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Influence of Traffic Flow Patterns on Air Quality inside the Longest Tunnel in Asia

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ABSTRACT

The long tunnel is a fixed, semi-closed environment where excessive concentrations of air pollutants are easily accumulated. This can potentially have a serious affect on drivers' health, especially when operating vehicles in the long tunnel for a lengthy period of time. Therefore, studies on pollutant emission characteristics and influential factors of emission in the tunnel are important. In this study, several sampling sites were arranged in the 12.9 km long Hsueh-shan Tunnel, to help understand the piston effect of pollutant emission characteristics and spatial concentration distribution. In order to understand the influential factor of air quality in the long tunnel, several tests were run during a closed period, an open period, a non-rush hour period, and a rush hour period. The results showed that during the closed period, the CO, SO_2, NO_x, and PM_{10} concentrations in the Hsueh-shan Tunnel were in the range of: 0.58–0.64 ppm, 0.94–1.08 ppb, 6.33–7.11 ppb, and 45.4–54.3 μg/m^3, respectively. In contrast, during the open period, the CO, SO_2, NO_x, and PM_{10} concentrations reached 12–39 ppm, 20–48 ppb, 1.2–3.1 ppm, and 75–177 μg/m^3, respectively. In the Hsueh-shan Tunnel, the number of vehicles at rush hour was about 1400 per hour, three times higher than during non-rush hour. The piston effect is very obvious since pollutant concentrations are elevated with increasing distance from the inlet. This study found that the pollutant concentration near the outlet can be three times higher than that near the inlet.

Keywords: Hsueh-shan Tunnel; Air pollutants; Traffic flow; Piston effect.

INTRODUCTION

The 12.9 km Hsueh-shan Tunnel, the fifth longest tunnel in the world, is located between Taipei and I-Lan and was opened at June 16, 2006. The air flow velocity of the tunnel, under natural ventilation and forced ventilation, is 3–4 m/s and 10–15 m/s, respectively. The Hsueh-shan Tunnel provides convenient travel but simultaneously causes air pollution due to poor dispersion conditions compared to a common road, and hence may pose a health risk. The concentrations of PM_{10}, CO, NO, NO_2, and SO_2 are increased in the tunnel due to the "piston effect" in such a half-sealed space causing higher concentrations (Lonneman *et al*., 1974; Wark *et al*., 1998). Health studies have demonstrated that exposure to roadway PM can increase the risk of respiratory illnesses and be detrimental to human health (Mauderly, 1994; Lin *et al*., 2002; Peden, 2002). Therefore, a study on air quality in the long tunnel, to help understand the effect of air pollution as a health risk to drivers, is necessary (Chang *et al*., 2009; Cheng *et al*., 2010). Lonneman *et al*. (1986) pointed out that the CO and NO_x hourly average concentrations in the Lincoln Tunnel can reach 65.8 ppm and 6290 ppb, respectively. Pierson (1996) investigated the main air pollutant concentration in the Tuscarora Mountain and Fort McHenry Tunnel from 1992 to 1993 and found that the air pollutant concentration in the tunnel was 12–14 times higher than that in ambient air. In Asia, Chan *et al*. (2002) and Chow *et al*. (2003) monitored the air quality in a road tunnel in Hong Kong from 2002–2003 and determined that the CO concentration was in the range of 8–28 ppm. He *et al*. (2008) reported a comprehensive characterization of $PM_{2.5}$ emissions in the Zhujiang Tunnel in the Pearl River Delta region of China. Duffy *et al*. (1996) and Rogak *et al*. (1998) studied the air quality in the Harbour Tunnel in Sydney and the Cassiar Tunnel in Canada, respectively. They similarly discovered that the main air pollution source in the tunnel was the burning of vehicle engine gasoline or diesel, and that NO and CO was the main air pollutants. Beyea *et al*. (2008) identified 13 historical measurements of polycyclic aromatic hydrocarbons (PAHs) in U.S. vehicular traffic tunnels, that were either directly presented as tailpipe emission factors in μg per vehicle-kilometer or convertible to such a form.

