFP levels were about 1.0×10^5–3.0×10^5 particles cm^{-3} at normal traffic volume. A traffic jam in the tunnel could raise UFP levels to over 1.0×10^6 particles cm^{-3}. UFP levels at the uphill bore were significantly higher than those at the downhill bore due to high UFP levels exhausted from vehicles going uphill at high engine load conditions. UFP levels eventually diluted 10–50% with fresh air from tunnel air shafts. Gas-to-particle condensation conversion markedly produced nucleation mode particles at the tunnel entrance section. Observations also showed Aitken mode particles markedly formed by coagulation growth of nucleation mode particles in the tunnel middle section and exit section. That is, the particle size distributions changed significantly inside the tunnel. Measurement results suggest that particles in the Aitken mode in the long tunnel governed UFP levels.

1. Introduction

Epidemiologic researches have shown increased adverse cardiovascular and respiratory outcomes related to freshly generated ultrafine particles (UFPs) which diameters less than 100 nm (Gilmour et al., 2004; Sioutas et al., 2005). UFPs are more harmful to health than large particles because they have higher order of magnitude particle number concentrations and surface area, and larger concentrations of adsorbed or condensed toxic air pollutants than large particles with the same mass. These particles reach and become deposited in the alveoli where they interact with epithelial cells (Oberdörster, 2001; Brown et al., 2002). The blood transports UFPs to other organs such as the liver, within 4–24 h after exposure (Oberdörster et al., 2002). Researches have also demonstrated UFP transport to the brain via the olfactory nerve (Oberdörster et al., 2004). UFPs from traffic exhausts can induce DNA damage due to systemic oxidative stress (Bräuner et al., 2007; Møller et al., 2008), thus exposure to fresh ultrafine particulate pollution is a serious environmental risk factor for cardiopulmonary and lung cancer mortality.

Over 80% of airborne particles in urban air are in the ultrafine size range (Shi et al., 2001). The concentration of UFPs correlates strongly with concentrations of NO_x and CO (Ketzel et al., 2003; Sardar et al., 2004; Pirjola et al., 2006; Beckerman et al., 2008; Hagler et al., 2009), suggesting that traffic emissions are the primary source of UFPs in urban environments. Mean number concentrations of UFPs in urban areas range between 1.0×10^4 and 2.0×10^4 particles cm^{-3} (Noble et al., 2003; Hussein et al., 2004; Matson, 2005). Number concentrations of UFPs near a major highway are $>10^5$ particles cm^{-3}, significantly higher than those for urban backgrounds by 5–10 times, and the UFP levels decrease exponentially with increased downwind distance from a highway (Zhu et al., 2002; Reponen et al., 2003; Pirjola et al., 2006; Beckerman et al., 2008; Hagler et al., 2009; Buonanno et al., 2009). For example, Hitchins et al. (2000) measure that at a distance of 100–150 m downwind from the road, UFP levels decrease to around half the level at 15 m from the road. Zhu et al. (2002) also note that the average UFP level at 30 m downwind from a highway is 1.5×10^5 particles cm^{-3}, and the UFP level decreases exponentially to background levels at 300 m downwind from the highway. Despite dilution of the exhaust plume downwind of the highway, Barone and Zhu (2008) note that particles may collide and merge causing an increase in the fraction of larger particles. Thus, coagulation may play a role in altering the particle size distribution at downwind of the highway.

* Corresponding author. Tel.: +886 2 29089899; fax: +886 2 29084513.
E-mail address: yhcheng@mail.mcut.edu.tw (Y.-H. Cheng).

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Studies have also found high levels of UFPs in highway tunnels since the tunnel is a confined space that may imprison particulate matter. Kirchstetter et al. (1999) show that UFP levels are $>2.0 \times 10^5$ particles cm^{-3} inside the Caldecott tunnel in San Francisco Bay. Geller et al. (2005) also obtain similar results in this tunnel and suggest that UFPs exhausted from diesel vehicles are higher than those exhausted from gasoline vehicles. Gouriou et al. (2004) demonstrate that UFP levels inside the uphill traffic bore are significantly higher than those inside the downhill traffic bore in the Grand Mare tunnel in Rouen. The levels of UFPs in the uphill traffic bore are $>5.0 \times 10^5$ particles cm^{-3}. This result indicates that high levels of UFPs exhausted from vehicles going uphill at high engine load conditions. UFP profiles inside the tunnel are a distance function from the tunnel entrance. UFP levels increase as downwind distance from the tunnel entrance increases. Weijers et al. (2004) note a nonsymmetrical number profile of UFPs inside the tunnel. Observations show the lowest levels of UFPs inside the tunnel entrance due to turbulence dilution by wind and moving vehicles. In addition, the levels of UFPs decrease abruptly at the tunnel exit. These measurement results indicate that UFP levels in the tunnel are over ten times higher than those for urban backgrounds. Passengers passing through these tunnels may be exposed to high levels of UFPs (Kaminsky et al., 2009). However, previous studies have been carried out in short tunnels (<2 km) to evaluate UFP levels. Research knows little about the magnitude of UFP number concentrations and their profiles inside the long highway tunnel and information on changing UFP size distributions inside the long tunnel is limited.

