Retraction for *Journal of Environmental Monitoring*:

On-road measurements of pollutant concentration profiles inside the CLEM7 road tunnel

Xiao Chun Cong, Ya Nan Kong, Leigh R. Crilley, Luke D. Knibbs, Lidia Morawska

J. Environ. Monit., 2011, DOI: 10.1039/C2EM10924G. **Retraction published 4 April 2012**

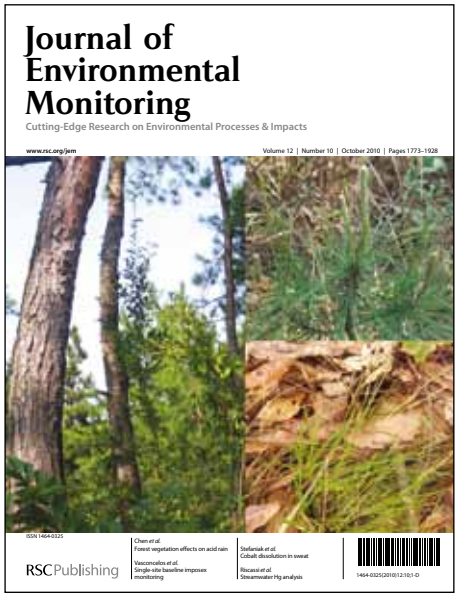
We, the named authors, hereby wholly retract this Journal of Environmental Monitoring article, due to data interpretation errors that were raised by the co-authors of Dr Cong after publication.

Signed: Xiao Chun Cong, Ya Nan Kong, Leigh R. Crilley, Luke D. Knibbs, Lidia Morawska, April 2012

Retraction endorsed by Harp Minhas, Editor, Journal of Environmental Monitoring.

Journal of Environmental Monitoring

Accepted Manuscript



This is an *Accepted Manuscript*, which has been through the RSC Publishing peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, which is prior to technical editing, formatting and proof reading. This free service from RSC Publishing allows authors to make their results available to the community, in citable form, before publication of the edited article. This *Accepted Manuscript* will be replaced by the edited and formatted *Advance Article* as soon as this is available.

To cite this manuscript please use its permanent Digital Object Identifier (DOI®), which is identical for all formats of publication.

More information about *Accepted Manuscripts* can be found in the **Information for Authors**.

Please note that technical editing may introduce minor changes to the text and/or graphics contained in the manuscript submitted by the author(s) which may alter content, and that the standard **Terms & Conditions** and the **ethical guidelines** that apply to the journal are still applicable. In no event shall the RSC be held responsible for any errors or omissions in these *Accepted Manuscript* manuscripts or any consequences arising from the use of any information contained in them.

Journal of Environmental Monitoring

Dynamic Article Links ►

Cite this: DOI: 10.1039/c0xx00000x

www.rsc.org/jem

PAPER

On-road measurements of pollutant concentration profiles inside the CLEM7 road tunnel

Xiao Chun Cong[a,b,c]*, Ya Nan Kong[a], Leigh R. Crilley[d], Luke D. Knibbs[d], Lidia Morawska[d]

Received 26th Auguest 2011, Accepted Xth XXXXXXXXX 201X
DOI: 10.1039/b000000x

To obtain physical properties of pollutant concentrations encountered by vehicle commuters during travelling Clem 7 tunnel, particle concentration measurements are accompanied by the measurements of gaseous species (CO and CO_2). The field campaigns are on-road conducted from March 25 to September 7, 2010. Results demonstrate that the mean particle number concentrations observed within the tunnel at the normal traffic volume are 1.15×10^5 particles cm^{-3} and 1.24×10^5 particles cm^{-3} for the southbound and northbound trip, respectively. They are one order of magnitude higher than urban background levels of Brisbane. Furthermore, the significance level of traffic volume to particle number concentration is analyzed by multivariate regression model. And the perfect consistency of pollutant concentrations with traffic intensity is presented. Consequently, the fuel-based emission factors of pollutants inside the tunnel are calculated and the personal exposures are derived. In addition, the profile of particle number concentration exhibits distinct dilution features between the exit of northbound bore and the exit of southbound bore. The explanation is attributed to the different long uphill trip within the tunnel. Results in this study offer meaningful understanding to explore the nature of pollutants within long tunnels.

1 Introduction

It is well known that motor vehicles are one of sources for air pollutants such as particle matter (PM), CO, NO_x, and non-methane hydrocarbons, especially in urban areas.[1, 2] Road tunnel, as a confined micro-environment that can trap polluted air, implicates that vehicle passengers passing through it will be exposed to high levels of PM.[3] Epidemiological studies have shown that increased adverse cardiovascular and respiratory disorders are related to PM in the air.[4,5] Svartengren et al.[6] and Larsson et al.[7] reported undesirable respiratory effects had some connections with road tunnel air exposure in asthmatic test subjects.

Given the health concerns of road tunnel exposures, many studies have been conducted on the particle concentration profiles within tunnels.[8~10] High levels of fine particles, especially ultrafine particles (UFPs) with diameters less than 100 nm, are observed in highway tunnels. Kirchstetter et al.[11] showed that UFP concentrations were higher than 2.0×10^5 particles cm^{-3} inside the Caldecott tunnel while the average number concentrations of UFPs in urban areas were in the range of 1.0×10^4 ~ 2.0×10^4 particles cm^{-3}.[12~14] Geller et al.[15] also obtained similar results in that tunnel and concluded that UFPs exhausted from diesel vehicles were higher than those exhausted from gasoline vehicles. Gouriou et al.[16] demonstrated that UFP levels inside the uphill bore were significantly higher than those inside the downhill bore in the Grand Mare tunnel. Weijers et al.[17] noted a nonsymmetrical profile of UFPs inside the tunnel of the Netherlands. However, these studies have been carried out in short tunnels (<2.0 km). For long highway tunnels, there is little knowledge on PM profiles.[10] This study, taking Clem Jones Tunnel 7 (4.5 km long) as an example, aims to quantify the pollutant concentrations and characterize actual profiles of pollutants inside the long tunnel. The results will improve understanding on physical properties of particles and associated

[a] *Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266510, China. Xiao Chun Cong; E-mail: congxiaochun@126.com.*
[b] *Laboratory of Environmental Protection in Water Transport Engineering, Tianjin Research Institute of Water Transport Engineering, Tianjin 300456, China*
[c] *Environment science and engineering college, Nankai University. Tianjin 300071, China*
[d] *International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, QLD, Australia.*

Environmental impact

It has scientific implications as follows: (1) The mean particle number concentration inside the tunnel at the normal traffic volume is one order of magnitude higher than urban background level of Brisbane. (2) Pollutant temporal and spatial profiles inside the tunnel are illustrated and measured results are compared with previous studies. (3) The significance level of traffic volume to particle number concentration is analyzed by multivariate regression model. Consequently, the fuel-based emission factors of pollutants inside the tunnel are calculated and the personal exposures of pollutants are presented. (4) The profile of particle number concentrations exhibits distinct dilution features between the exit of northbound bore and the exit of southbound bore and the related reason is discussed.

gas pollutants to which vehicle commuters and tunnel staffs are exposed.