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The aim of this study was to describe air pollutant concentrations in the Hsueh-shan Tunnel. The influence of the number and speed of vehicles, day of week, and sampling positions in the tunnel were also studied. In this study, concentrations of TSP, PM_{10}, CO, NO, NO_2, and SO_2 were measured at various sampling sites at different periods, including closed and open periods. The closed period prohibits all vehicles from passing through and the open period allows all vehicles to pass through the Hsueh-shan Tunnel. The closed period is at the evacuation exercises (22:00–06:00); open period is the normal period. From the start of traffics prohibited time to the start of sample collection is 1hr, and the environment in tunnel becomes a steady-state after 1hr the evacuation exercises in closed period with ventilation system. The relationship between air quality and the traffic flow at different periods were also established to understand the performance of the ventilation system.

MATERIALS AND METHODS

The sampling positions were located in eight safety borders, three medium ventilation sites, three vertical ventilation sites, one meter sampling height, and in the inlet/outlet of the tunnel. There is a vehicle link line and emergency exit between the north and south line. Furthermore, the air zones of the north and south directions are separated. To compare the difference of the air quality during the closed and open periods, the air quality was monitored in each period, including March to June and July to December in 2006, respectively. Furthermore, the gaseous pollutant sampling sites were located at each safety border, and the TSP and PM_{10} samplers were set up in the sites shown in Fig. 1. The cross section of the tunnel is shown in Fig. 2. The air pollutants were monitored for three hours during rush hour and non-rush hour periods to understand the relationship between pollutant concentrations and traffic flow in the tunnel. Particulates were collected with high volume TSP (Wedding Inc.) and PM_{10} samplers (Kimoto Inc.) under a total flow rate of 1.1–1.7 m^3/min. The Whatman quartz fiber (type QAT-UP 8” × 10”) was used to collect particulates. Gaseous pollutants, including carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) were continuously monitored with a Horiba APMA-360, Horiba APNA-360, and API 100A, respectively. The resolution, accuracy, detection range of TSP, PM_{10}, CO, NO_x and SO_2: 0.5 μg/m^3, 1.0 μg/m^3, 0.3 μg/m^3, 0.5 μg/m^3, 1.0 μg/m^3, 0.3 μg/m^3; 0.01 ppm, 0.02 ppm, 0.005 ppm; 0.5 ppb, 1.0 ppb, 0.3 ppb; 0.5 ppb, 1.0 ppb, 0.3 ppb, respectively. All the aforementioned instruments were calibrated at multi-points by standard gas and zero gas before and after the experiment according to the usual routines of quality control. The traffic flow was monitored simultaneously by video recording and counting. The traffic flow data were also compared with image analysis data supplied by the Ping-Lin Control Centre. The results show that there is around 5% standard deviation of the traffic data compared with the counting data of Ping-Lin Control Centre.

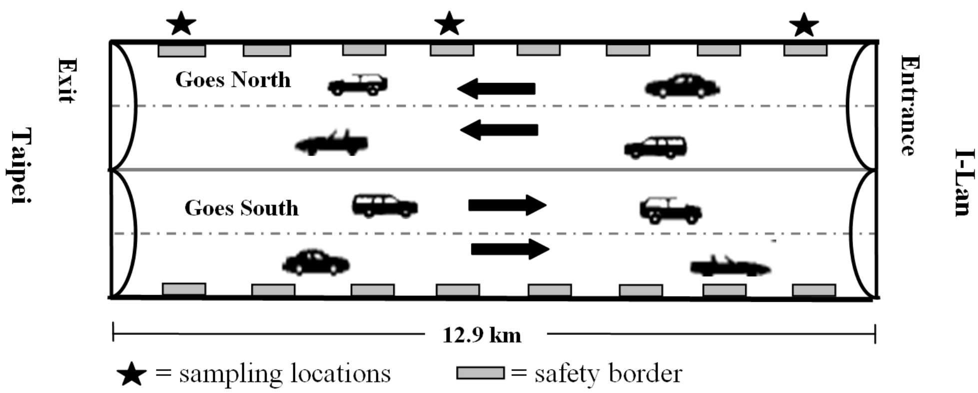

Fig. 1. The air quality sampling locations in Hsueh-shan Tunnel.

