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Measurements of Gaseous Pollutant Concentrations in the Hsuehshan Traffic Tunnel of Northern Taiwan

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ABSTRACT

Concentrations of carbon monoxide (CO) and nitrogen oxides (NO_x) were measured from 14–17 November 2008 in a cross-mountain Hsuehshan traffic tunnel stretching 12.9 km and containing eastward and westward channels. Traffic and pollutant concentrations during the weekends exceeded those during the weekdays. Measured concentrations of CO at the two tunnel outlets (14.45–22.77 ppm) were approximately three times higher than those at the two tunnel inlets (3.17–7.33 ppm), while concentrations of NO_x at the two tunnel outlets (1.92–2.88 ppm) were approximately four to five times higher than those at the two tunnel inlets (0.32–0.78 ppm). The outlet of vertical draft 2 had the highest pollutant concentrations (CO = 12.27 ppm; NO_x = 1.85 ppm), followed by vertical drafts 1 and 3. The emission factors for the upslope, west-ward lanes (CO = 1.90 ± 0.43 g/km-veh; NO_x = 0.38 ± 0.07 g/km-veh) are higher than those for the down-slope, eastward lanes (CO = 1.45 ± 0.13 g/km-veh; NO_x = 0.26 ± 0.03 g/km-veh). High traffic volume and low traffic speed result in high concentrations and emission factors of the pollutants in the tunnel.

Keywords: Tunnel air quality; Hsuehshan tunnel; CO; NO_x; Vertical draft.

INTRODUCTION

The Hsuehshan Tunnel, in northern Taiwan, passes through the Hsuehshan Mountain from Pingling country in Taipei County to Toucheng town in Yeelan County (Fig. 1). The tunnel stretches approximately 12.9 km long, i.e. the second longest in Asia and the fifth longest traffic tunnel worldwide (Gluck, 2006). Fig. 2 depicts its top view. The tunnel was constructed in July 1991 and completed in September 2004. Traffic passing of the tunnel started on June 16 of 2006. Since Yeelan County contains many touring resources, e.g. spouts, waterfalls, eco-parks and beaches, the tunnel promotes weekend tourism, in addition to reducing the commute time between Taipei City and Yeelan City from two hours to 50 minutes on weekdays. On average, the traffic flow rate on weekdays (weekends) were from 326–377 vehicles/hr (376–877 vehicles/hr) nearby the inlet of eastward channel (Pingling county) and 1,006–1,976 vehicles/hr (1,208–1,669 vehicles/hr) nearby the inlet of westward channel (Toucheng town), respectively. Light duty trucks comprised 77.0% to 95.2% (average 89.1%) of vehicles (Wang, 2009).

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The primary air pollutants in traffic exhausts are carbon monoxide (CO), nitrogen oxides ($NO_x = NO + NO_2$), and hydrocarbons. The air quality in a tunnel environment easily deteriorates if the air pollutants emitted from the vehicles are not diluted efficiently because a traffic tunnel is an enclosed or a partially enclosed space. The situation worsens during traffic congestion where more pollutants are emitted at low vehicular speeds and pollutants accumulate in the tunnel. A polluted tunnel environment especially harms motorcycle drivers or pedestrians directly exposed to it (Gorse, 1984; Schwartz, 1994; Kanaoka *et al*., 2006; Chiang *et al*., 2007; Kaminsky *et al*., 2009; Ma *et al*., 2011). Proper ventilation system design, including fans and/or vertical drafts, is essential to maintain the pollutant concentrations in a traffic tunnel at safe levels. CO is normally adopted as an indicator of air quality to assist the design and operation of tunnel ventilation systems. Permanent International Association of the Road Congress (PIARC) proposed a safe value in a traffic tunnel, with 100 ppm for CO, and 25 ppm for NO (PIARC, 1995).