2 Materials and Methods

2.1 Description of the tunnel

Clem 7 tunnel is a newly built road tunnel located in Brisbane, operating since March 2010. It is one of the largest infrastructure projects in Queensland State of Australia. The tunnel runs in a north-south direction and is composed of two unidirectional 2-lane bores with approximately 10 meters apart. There are one entry at the northern end and two exits at the southern end with a distance of 0.5 km apart.

From the northern entry, there are four sections with different gradients in the tunnel (Figure 1). The first section is downhill with 3.5% slope for 1.5 km extension to the lowest point of the tunnel (60 m under the Brisbane River). The second section is the uphill part with 3.5 % slope for 1.5 km span to the first exit. The third section is a flat one with 1 km length and finally, the fourth section is a 0.5 km uphill one with a maximum gradient 5 % to the south end.

2.2 Traffic flow in the tunnel

The detailed information on traffic counts and fleet compositions in the tunnel is offered by operators of Clem 7 tunnel. According to traffic volume of Brisbane, traffic density inside the tunnel is classified into four grades defined as 1 to 4 from very light traffic to heavy traffic condition. It is recorded that nearly 1,113, 1,029 and 1,695 vehicles per hour pass through the tunnel in one direction during measurement campaign I (from March 26 to 31, 2010), campaign II (July 19 to 25, 2010) and campaign III (from August 26 to September 7, 2010), respectively. Traffic records also reveal that heavy vehicles occupy approximately 24 %, 23 % and 21 % of total traffic counts for campaign I, II and III, respectively. Fig. 2 indicates average vehicle flow and traffic fleet proportions traversing the tunnel during the whole sampling period. A bimodal mode is observed at 8:00 in the morning with 1,416 vehicles h^{-1} and at 17:00 in the evening with 1,716 vehicles h^{-1} (Figure 2). Obviously, it is corresponded to the diurnal pattern of traffic rush hours. It is implied that the commuters through the tunnel account for a large proportion of tunnel users. From this viewpoint, investigating the pollutant concentration profiles inside the tunnel and estimating the potential exposures to the passengers become meaningful. The personal exposures inside the tunnel are presented in section 3.3.3.

2.3 Sampling schedule

The real on-road measurements are carried out since March 26, 2010. The whole campaign is comprised of three stages named as campaign I, campaign II and campaign III. Each sampling time lasts 12 hours (from 07:00 to 19:00 on weekdays) to capture various traffic conditions that comprise of different traffic fleets. A total of 182 trips are conducted and distributed into 50 runs in campaign I, 60 runs in campaign II and 72 runs in campaign III. On the whole, the accumulated sampling distance is almost 873.6 km with approximately 12.45 hours inside the tunnel.

On every measurement day, the sampling route is designed from the Queensland University of Technology (QUT) campus, through 8~9 sampling trips of traversing the tunnel, finally returning to the campus. During the measurements, a videotape of each tunnel run is made by video camera installed in the middle of the front windscreen. The videotape, serving as documentation of the traffic conditions and events of runs, is used to confirm and identify emission sources and oral record of driver observations.

2.4 Sampling instruments and data calibration

A four stroke spark unleaded petrol car is used as experimental vehicle. It is in a good mechanical condition. Due to fuel combustion representing the major pollution source in the tunnel, PM, CO_2 and CO as main descriptors are monitored during the measurement periods. Hence a condensation particle counter (CPC, Model 3007) and DustTrak™ aerosol monitor (Model 8520) mounted in the research car are used to measure particle number concentration and mass concentration, respectively. TSI Q-Trak (Model 8552) monitor is used to measure CO_2 and CO and report ambient air temperature and relative humidity (R.H.). All instruments are placed on a fixed board to reduce vibration and the tilt effects associated with traversing the tunnel. The sampling platform is settled on the front passenger seat.

Q-Trak instrument is mainly used for investigating and monitoring indoor air quality. Since this measurement is conducted inside the tunnel (relatively confined space), the measurement range, accuracy and resolution as well as operating temperature designed for Q-Trak can satisfy the on-road measurement requirements.[18, 19] In addition, Q-Trak is of easy operation feature, allowing samplers to set start/stop times whenever special event is encountered (such as long-time traffic jam caused by front vehicle breakdown within the tunnel).

To minimize the associated sample residence time and particle deposition, ambient air is sampled directly through conductive tube with an inner diameter of 5.0 mm. This tube passes through front passenger side window of the experiment vehicle and is sealed. Sampling air is captured by sample inlet always facing travel direction and then is transported to the CPC and DustTrak by an automated Y-type pinch valve. Tube length from the sample point to the CPC inlet is approximately 0.7 m with a flow rate of 0.9 L min^{-1} (Reynolds number is about 718).

Prior to each use, CPC is zero-checked with a filter and set as calibrated flow rate. Similarly, zero checking is always applied to the DustTrak with the zero-filter. Q-Trak is calibrated by performing zero with gas standards provided by the manufacturer. All instruments are set as 1 s measurement interval and started synchronously for each time. When measured data is over 10,000 particle cm^{-3}, an exponential correction factor provided by Westerdahl et al.[8] is employed to calibrate particle number concentration. Likewise, the DustTrak data is corrected by using the linear correction factor proposed by Jamriska et al.[20].

3 Results and Discussion

3.1 Data processing

The 182 trips distributed evenly between the southbound and northbound bores. It is counted that 6.18 hours are spent in the southbound trip and 6.27 hours in the northbound trip. The average duration time for travelling through the southbound trip is 245 s with an average speed of 66.26 km h^{-1}, while the equivalent for northbound trip is 248 s with an average speed of 65.31 km h^{-1}.

The average capture ratio of particle number and mass is 76 %, 90 % and 98 % for campaign I, II and III, respectively. Likewise, capture ratio of CO_2 is obtained with 96 %, 100 % and 94 % for campaign I, II and III, respectively. Due to Q-Trak failure in campaign II, CO is recorded only in campaign I and III with 96 % and 100 %, respectively. The statistical analysis on CO concentration may be affected by the missing data. However, the effect can be diminished by over one hundred repeated samplings conducted in campaign I and campaign III. Besides, the CO_2 data recording is fairly good and can offer some references for CO concentration statistics.