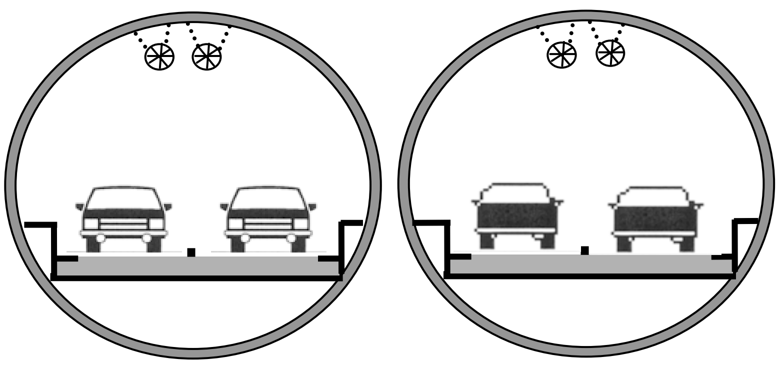

Fig. 2. The cross section of the Hsueh-shan Tunnel.

RESULTS AND DISCUSSION

Pollutant Concentrations during the Closed Period

For the closed period, the pollutant concentrations of different sampling sites in the tunnel are shown in Table 1. PM_{10} concentrations were 45.4–54.3 μg/m^3 at the sampling sites in the tunnel, higher than at the tunnel inlet and near the vertical shaft (20.9–34.3 μg/m^3). The results show that air pollutant dispersion is poor in the long tunnel in a closed period, causing elevated concentrations. Furthermore, during the closed period CO, SO_2, and NO_x concentrations were: 0.58–0.64 ppm, 0.94–1.08 ppb, and 6.33–7.11 ppb, respectively. In contrast, concentrations of CO, SO_2, and NO_x were only 0.46 ppm, 1.04 ppb, and 6.25 ppb, respectively, in the ambient air near the tunnel inlet and only a little lower than in the tunnel. Additionally, NO_2 concentrations near the vertical shaft area were roughly 4.85 ppb, almost the same as that at the tunnel inlet and inside the tunnel. Higher PM concentration around the horizontal shaft is due to the dust in tunnel. The dust will not be carried out by the horizontal velocity of the wind since all vehicles are prohibited from passing through during the closed period. Lower PM and CO concentration would be resulted in around the vertical shaft than those at the other sites since no PM and CO emission from vehicles in closed period.

Pollutant Concentrations during the Open Period

(1) Particles less than 10 microns (PM_{10})

During the open period, PM_{10} concentrations were 148–178 μg/m^3 as shown in Fig. 3. The values were much higher than during the closed period and beyond the 133 μg/m^3 Taiwan air quality standard during rush hour. In contrast, the values were only 81–93 μg/m^3 during non-rush hour. Furthermore, the concentration near the outlet of the tunnel was higher than that near the inlet of the tunnel due to the piston effect (Chen *et al.*, 1998). This means that air flow was produced by the movement of cars in the tunnel in the same direction as the moving vehicles. In addition, the average temperature in tunnel keeps around 30–35°C for all seasons. Therefore, the pollutant level didn't change seasonally.