Measurement results by Pursall and West (1979) from a model tunnel and in an empty traffic tunnel containing jet fans by Baba *et al*. (1979) indicated substantial non-uniformities in the velocity profiles. Mainly driven by axial fans and moving vehicles, air flow in a traffic tunnel is often analyzed using a lumped, one-dimensional, pipe/duct approach to satisfy requirements (Bellasio, 1997; Chung *et al*., 2001). Elucidating

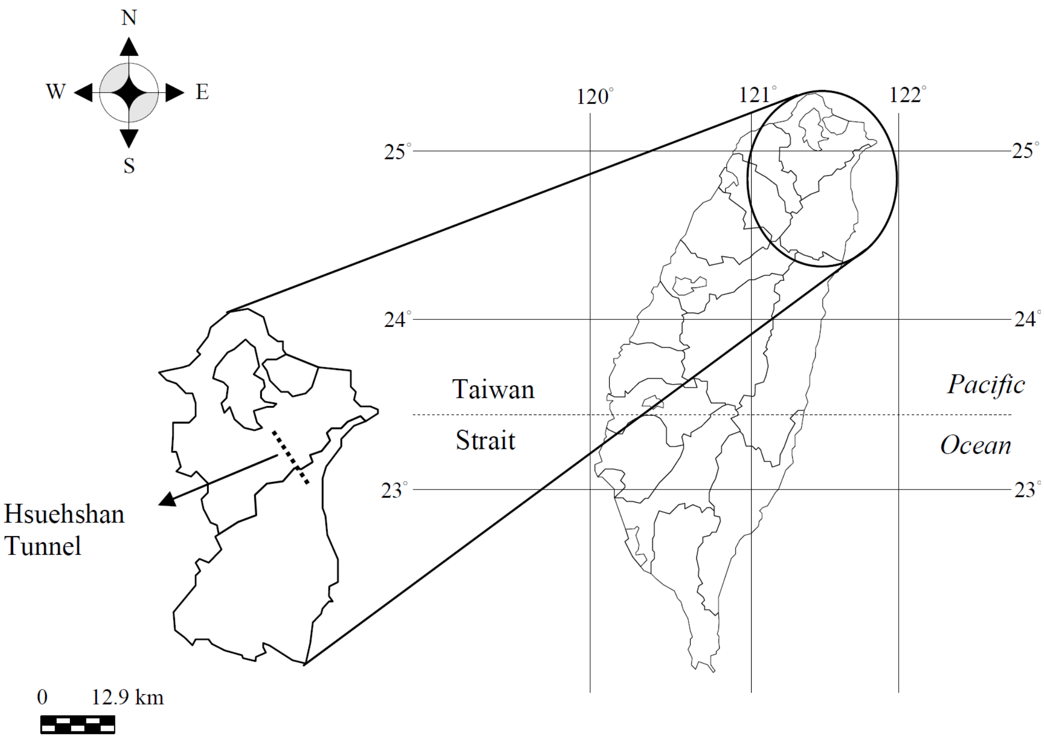

Fig. 1. The map of the Hsuehshan Tunnel in Northern Taiwan.

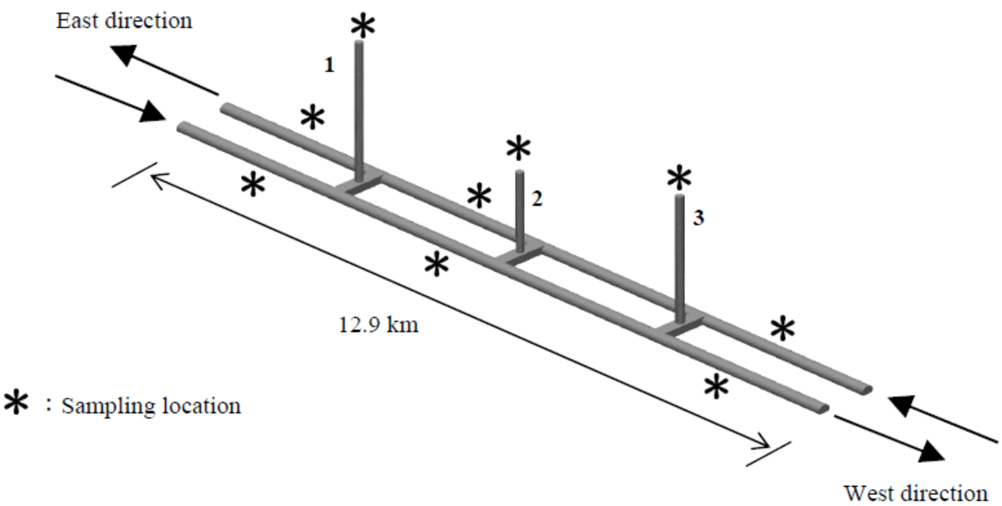

Fig. 2. Top view of the Hsuehshan Tunnel and sampling locations.

the pollutant distribution in a tunnel is essential for effectively managing traffic and ventilation systems, which is particularly relevant given the increasing demand for clean tunnel environments.