Measurements indicate that temperature inside the tunnel during campaign I (Australian summer) is approximately 26.4□ at late night and 31.6□ in early morning with R.H. as 51.0 % and 74.1 %, respectively. While campaign II is conducted in Australian winter with in-tunnel temperature ranging from 20.2℃ to 24.5℃ and R.H. ranging from 30.1 % to 67.4 %. Campaign III is performed in Australian spring with in-tunnel temperature varying from 21.1℃ to 26.7℃ and R.H. varying from 28.3 % to 73.9 %. On average, the outside temperature on the mixed road route is 1.5 □, 2.1 □ and 1.5 □ lower than in-tunnel temperature for campaign I, II and III, respectively. Little temperature difference between the outside and inside the tunnel makes an assumption that the temperature of dilution air is nearly identical with that of sample air. As the consequence, the influence of thermophoretic loss or particle condensation in sampling lines can be ignored.[21]

3.2 General results

For the whole measurements, average particle number and mass concentration inside the tunnel at normal traffic volume are 1.15×10^5 particles cm^{-3} and 30.1 μg m^{-3} respectively in the southbound bore, and the equivalents are 1.24×10^5 particles cm^{-3} and 39.0 μg m^{-3} respectively in the northbound bore. The particle number concentration observed in the tunnel is over ten times higher than urban background concentration of Brisbane (approximately 9.8×10^3 particle cm^{-3} reported by Morawska et al.[22]). Average concentrations of pollutants for each campaign are shown in Table 1. Herein, campaign II exhibits the lowest concentrations for all measured pollutants among three campaigns. It is attributed to the decrease of the traffic counts (1,029 vehicles h^{-1}) since a toll was introduced from April 1, 2010. Nevertheless, the traffic volume increases again during the campaign III (1,695 vehicles h^{-1}). Consequently, pollutant concentration levels rise.

We note that pollutant levels of campaign I are higher than those of campaign III (Table 1), although the traffic volume of campaign I is smaller. The likely reason is that the proportion of heavy vehicles in campaign I is larger than that in campaign III. Fruin et al.[9] reported a strong association between diesel truck counts (R^2=0.84) and on-road PM concentrations on Los Angeles freeways. Knibbs et al.[23] concluded that hourly heavy diesel vehicle (HDV) traffic volume was a good determinant of UFPs concentration (R^2=0.87) in E5 road tunnel of Sydney, Australia. In this study, the impact of HDV on pollutant concentrations is discussed in section 3.3.2.

Table 2 summarizes the comparisons between the previous long tunnel studies and this measurement, independent of some differences in sampling equipments and measured particle size ranges and studied environment. We find that the PM concentrations in current study are more comparable with those in the tunnel of Netherlands, [17] while over ten times lower than particle concentrations of E5 tunnel [23] despite of similar length of the two tunnels.

3.3 Temporal evolutions of pollutants in the tunnel

3.3.1 Temporal profiles

Pollutant profiles for northbound and southbound trips are very similar. Figure 3 shows typical variation of pollutant concentrations for the southbound and northbound trip at non-traffic jam periods. All pollutants take on increasing trend from the tunnel entrance. Particularly, particle number concentration presents a rapidly linear increase from the entrance and an abruptly decrease at about 100~200 m near the exit of the tunnel due to dilution. It is obvious that particle number is more sensitive to PM level compared with particle mass, because traffic emits mostly UFPs that dominated the particle number, not the mass.

It is worth noting that the mechanical ventilation system is not in operation conditions during whole measurement campaigns. Instead, moving vehicles provide the main aerodynamic drag force. That is to say, the tunnel airflow is driven by the movements of passing vehicles that push the air through the tunnel. Therefore, pollutants are mainly pushed through the tunnel by moving vehicles and diluted by outside fresh air that makes pollutant concentrations reduce near the tunnel exit. It is exhibited that PM levels at the exit drop approximately 4~6 times lower than what are measured at the mid-part of the tunnel. This result is in accordance with the findings of Gouriou et al.[16] and Cheng et al.[10]. A mean factor of 8 for PM number level between the exit and entrance was reported in Gubrist tunnel, [24] while the factor of 3 was derived in Grand Mare tunnel.[16]

In contrast with PM concentrations, CO and CO_2 show moderate increase trends inside the tunnel. Results show that there are 4.06 and 1.01 times of enhanced magnitude from entrance to exit respectively in southbound trip, and 3.48 and 1.98 times respectively in northbound trip. Because CO and CO_2 are main affected by proximity to general traffic density rather than specific vehicles,[8] the enhanced magnitudes of their concentration levels are not as large as PM concentrations when the traffic volume is stable in the measurement.

3.3.2 HDV and traffic volume influence

The influence of HDV on the specific event may be highlighted. Herein, a noticeable increase in particle number concentration

marks the moment when a heavy diesel vehicle occurs in the measurement trip (Figure 3b). A discernible increase of the particle number concentration is readily found (from 9.5×10^4 to 1.42×10^5 particles cm^{-3}) when a heavy diesel truck appears. This event confirms that HDV traffic has a considerable contribution to particle number level, especially when HDV is present in the immediate vicinity to the research vehicle. Similar results are derived in the Kaisemühlen tunnel.[25]

When pollutant profiles for tunnel runs are classified as with and without HDV for both trips, we find pollutant concentrations with HDV are mostly higher than those without HDV, especially when the traffic density is heavy (Table 3). Nevertheless, employing linear regression method, HDV ratio is presented to be poor correlations to pollutants levels (R^2=0.008 for particle number concentration, R^2=0.049 for mass concentration). This result can be attributed to the fact that the absolute number of HDV encountered in the tunnel is quite low at the sampling moments. Since mobile sampling is heavily depended on the driving conditions and fleet compositions of vehicles in front, measurements carried out very close to vehicles are able to take into account the atmospheric conditions actually encountered. In this measurement, a large percentage of the precursor vehicles are light gasoline vehicles (LGV_s) rather than HDV_s. Hence, it is responsible for the presence of HDV being a poor determinant of pollutant concentrations.

The factors possibly affecting pollutant concentrations can be classified into several categories, including vehicle fuel type, traffic volume, vehicle speed, background air concentration and meteorological parameters. Based on a generalized linear model (GLM) used by Westmoreland et al.[26] and Carslaw et al.[27], pollutant concentration can be expressed as a function of independent variables:

$$logC=\beta_0+\beta_1 Traffic+\beta_2 Vehicle+\beta_3 BP+\beta_4 Temp+\beta_5 RH+\varepsilon \quad (1)$$

where C is the pollutant concentration, β_1~β_5 are regression coefficients, BP is the background concentration of pollutants, $Temp$ and $R.H.$ are the in-tunnel air temperature and relative humidity, respectively, ε is residual.