(2) Carbon monoxide (CO)

CO is emitted from vehicles under incomplete combustion. Therefore, CO may be used as an indicator for assessment of the performance of the ventilation system in the long tunnel. Fig. 4 shows that during rush hour and non-rush hour, CO concentrations were 18.8–20.7 and 10.7–13.9 ppm, respectively. The spatial CO concentration distribution in the tunnel was examined and the ratio of CO concentrations near the outlet to that of the inlet was 1.9 to 3.9. The piston effect obviously affected the CO concentration dispersion in the long tunnel. This is important since CO, more easily than oxygen, combines with the hemoglobin in blood and reduces the content of oxygen in the blood of exposed drivers. Therefore, the health risk is elevated due to the long exposure time of drivers in the long tunnel.

Table 1. Pollutant concentrations in each site during close period.

Pollutants	Site				
	tunnel inlet	safety border	vertical ventilation	medium ventilation	near vertical shaft
PM_{10} (μg/m^3)	34.3 ± 4.7	54.3 ± 5.2	53.8 ± 1.2	45.4 ± 3.7	20.9 ± 2.5
CO (ppm)	0.46 ± 0.08	0.64 ± 0.04	0.63 ± 0.06	0.58 ± 0.11	0.16 ± 0.05
SO_2 (ppb)	1.04 ± 0.10	0.94 ± 0.05	1.03 ± 0.12	1.08 ± 0.11	1.27 ± 0.13
NO (ppb)	2.38 ± 0.24	2.01 ± 0.18	2.57 ± 0.17	2.33 ± 0.26	2.08 ± 0.21
NO_2 (ppb)	3.87 ± 0.25	4.31 ± 0.19	4.50 ± 0.26	4.78 ± 0.31	4.85 ± 0.36
NO_x (ppb)	6.25 ± 0.33	6.33 ± 0.25	7.07 ± 0.40	7.11 ± 0.20	6.93 ± 0.34

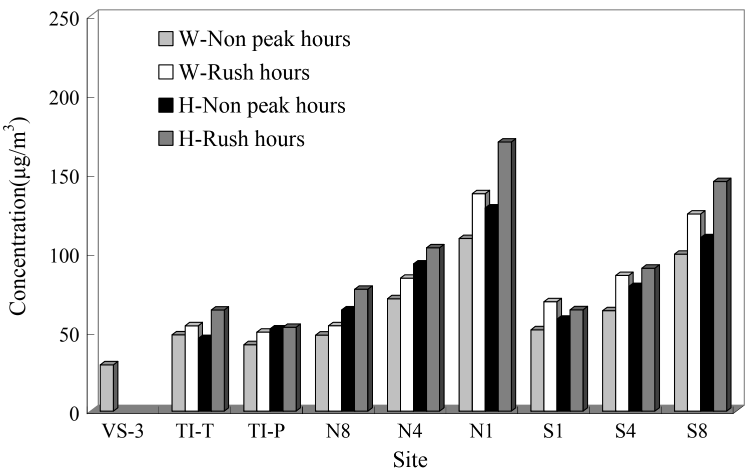

Fig. 3. The spatial variation of PM_{10} concentrations depending on site and time of day during open period: W: weekends, H: weekdays.