The Hsuehshan tunnel is the longest highway tunnel in Southeast Asia (ranked fifth in the world) with a total length of 12.94 km. This study measured UFP concentration profiles and their size distributions in the Hsuehshan tunnel using a Fast Mobility Particle Sizer (FMPS).

2. Materials and methods

2.1. Sampling site and ventilation system

Highway 5 (the Taipei-Yilan highway) is located in Northern Taiwan extending southeastward from metropolitan Taipei to Yilan County. The sampling site in this study was on Highway 5, 30 km southeast of Taipei City center (Fig. 1). The Hsuehshan tunnel cuts through the northern branch of Taiwan's central mountain range. The tunnel has two separate bores (southbound and northbound). Each bore is unidirectional with two lanes. The tunnel descends steadily from an elevation of 208 m at Pinglin at the north end with a downhill rate of 1.25% to an elevation of 44 m at Toucheng at the south end. Only passenger cars and buses are permitted to pass in the tunnel, and no trucks were allowed at the time of the current study. The vehicle speeds in the tunnel are limited to 50–80 km h^{-1} and 50–70 km h^{-1} for passenger cars and buses, respectively, with a distance between two vehicles maintained at around 50 m.

The tunnel is equipped with a ventilation system to maintain air quality containing three air exchange stations and three air interchange stations (Fig. 2). Fifty-six jet fans on the ceiling along the tunnel in each bore are also used as auxiliary equipments. The polluted air in each bore is exchanged with fresh air at the exchange station, using separate fresh and exhaust air shafts. The fresh air shaft is comprised of four sets of fans. Two sets of fans are used for supplying fresh, cold air from the shaft into the southbound bore

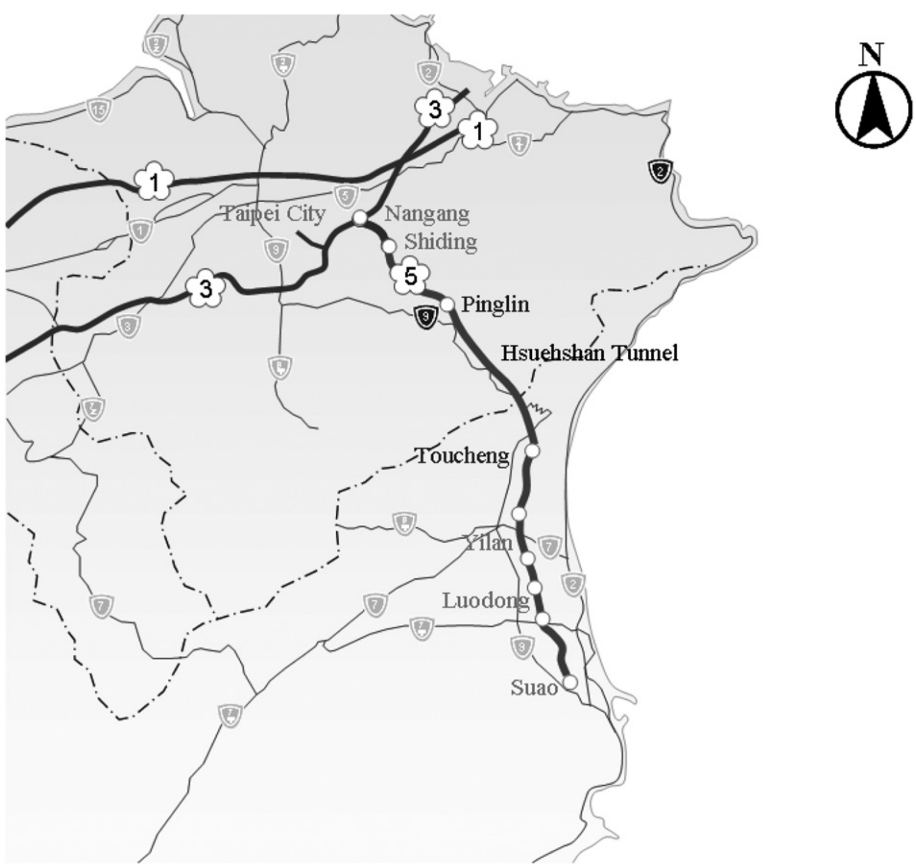

Fig. 1. Map of Northern Taiwan showing Highway 5 and the Hsuehshan tunnel.