Following the views of Richmond Bryant et al.,[28,29] a logarithmic function of concentration is used in the model to improve normality of the input data and also account for nonlinear trends in the independent variables. The multivariate regression for particle number concentration is performed. And significance of each independent coefficient of the regression is determined by use of the Student T-test.

Table 4 demonstrates that the traffic volume is a significant predictor of particle number concentration inside the tunnel with good correlation (R^2=0.859). Apart from traffic volume, the significance levels of other variates are relatively small. This result confirms that the PM concentrations in the tunnel positively depend on the vehicle counts.

Using a similar regression method, relationship between the traffic density and pollutants are made for all trips. Results reveal that particle number concentration exhibits a high linear correlation with vehicle flow (R^2=0.922) and so does CO_2 (R^2=0.976) (Figure 4).

3.3.3 Emission factors and personal exposures

Since gas-phase carbonaceous products are dominated by CO_2, [18, 30] we consider CO_2 and CO to be the primary carbonaceous products emitted during the combustion process, neglecting the contributions of black carbon and hydrocarbon gases. Then the fuel-based emission factor of pollutants is employed based on a carbon balance of the major carbon-containing exhaust constituents.[31, 11] The emission factors for pollutants inside the tunnel are calculated by use of the data collected during the present measurements.

$$EF_i = [\frac{\Delta[C_i]}{\Delta[CO_2]\times\frac{MW_c}{MW_{co_2}}+\Delta[CO]\times\frac{MW_c}{MW_{co_2}}}]\times w_c \quad (2)$$

where EF_i is fuel-based emission factor of pollutant species i (i is PM, CO and CO_2, respectively), $\Delta[C_i]$, $\Delta[CO_2]$ and $\Delta[CO]$ are the pollutant species i , CO_2 and CO concentrations inside the tunnel corrected by background concentrations, respectively, MW_c and MW_{CO2} are the molecular weights of the carbon and CO, respectively, w_c is the weight fraction of carbon in fuel and is assumed to be 0.85 and 0.87 for gasoline and diesel fuel, respectively.[11]

It is known personal exposure is a function of the concentrations within various micro-environments visited, as well as the time spent in those environments. Because pollutant levels heavily depend on volume counts of vehicles passing the tunnel, it makes more sense to use traffic volume as the main independent variable to determine the pollutant concentrations. Hence personal exposure can be written as follows:

$$PE_i = EF_i \times N \times \Delta t \quad (3)$$

where PE_i is personal exposure of pollutant species i, N is mean vehicle count passing the tunnel during Δt time, Δt is the average duration time traversing the tunnel.

With the availability of related information, personal exposure values of monitored pollutants inside the tunnel are derived based on (2) and (3), shown in Table 5. These results are useful to evaluate the human health exposures to concentrations of PM and associated gas pollutants encountered by vehicle commuters and tunnel staffs.

3.4 Spatial evolutions of pollutants inside the tunnel

3.4.1 Spatial profiles

Knowing the time of tunnel entry and exit, the average velocity during a trip can be computed. Thus it is easy to obtain the pollutant concentration levels in terms of distance. Due to different road topography (downhill or uphill) mixed in southbound and northbound trip, profiles of pollutant concentrations for each bound trip are illustrated separately.

Figure 5 illustrates that the pollutant concentrations rise as downwind distance increases from the tunnel entrance. At section 2 of the tunnel in the southbound trip, enhancement trend of pollutant concentrations is due to higher engine loads in the ascending road. This situation is consistent with the findings of Kittelson et al.[32] and Maricq. [33] In northbound trip, by contrast, section 2 is downhill due to different travelling direction. The increment trend of PM concentrations in this section is attributed

to the fact that drivers, taking advantage of the downhill slope, keep their cars in neutral.

With regard to gaseous pollutants, CO and CO_2 concentrations have the same trends as the particle number concentration. It is known that CO emissions are primarily from gasoline-powered vehicles and poor related to those pollutants dominated by diesel vehicles, while CO_2 is emitted in high quantities from fossil-powered vehicles. Due to LGV_s account a dominating proportion of traffic compositions in this measurement, the enhanced magnitude of CO inside the tunnel is greater than that of CO_2 for both trips.

3.4.2 Long tunnel characteristics

Gidhagen et al.[34] and Ketzel and Berkowicz[35] found that the coagulation process for UFP_s occurred in long tunnels. They observed that a large number of nucleation mode particles congregated at the tunnel entrance section. As it is known, these particles are mainly from the exhausted plume emitted by precursor vehicles. Based on the conclusions of Yao et al.[36], these exhausted gases are quickly changed into the nucleation mode particles by gas-to–particle condensation conversion. As deeper into the tunnel, the coagulation process accelerates and Aitken mode particles are formed markedly. From this aspect, the long tunnel can offer enough time and sufficient high polluted levels for exhausted plume to change into nucleation mode particles.[10] Several studies showed that the size distribution of particles was changed remarkable inside long tunnels.[10] Sturm et al.[37] observed that UFP_s at the middle point inside the Plabutsch tunnel (about 10 km length) had a bimodal distribution with one peak <30 nm and a second peak at about 80 nm. The measurement of Cheng et al.[10] suggested that particles in the Aitken mode governed UFP levels in the long tunnel.

In this study, northbound trip has a longer final uphill section (1.5 km length) than the corresponding section of the southbound trip (0.5 km length). The longer uphill trip implies that more exhausted pollutants are emitted by vehicles with high engine load and consequently they have more possibility of being converted into particles via coagulation process. This elucidation may explain why the particle number concentration at the tunnel exit is about 6.1 times higher than that at the entrance in the northbound trip, while only 2.2 times higher in the southbound trip. Likewise, this explanation is also partly responsible for the different dilution feature of the northbound exit from that of the southbound exit. We have noticed that, at southbound exit, the dilution effect is so pronounced that decline trends of the pollutant concentrations are presented in whole final uphill section (Figure 5a). In contrast, at northbound exit, decreased pollutant concentrations are exhibited to be discernable at the very close to tunnel exit (Figure 5b). This observation illustrates that uphill trip affects pollutant concentration distribution inside long tunnels. Due to absence of scanning mobility particle sizing spectrometers (SMPS) in this study, the information on particle size distribution is unavailable. In future study, we will conduct supplementary measurements on particle size distribution within Clem 7 tunnel. The quantitative analysis on particle size distribution in the uphill trip will be carried out and the characteristics of long tunnels will be further explored.