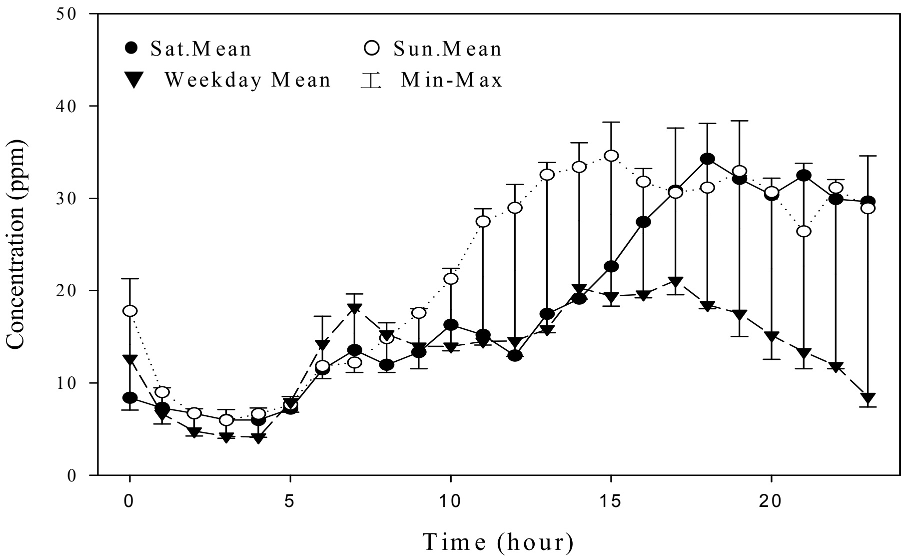

Fig. 4. The diurnal variation of CO concentrations during weekends.

(3) Sulphur dioxide (SO_2)

The diurnal variation of the average SO_2 concentrations of three sites, including the sites near the outlet, near the inlet, and in the middle of the tunnel on weekdays, Saturdays and Sundays, is shown in Fig. 5. During rush hour and non-rush hour, the SO_2 concentrations were: 36.9–48.4 and 15.1–21.4 ppb, respectively. The ratios of SO_2 concentrations near the outlet to that near the inlet were only 1.02–1.11. The difference in the SO_2 concentrations at the two sampling sites is small since buses and trucks are prohibited from travelling through the tunnel and these heavy-duty vehicles have high SO_2 emissions. The vehicle types which pass through the Hsue-shan Tunnel are mainly gasoline vehicles, and the sulfur content of gasoline is only 50–75 ppm in Taiwan. Therefore, the vehicle SO_2 emission and in-tunnel SO_2 concentrations are small.

(4) Nitrogen oxides (NO_x)

NO_x (NO and NO_2) is also an important air pollutant from mobile sources. In general, NO_x emissions in an engine exhaust typically consist of 85–95% NO and 5–15% NO_2 (Soltic and Weilenmann, 2003). As shown in Fig. 6, during rush hour and non-rush hour on weekends, NO_x concentrations were 2186–3097 ppb and 684–991 ppb, respectively. The NO_x composition is dominated by NO, whether near the inlet or near the outlet of the tunnel, and NO constitutes 96%–99% of the NO_x. The result is similar to the study of Soltic and Weilenmann (2003). Furthermore, the ratios of NO_x concentrations near the outlet over that near the inlet were about 3.0–3.2. It is obvious that the NO_x concentrations were easily accumulated in the tunnel. Additionally, the spatial concentration distribution was affected by the traffic flow and showed that the NO_x and CO concentrations were all affected by the piston effect.