Air quality associated with traffic flow inside the Hsuehshan Tunnel has seldom been studied. Recently, Chang *et al.* (2009), Cheng *et al.* (2010), and Ma *et al.* (2011) measured gaseous and/or particulate matters inside the Hsuehshan Tunnel, however, these measurements were conducted before 2006 during which the vertical drafts were not operated and the traffics comprised only light duty vehicles. This study measured the concentrations of gaseous CO and NO_x in the tunnel at 2008 in which vertical drafts were operated and diesel trucks were allowed. Samples were collected at six axial locations and at three outlets of vertical drafts from November 14–17 2008, including weekdays and weekends. Traffic flow data, monitored by Taiwan Area National Freeway Bureau, were also examined.

EXPERIMENTAL

Hsuehshan Tunnel

Fig. 3 depicts the cross-sectional view of the tunnel, which is 4.6 m high for vehicles and 9.6 m wide. The tunnel contains eastward and westward channels, each with 56-paired axial fans. Each channel has two lanes for passenger

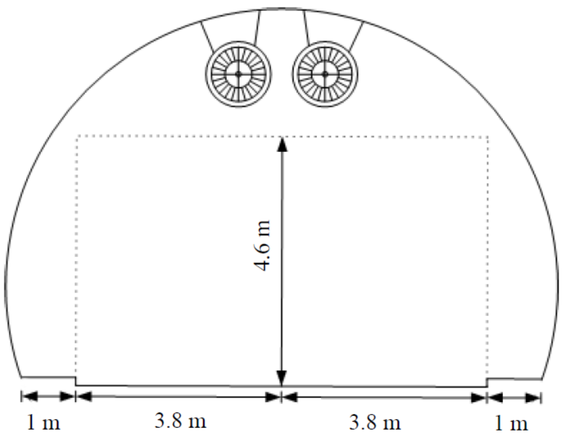

Fig. 3. Cross-sectional view of the Hsuehshan Tunnel.

cars and trucks, with an allowable speed from 60–80 km/hr, depending on road conditions. The westward lanes are upslope, while the eastward lanes are down slope, with an average slope of 1.25% over 12.9 km. Due to tailpipe exhausts, air temperatures increased from channel inlets (23.5°C for the eastward channel, 22.2°C for the westward channel) to the outlets (38.9°C for the eastward channel, 36.9°C for the westward channel), during the survey period. Namely, tunnel temperature is increased by around 15°C over 12.9 km in each direction.

The tunnel is equipped with a ventilation system to maintain air quality. It includes three air exchange stations and three air interchange stations. The tunnel has three exhaust air drafts that comprise a forced ventilation system. The altitudes of No. 1, No. 2, and No. 3 drafts are 512.3 m, 260.1 m and 470.3 m, respectively. The internal diameter of No.2 draft is 6.5 m, and that of the others is 6.0 m. The Nos. 1, 2 and 3 exhaust air drafts are 2.28 km, 5.97 km, and 9.69 km, respectively, from the entrance of the eastward channel. The polluted air in each channel is exchanged with fresh air at the exchange station, using separated fresh and exhaust air drafts. The average flow rate of exchange air was 31 m^3/s during sampling periods. The polluted, hot air is discharged to the exhaust drafts using four sets of fans. Fans in the exchange stations trigger individually at a temperature of > 40°C or a CO level of > 75 ppm in the tunnel.

Sampling and Analysis of Gaseous Pollutants

Gaseous samples of CO and NO_x (= NO + NO_2) were collected simultaneously using air pumps (Gilian, Model GilAir–3RP) and sampling bags (SKC 10L, Model 231–939) at three axial locations in each channel: x = 1,700 m, 5,800 m, and 11,500 m from the inlet of eastward channel, and at three outlets of vertical drafts (x = 2,400 m, 5,900 m, and 9,300 m for vertical drafts 1, 2, and 3, respectively) (Fig. 2). Each of the three pumps was operated at a fixed flow rate of 0.16 L/min. The sampling ports were around 2 m above the ground and 1 m away from the nearest wall. Experiments were performed for four consecutive days from November 14–17 2008, including weekdays and weekends. Each day consisted of three 1-hr sampling periods, namely 09:30–10:30 a.m., 01:00–02:30 p.m., and 0:30–05:30 p.m.