4 Conclusions

On-road experiments offer an approach for evaluating pollutants of concern in diverse environments. In this study, pollutant profiles inside Clem 7 tunnel are measured with a mobile platform. As expected, car commuters are exposed to higher PM concentrations at the normal traffic volume during the tunnel journey than those encountered in urban areas. The measurements demonstrate good correlations exist between traffic volume and pollutant concentrations. Consequently, the fuel-based emission factors of pollutants are calculated and personal exposures of in-tunnel pollutants are presented. These results offer information to assess the urban tunnel microenvironment.

In the studied tunnel, for both descending and ascending routes, pollutant levels enhance with increasing downhill distance from the tunnel entrance. They also progressively increase in the uphill section within the tunnel due to vehicles going uphill at high engine loads. The more interesting, pollutant concentrations at the tunnel exit illustrate different dilution features between the northbound trip and the southbound trip. These profiles suggest the long uphill trip affects not only the pollutant concentrations but also particle size distributions. Further studies should focus on the relationship between the particle size distribution and pollutant levels in the uphill section. It will better reveal the pollutant emission characteristics inside the long tunnel.

Acknowledgements

This study is supported by the Nature Scientific Foundation of P. R. China (NSFC) with the Number 50808115 and Nature Scientific Foundation of Shandong Province in China with Number 2009ZRB01240 and the education plan on young excellent college staffs for over-sea academic visit supported by Education Department of Shandong Province.

References

1 D. Westerdahl, A. Scott, P. F. L. Fruin and S. Constantinos, The Los Angeles International Airport as a source of ultrafine particles and other pollutants to nearby communities, *Atmos Environ.*, 2008, **42**, 3133-3155

2 K. F. Ho, S. S. H. Ho, Y. Cheng, S. C. Lee and Z. Y. Jian, Real-world factors of fifteen carbonyl compounds measured in a Hong Kong tunnel, *Atmos enivron.*, 2007, **41**,1747-1758

3 J. A. Kaminsky, E. A. M. Gaskin, M. Matsuda and A. H. Miguel, In-cabin commuter exposure to ultrafine particles on commuter roads in and around Hong Kong's Tseung Kwan O Tunnel, *Aerosol and Air Quality Research.*, 2009, **9**, 353-357

4 P. S. Gilmour, A. Ziesenis, E. R. Morrison, M. A. Vickers, E. M. Drost, I. Ford, E. Karg and C. Mossa, Pulmonary and systemic effects of short-term inhalation exposure to ultrafine carbon black particles, *Toxicology and Applied Pharmacology.*, 2004, **195**, 35-44

5 C. Sioutas, R. J. Delfino and M. Singh, Exposure assessment for atmospheric ultrafine particles (UFPs) and implications in epidemiologic research, *environmental health perspective.*, 2005, **113**, 947-955

6 M. Svartengren, V. Strand, G. Bylin, L. Järup and G. Pershagen, Short-term exposure to air pollution in a road tunnel enhances the asthmatic response to allergen, *European Respiratory Journal.*, 2000, **15**, 716-724

7 B. M. Larsson, M. Sehistedt, J. Grunewald, C. M. Skőld, A. Lundin and A. Blomberg, Road tunnel air pollution induces bronchoalveolar inflammation in healthy subjects, *European Respiratory Journal.*, 2007, **29**, 699-705

8 D. Westerdahl, S. Fruin, T. Sax, P. M. Fine and C. Sioutas, Mobile platform measurements of ultrafine particles and associated concentrations on freeways and residential streets in Los Angeles, *Atmos Environ.*, 2005, **39**, 3597-3610

9 S. Fruin, D. Westerdahl, T. Sax, C. Sioutas and P. M. Fine, Measurements and predictors of on-road ultrafine particle concentrations and associated pollutants in Los Angeles, *Atmos. Environ.*, 2008, **42**, 207-219

10 Y. H. Cheng, Z. S. Liu and C. C. Chen, On-road measurements of ultrafine particle concentration profiles and their size distributions inside the longest highway tunnel in Southeast Asia, *Atmos. Environ.,* 2010, **44,** 763-772

11 T. W. Kirchstetter, R. A. Harley, N. M. Kreisberg, M. R. Stolzenburg and S. V. Hering, On-road measurement of fine particle and nitrogen oxide emissions from light and heavy-duty motor vehicles, *Atmos Environ.*, 1999, **33**, 2955-2968

12 C. A. Noble, S. Mukerjee, M. Gonzales, C. E. Rodes, P. A. Lawless and S. Natarajan, Continuous measurement of fine and ultrafine particulate matter, criteria pollutants and meteorological conditions in urban El Paso, Texas, *Atmos Environ.,* 2003, **37**, 827-840

13 T. Hussein, A. Puustinen, P. P. Aalto, J. M. Mäkelä, K. Hämeri and M. Kulmala, Urban aerosol number size distributions, *Atmospheric Chemistry and Physics.*, 2004, **4**, 391-411

14 U. Matson, Indoor and outdoor concentrations of ultrafine particles in some Scandinavian rural and urban areas, *The Science of the Total Environment.,* 2005, **343**, 169-176

15 M. D. Geller, S. B. Sardar, H. Phuleria, P. M. Fine and C. Sioutas, Measurements of particle number and mass concentrations and size distributions in a tunnel environment, *Environmental Science and Technology,* 2005, **39**, 8653-8663

16 F. Gouriou, J. P. Morin and M. E. Weill, On-road measurements of particle number concentrations and size distributions in urban and tunnel environments, *Atmosc Environ.,* 2004, **38**, 2831-2840

17 E. P. Weijers, A. Y. Khlystov, G. P. A. Kos and J. W. Erisman, Variability of particulate matter concentrations along roads and motorways determined by a moving measurement unit,*Atmos Environ.*, 2004, **38,** 2993-3002

18 Z. Ning, A. Polidori, J. J. Schaner, C. Sioutas, Emission factor of PM species based on freeway measurements and comparison with tunnel and dynamotor studies, *Atmos Environ.*, 2008, **42**, 3099-3114.