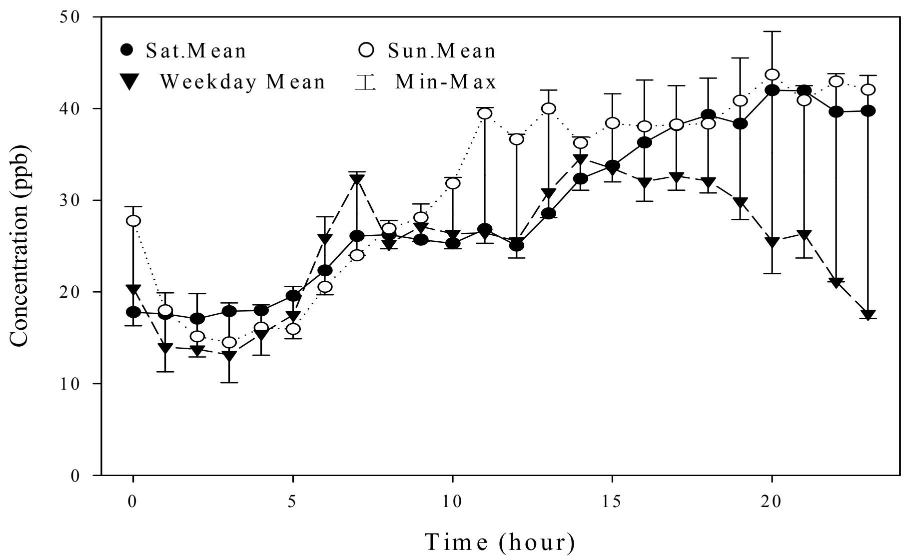

Fig. 5. The diurnal variation of SO_2 concentrations during weekends and weekdays.

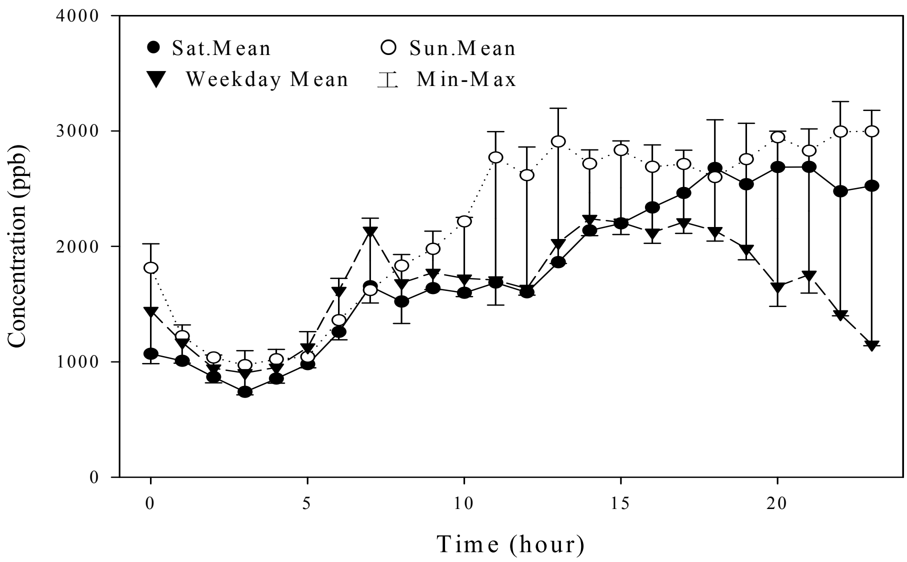

Fig. 6. The diurnal variation of NO_x concentrations during weekends and weekdays.

The Relationship between Air Pollutant Concentrations and Traffic Flow

The maximum traffic flow in a northerly direction can be above 23,000 vehicles per day, as shown in Fig. 7. The ratio of the number of vehicles during rush hour to that of non-rush hour was 14–20 during weekdays. Furthermore, the peak flow can be up to 17,000 vehicles per day during non-rush hour on weekends, roughly 60% higher than during non-rush hour on weekdays. Therefore, the traffic flow is high and results in degradation of the air quality if ventilation is not sufficient. After analyzing the relationship between air quality and traffic flow data on weekends and weekdays with a linear regression, it is seen that the pollutant concentrations increase with an increase in traffic flow, as shown in Figs. 8, 9 and 10. The R-square value, square of relative coefficient, of the relationships between CO, SO_2 and NO concentrations and traffic flow were about: 0.78–0.82, 0.78–0.87, and 0.80–0.84, respectively. It is seen that traffic flow has a high impact on CO, SO_2 and NO concentrations on weekends and weekdays.