After sampling, the sampling bags were collected into black bags for preventing from the light decay, and the samples were analyzed instantly by the mobile air quality station nearby the Hsuehshan tunnel. Gaseous pollutants analyzed included CO, NO and NO_2, with the procedural details in Lodge (1989) and Chang (2007). The CO concentration was analyzed using an API model 300 monitor based on the non-disperse infrared absorption principle (US-EPA method 10), with a detection limit of 0.04 ppm. Concentrations of NO and NO_2 were analyzed using an ultraviolet spectral-photometer (API Model 200) based on US-EPA Method 7B, with a detection limit of 0.4 ppb.

The emission factor, EF (g/km-veh), of a pollutant due to tailpipe exhausts of vehicles in the tunnel can be determined by (Hsu *et al.*, 2001; Jamriska *et al.*, 2004):

$$M = \overline{V} \times A \times \left(\overline{C}_2 - \overline{C}_1\right) \times t \quad (1)$$

$$EF = \frac{M}{N \times L} \quad (2)$$

In above, M represents total amount of pollutant emitted by vehicles from tunnel inlet to tunnel outlet (g); $\overline{V}$ is the averaged cross-sectional air flow rate (m/s); A is cross-sectional area (m^2); $\overline{C}_2$ and $\overline{C}_1$ represent averaged concentration of the pollutant at cross-sections 2 and 1 (g/m^3), respectively, separated by a distance L (m); and N is the vehicle number during the sampling time t (s).

RESULTS AND DISCUSSION

Measured Traffic

Fig. 4 displays traffic volume, i.e. number of vehicles per day, in the eastern and western directions on four sampling days, as measured by Taiwan Area National Freeway Bureau. On average, the traffic volume in the east direction was around 21,057 on weekdays (November 14/Friday and 17/Monday) and 30,958 on weekends (November 15/Saturday and 16/Sunday), and the traffic volume in the west direction

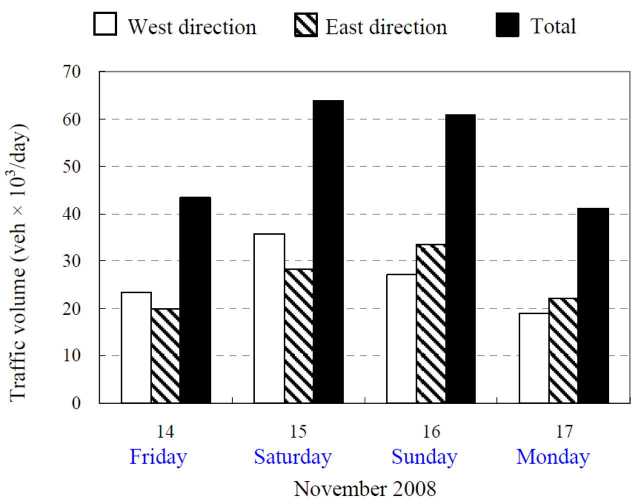

Fig. 4. Traffic volume from November 14–17 2008 in the Hsuehshan Tunnel.

was around 21,165 on weekdays and 31,412 on weekends. Restated, traffic volume on weekends was around 50% higher than that on weekdays in each direction. Fig. 5 presents the traffic flow rate *N*, i.e. number of vehicles per hour, against the traffic speed V (km/hr). The traffic condition was generally satisfactory during the survey period, i.e. traffic speed mostly exceeded 60 km/hr, which is the lower limit in the Hsuehshan Tunnel).