19 D. Westerdahl, X. Wang, X. C. Pan and K. M. Zhang, Characterization of on-road vehicle emission factors and microenvironmental air quality in Beijing,China, *Atmos Environ.,* 2009, **43**, 697-705

20 M. Jamriska, L. Morawska, S. Thomas and C. R. He, Diesel Bus Emissions Measured in a Tunnel Study, *Environmental Science and Technology.*, 2004, 3**8**, 6701-6709

21 A. B. Paul, W. Klaus, *Aerosol measurement principles, techniques and application (second edition)*, 2001, A Joln Wiley & Sons, Inc., Publication

22 L. Morawska, M. Jamriska, S. Thomas, L. Ferreira, K. Mengersen, D. Wraith, F. McGregor, Quantification of particle number emission factors for motor vehicles from on-road measurements, *Environmental Science and Technology.*, 2005, **39**, 9130-9139

23 L. D. Knibbs, R. J. Dear, L. Morawska and K. L. Mengersen, On-road ultrafine particle concentration in the M5 East road tunnel, Sydney, Australia, *Atmos Environ.*, 2009, **43**, 3510-3519

24 E. Weingartner, C. Keller, W. A. Stahel, H. Burtscher and U. Baltensperger, Aerosol emission in a road tunnel, *Atmos Environ.*, 1997, **31,** 451-462

25 M. Handler, C. Puls, J. Zbiral, J. Marr, H. Puxbaum and A. Limbeck, Size and composition of particulate emissions from motor vehicles in the Kaisermühlen-Tunnel Vienna, *Atmos Environ.*, 2008, **42**, 2173-2186

26 E. J. Westmoreland, N. Carslaw, D. C. Carslaw, A. Gillah and E. Bates, Analysis of air quality within a street canyon using statistical and dispersion modeling techniques, *Atmos Environ.*, 2007, **41**, 9195–205

27 D. C. Carslaw, S. D. Beevers and J. E. Tate, Modelling and assessing trends in traffic-related emissions using a generalized additive modeling approach, *Atmos. Environ.,* 2007, **41,** 5289–99

28 J. Richmond-Bryant, C. Saganich, L. Bukiewicz and R. Kalin, Associations of PM2.5 and black carbon concentrations with traffic, idling, background pollution, and meteorology during school dismissals, *Science of the Total Environment*., 2009, **407**, 3357–3364

29 J. Richmond-Bryant, L. Bukiewicz, R. Kalin, C. Galarraga and F. Mirer, A multi-site analysis of the association between black carbon concentrations and vehicular idling, traffic, background pollution, and meteorology during school dismissals, *Science of the Total Environment.*, 2011, **409**, 2085–2093

30 Y.-T. Tarja, A. Paivi, P. Liisa, M. Timo, H. Risto and J. Matti, Emission of fine particles, NO_x and CO from on-road vehicles in Finland, *Atmos Environ.*, 2005, **39**, 6696-6706

31 A.H. Miguel and T.W. Kirchestetter, On-road emissions of particlualte polycyclic aromatic hydrocarbons and black carbon from gasline and diesel vehicle.Environmental, *Environmental Science and Technology.*, 1998, **32(4)**, 450-455

32 D. B. Kittelson, W. F. Watts and J. P. Johnson, Nanoparticle emissions on Minnesota highways, *Atmos Environt.*, 2004, **38**, 9-19

33 M. M. Maricq, Chemical characterization of particulate emissions from diesel engines: A review, *Aerosol Science.*, 2007, **38**, 1079-1118

34 L. Gidhagen, C. Johansson, J. Strŏm, A. Kristensson, E. Swietlicki, L. Pirjola and H. C. Hansson, Model simulation of ultrafine particles inside a road tunnel, *Atmos.Environ.*, 2003, **37**, 2023-2036

35 M. Ketzel and R. Berkowicz, Modeling the fate of ultrafine particles from exhaust pipe to rural background: an analysis of time scales for dilution, coagulation and deposition, *Atmos Environ.*, 2004, **38**, 2639-2652

36 X. Yao, N. T. Lau, M. Fang and C. K. Chan, Real-time observation of the transformation of ultrafine atmospheric particle modes, *Aerosol Science and Technology.*, 2005, **39**, 831-841

37 P. J. Sturm, U. Baltensperger, M. Bacher, B. Lechner, S. Hausberger and B. Heiden, Roadside measurements of particulate matter size distribution, *Atmos Environt.*, 2003, **37**, 5273-5281

Table captions:

Table 1 Average values measured during three campaigns

Campaign		T	RH	Particle Number	Particle Mass	CO	CO2
		□	%	$\times10^3$ *p cm*$^{-3}$	*μg m*$^{-3}$	*ppm*	*ppm*
Campaign I	Southbound	29.2	60.9	125.1	35.7	6.7	546.7
	Northbound	29.2	60.3	130.9	49.1	6.2	526.1
Campaign II	Southbound	22.3	50.8	96.8	23.4	/	480.8
	Northbound	22.7	49.4	115.3	27.0	/	488.6
Campaign III	Southbound	24.1	54.8	109.3	31.2	4.2	483.7
	Northbound	24.5	53.3	126.0	40.9	5.7	516.4
Total results	Southbound	25.2	55.5	110.4	30.1	5.45	503.74
	Northbound	25.5	54.3	124.1	39.0	5.95	510.4

Table 2 List of related long-tunnel studies

Study	Tunnel length/*km*	Size rang/*nm*	Equipment	HDV Proportion	PM /*p cm*$^{-3}$	Comments
This study	4.5	10 ~ >1000	TSI 3007 CPC	<20%	1.2×10^5	In-tunnel route, Short term average
Weijers et al. (2004)	2.0	>7	TSI 3022 CPC	/	1.6×10^5	Non-tunnel route
Luke et al. (2009)	4.0	10 ~ >1000	TSI 3007 CPC	~7%	6.0×10^6	In-tunnel route, Short term average
Cheng et al. (2010)	12.94	6~560	TSI 3091 FMPS	/	$(1.0\sim3.0)\times10^5$	In-tunnel route, Short term average

Table 3 Average concentrations with/without HDV in sampling trips

Traffic density	Bound	Traffic	Particle Number($\times10^3$ *p cm*$^{-3}$)	Particle Mass(*μg m*$^{-3}$)	CO(*ppm*)	CO_2(*ppm*)
Grade 1 (very light traffic)	Southbound	No HDV	109.1	23.3	/	468.2
		HDV	/	/	/	/
	Northbound	No HDV	88.1	25.6	/	438.0
		HDV	70	24.2	/	420.1
Grade 2 (light traffic)	Southbound	No HDV	116.3	29.6	2.5	490.4
		HDV	132.4	36.2	3.9	522.3
	Northbound	No HDV	96.4	25.6	1.9	488.3
		HDV	113	26.1	2.9	468.6
Grade 3 (medium traffic)	Southbound	No HDV	113	27.6	3.9	483.4
		HDV	130.2	24.7	5.4	512.4
	Northbound	No HDV	91.5	24.2	3.9	515.1
		HDV	120.8	31.6	6.9	551.6
Grade 4 (heavy traffic)	Southbound	No HDV	65.9	24.1	5.9	507.1
		HDV	139	44.8	5.6	560.7
	Northbound	No HDV	75.4	24.8	2.5	514.2
		HDV	139.9	38.4	7.3	554.5

Table 4 Regression coefficients for particle number concentration during the sampling periods