CONCLUSIONS

In this study, the characteristics of air pollutants under different traffic flow conditions were analyzed; CO, SO_2, NO_x, and PM_{10} concentrations in the Hsueh-shan Tunnel were: 0.58–0.64 ppm, 0.94–1.08 ppb, 4.33–6.07 ppb, and 45.4–54.3 μg/m^3, respectively, during the closed period when all vehicles are prohibited from travelling through the tunnel. Traffic flow in non-rush hour on weekends was 60% higher than on weekdays. Furthermore, the ratio of the number of vehicles during rush hour to that of non-rush hour was 14–20 on weekdays. The PM_{10} concentrations were 148–178 μg/m^3 in rush hour near the outlet and higher

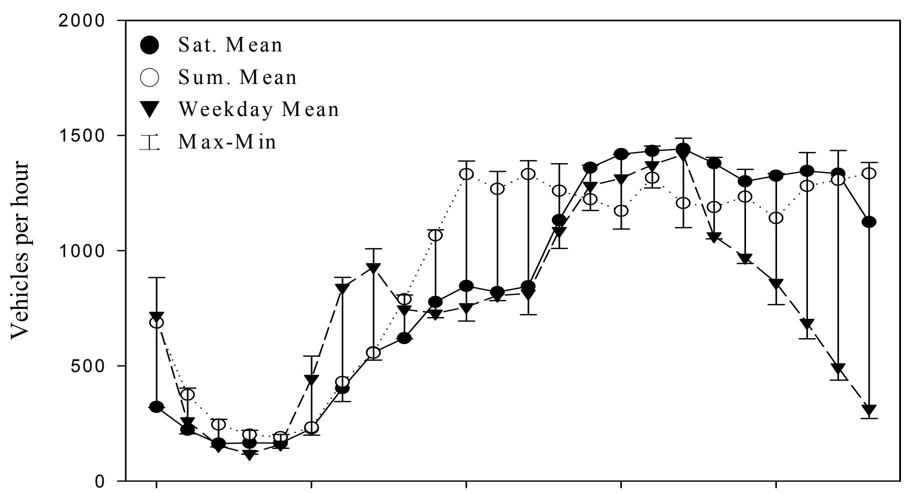

Fig. 7. The diurnal variation of traffic flows during weekends and weekdays.

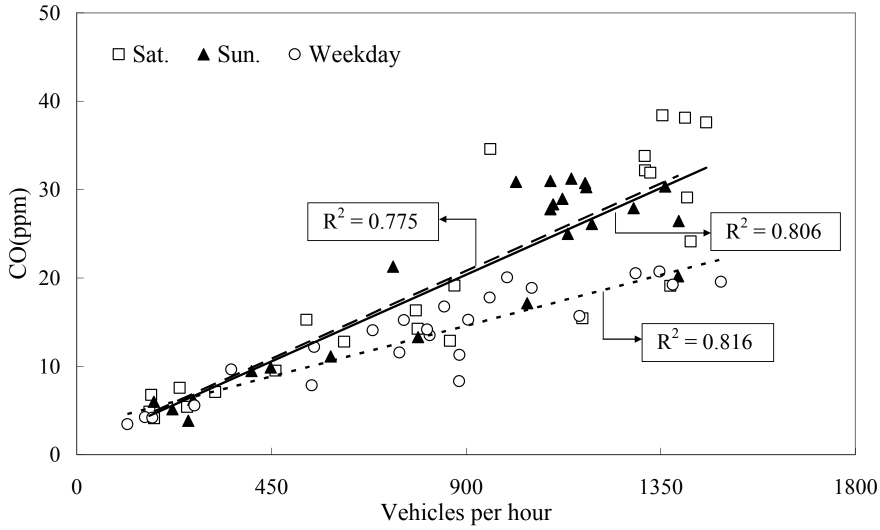

Fig. 8. The relationship between CO concentrations and traffic flows on weekends and weekdays.