Measured Pollutant Concentrations

Fig. 6 displays the measured averages of CO, NO, NO_2 and NO_x at the inlet, midway, and outlet on weekdays and weekends, both including the eastern and western directions. CO concentrations at the two outlets (14.45–22.77 ppm) were around three times higher than those at the two inlets (3.17–7.33 ppm). Meanwhile, NO_x concentrations at the two outlets (NO: 0.3–0.41 ppm; NO_2: 0.03–0.04 ppm) were around

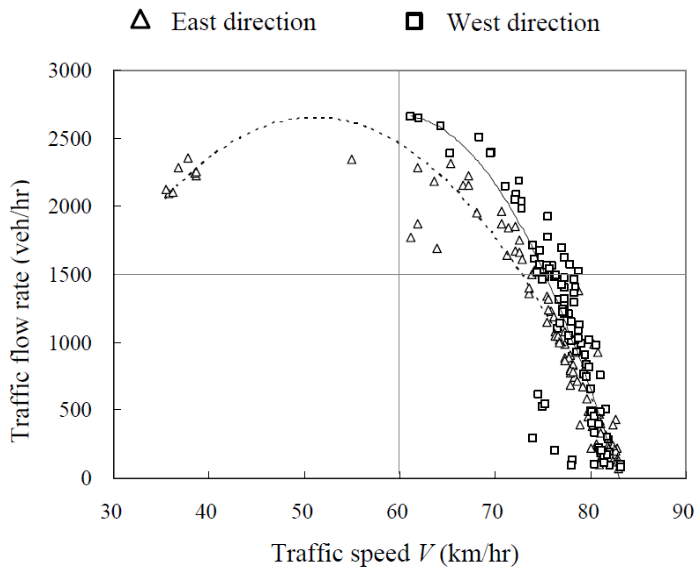

Fig. 5. Traffic flow rate vs. traffic speed in the Hsuehshan Tunnel.

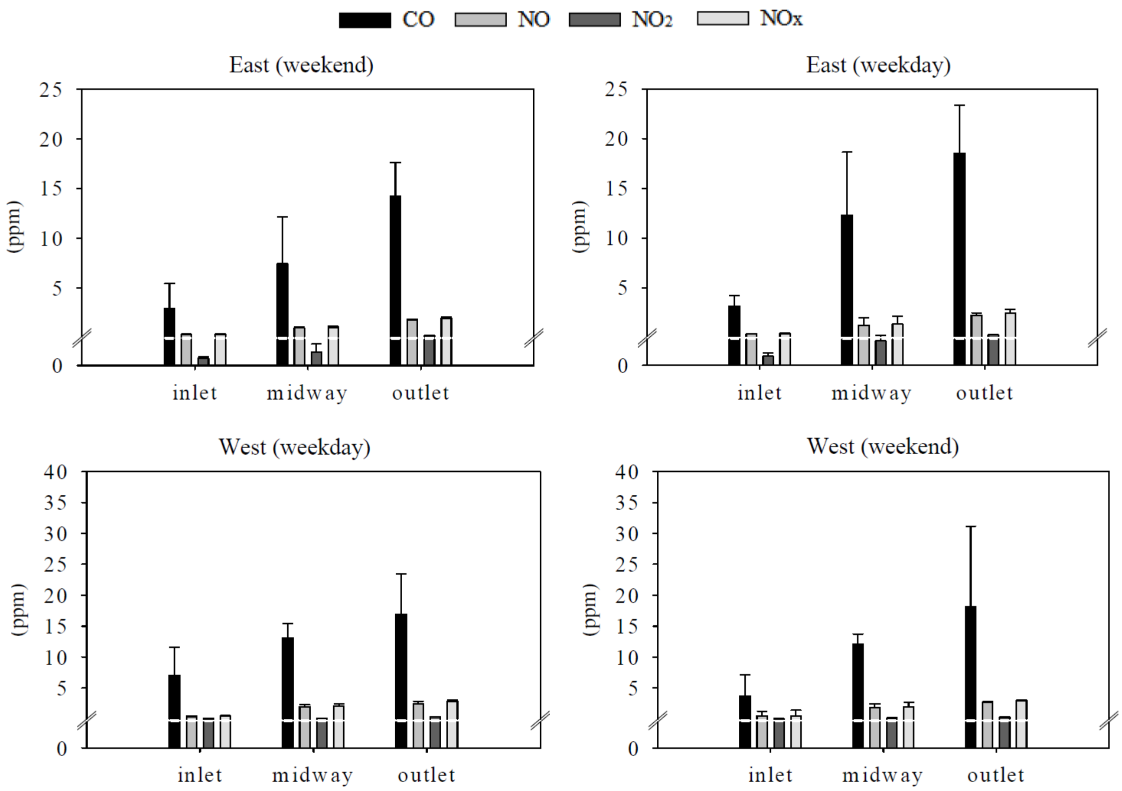

Fig. 6. Concentrations of CO, NO, NO_2 and NO_x at the inlet (x = 1,700 m), midway (x = 5,800 m), and outlet (x = 11,500 m) on weekdays and weekends in the Hsuehshan Tunnel.