Variables	Estimated Coefficient	Mean squared error	P-value
(Intercept)	4.56	0.112	<<0.001
Traffic volume	3.28×10^{-4}	2.99×10^{-5}	<<0.001
Vehicle speed	3.91×10^{-4}	8.55×10^{-4}	0.649
Background concentration	1.28×10^{-6}	1.01×10^{-6}	0.211
Air Temperature	1.50×10^{-3}	4.07×10^{-3}	0.715
Relative Humidity	-1.10×10^{-3}	7.80×10^{-4}	0.166

Table 5 Average personal exposure values

Trip	Travelling information	Emission Factor	Personal Exposure Level
Southbound	Fleet proportion: 28% for HDV	Particle number: 1.26×10^{14} *p (kg-fuel)*$^{-1}$	Particle number: 1.99×10^{18} *p*^{3} *s*
	Fuel consumption: 0.785 *kg veh*$^{-1}$	Particle mass: 0.0258 *g (kg-fuel)*$^{-1}$	Particle mass: 4.08×10^8 *μg s*
	Vehicles flow: 1203 *veh h*$^{-1}$	CO_2: 3.088 *g (kg-fuel)*$^{-1}$	CO_2: 6.19×10^4*g s*
	Travelling time: 245 *s*	CO: 0.0529 *g (kg-fuel)*$^{-1}$	CO: 834.94*g s*
Northbound	Fleet proportion: 19% for HDV	Particle number: 8.6×10^{13} *p (kg-fuel)*$^{-1}$	Particle number: 1.27×10^{18} *p s*
	Fuel consumption: 0.661 *kg veh*$^{-1}$	Particle mass: 0.0176 *g (kg-fuel)*$^{-1}$	Particle mass: 2.6×10^8 *μg s*
	Vehicles flow: 1306 *veh h*$^{-1}$	CO_2: 3.083 *g (kg-fuel)*$^{-1}$	CO_2: 6.88×10^4 *g s*
	Travelling time: 248 *s*	CO: 0.0559 *g(kg-fuel)*$^{-1}$	CO: 824.28 *g s*

Figure captions:

Fig. 1 Terrain schematic of Clem 7 tunnel

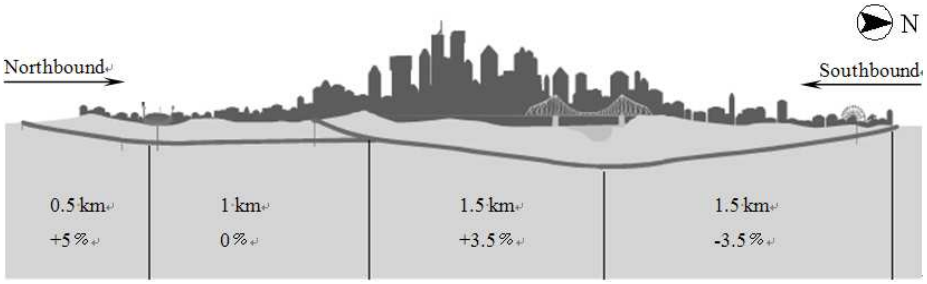


Fig. 2 Average traffic counts during the sampling time from 7:00 to 19:00

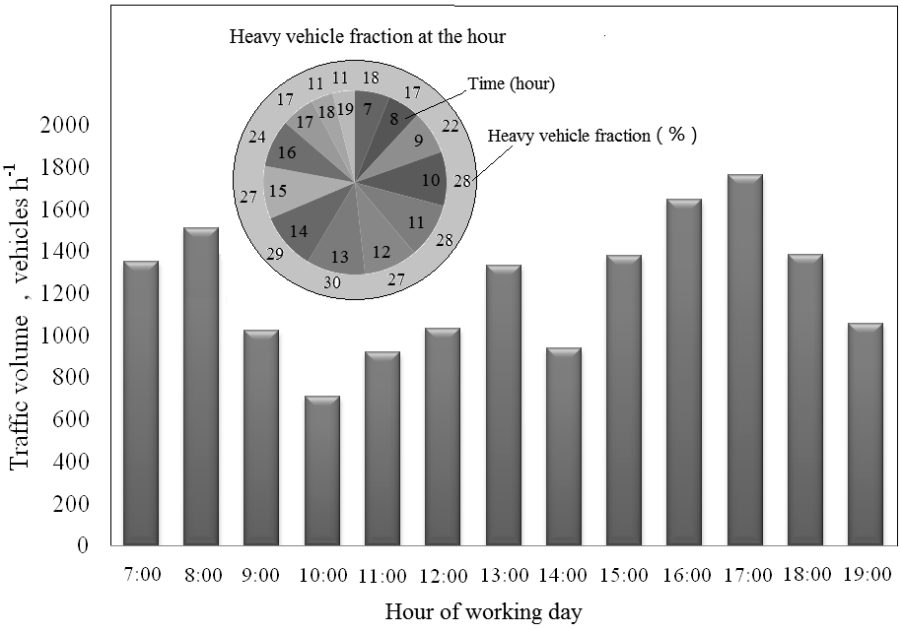
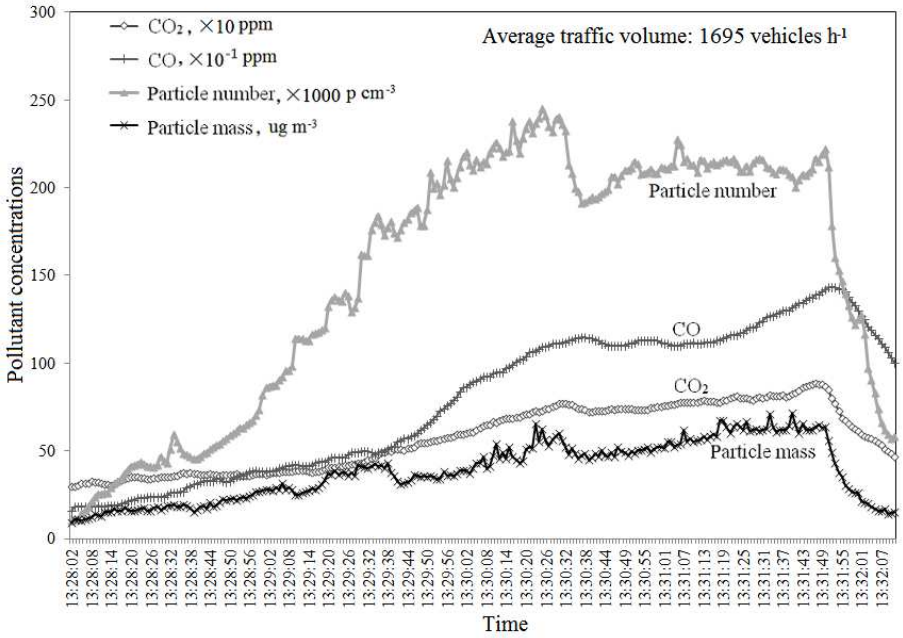
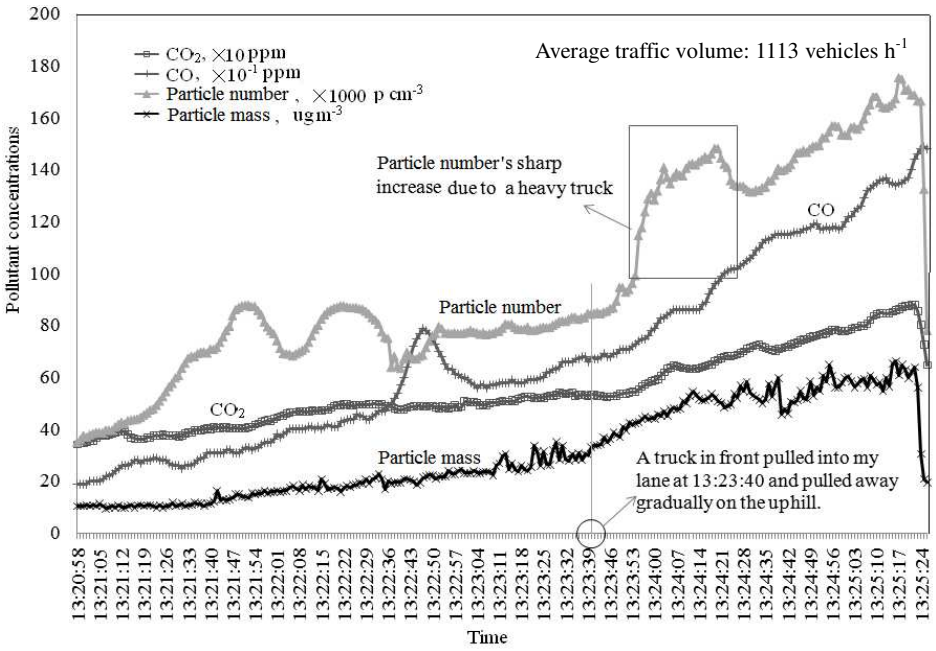