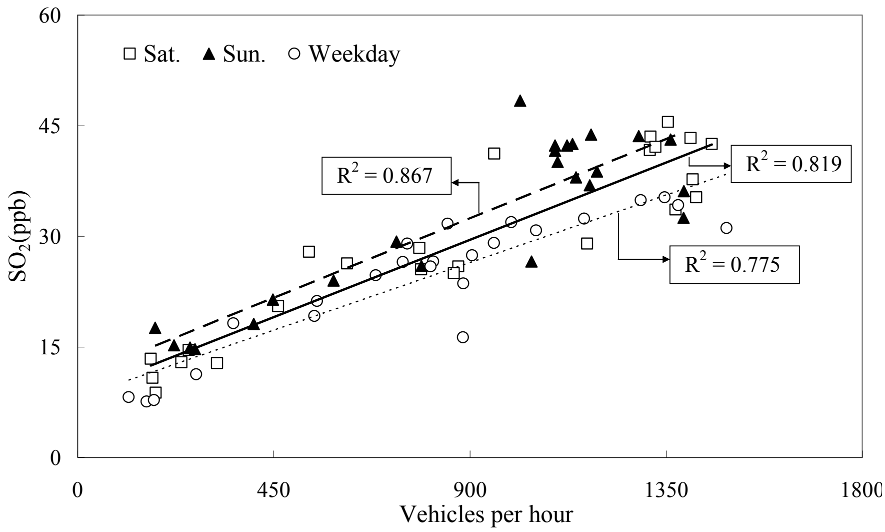

Fig. 9. The relationship between SO_2 concentrations and traffic flows on weekends and weekdays.

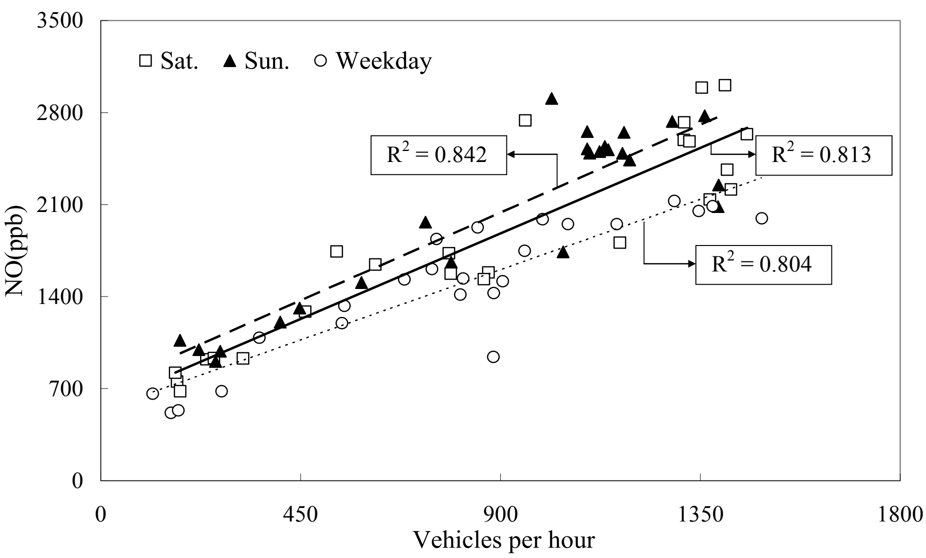

Fig. 10. The relationship between NO concentrations and traffic flows on weekends and weekdays.

than the air quality standard in Taiwan. Additionally, during the open period the CO, SO_2 and NO_x concentrations could be in the range of 12–39 ppm, 20–48 ppb, and 1.2–3.1 ppm, respectively. The ratios of NO_x (dominated by NO) and CO concentrations near the outlet to that of the middle of the tunnel were 1.2–2.0 and 1.6–1.7, showing the influence of the piston effect. In this study, the air pollutant concentrations had a high correlation with traffic flow on weekends and weekdays. The R-square values of the relationship between CO, SO_2 and NO concentrations and traffic flow were about: 0.78–0.82, 0.78–0.87, and 0.80–0.84, respectively. Depending on the characteristics of air pollutants in the long tunnel, this suggests that CO and NO can be used to assess the air quality and the performance of the ventilation system.

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