Fig. 3 Temporal profiles of pollutants concentrations inside the tunnel on a typical day



(a) Southbound trip on April 1 2010



(b) Northbound trip on March 30 2010

Fig. 4 Relationship between particle number (a), CO_2 (b) and traffic grade respectively

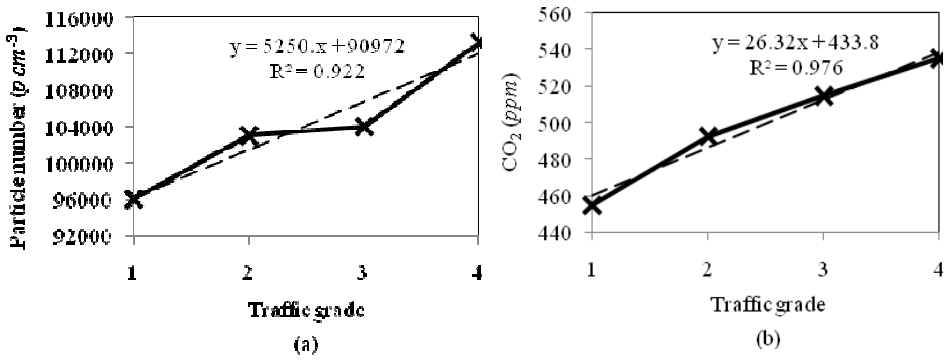
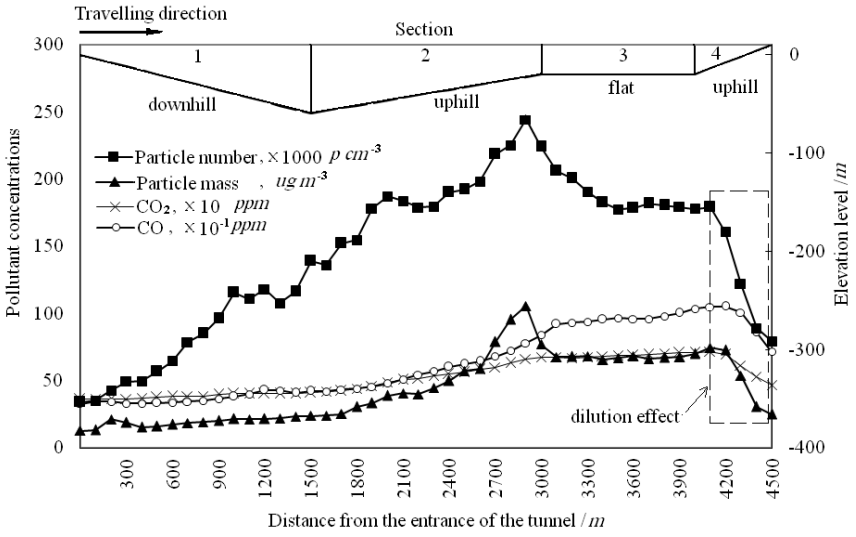
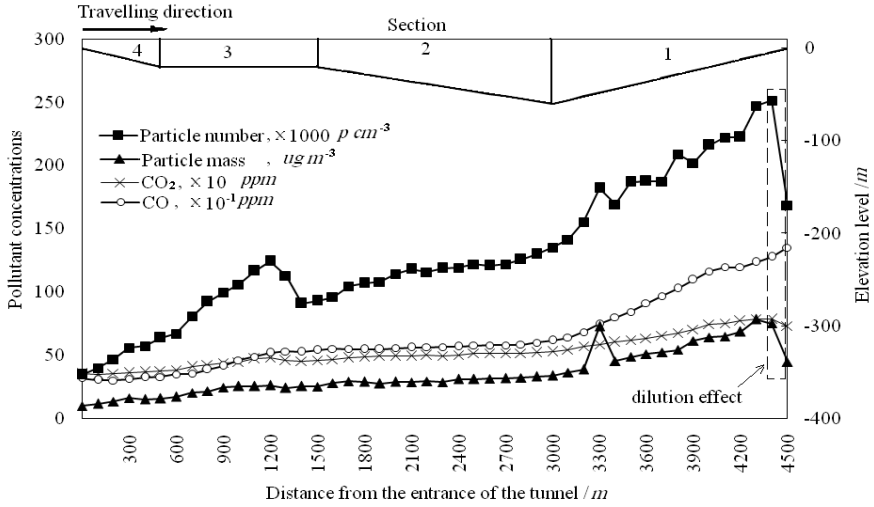


Fig. 5 Spatial profiles of pollutants average concentrations inside the tunnel



(a) Southbound trip



(b) Northbound trip