four to five times higher than those at the two inlets (NO: 1.75–2.59 ppm; NO_2: 0.17–0.29 ppm). Also, CO concentrations on the weekends (3.17–22.77 ppm) exceeded those on the weekdays (3.39–15.79 ppm) by about 63–155%; NO_x concentrations on the weekends (NO: 0.34–2.61 ppm; NO_2: 0.04–0.28 ppm) exceeded those on the weekdays (NO: 0.30–2.59 ppm; NO_2: 0.03–0.29 ppm) by about 100–173%, due to relatively high traffic flow volumes on the weekends. Pollutants concentrations in the eastern direction were slightly exceeded those in the western direction, due to the upward inclined in the eastward lanes. But a traffic accident was the main cause of the lower traffic speed of a group of vehicles in eastward channel (Fig.5). In this circumstance, the concentrations of CO and NO_x at the entrance of the tunnel raised to about 9.0 ppm and 2.0 ppm, respectively. Therefore, the concentrations of CO and NO_x were 3.5 and 4 times higher on traffic accident periods than those on other sampling periods, respectively. Above values were below the safe values (CO = 100 ppm, NO = 25 ppm) proposed by PIARC (1995). Also, concentrations of the four pollutants were good correlated with traffic volume, but negatively correlated with traffic speeds (Table 1), i.e. similar to the earlier findings by Hsu *et al.* (2001) and Schmid *et al.* (2001).

Fig. 7 displays the measured averages of CO, NO, NO_2 and NO_x at three outlets of vertical drafts, each including weekdays and weekends. Pollutant concentrations on weekends exceeded those on weekdays. The highest concentrations occurred on vertical draft 2 (CO = 12.27 ppm; NO = 1.47; NO_2 = 0.38), followed by vertical draft 1 and vertical draft 3. Above values, particularly for draft 2 and draft 1, are commensurate with or slightly lower than those in the respective results, as shown in Fig. 7. Hence, the first two vertical drafts are most important devices to transport tailpipe exhausts out of the tunnel.

Table 1. Correlation coefficient, *R*, between pollutant concentrations and traffic conditions.

	NO	NO_2	NO_x	CO
Eastward				
Traffic volume	0.82**	0.67*	0.86**	0.80**
Traffic speed	–0.82**	–0.83**	–0.90**	–0.85**
Westward				
Traffic volume	0.80**	0.68*	0.79*	0.72*
Traffic speed	–0.67*	–0.51*	–0.65*	–0.62*

Emission Factor

The emission factors in the Hsueshan Tunnel, derived from Eq. (2), are CO = 1.90 ± 0.43 g/km-veh, NO = 0.31 ± 0.05, NO_2 = 0.07 ± 0.02 and NO_x = 0.38 ± 0.07 g/km-veh for the westward lanes higher than CO = 1.45 ± 0.13 g/km-veh; NO = 0.21 ± 0.03, NO_2 = 0.05 ± 0.009 and NO_x = 0.26 ± 0.03 g/km-veh) for the eastward lanes, due to upslope inclined in westward lanes and down-slop inclined in the eastward lanes (Table 2). Similar results due to road inclination were observed in Lai *et al.* (2008) and Colberg *et al.* (2005). The emission factors in road tunnel from other studies are summarized in Table 2.

Table 3 shows that concentrations of CO, NO, NO_2 and NO_x are well-correlated with traffic volume (negatively) and traffic speed (positively), similar to those observed by Colberg *et al.* (2005). That is, high traffic volume and low traffic speed result in high concentrations and emission factors of the pollutants in the tunnel; and vice versa.

CONCLUSIONS

Concentrations of CO, NO, NO_2 and NO_x in the Hsueshan Tunnel were measured, driven primarily by the combined effect of axial fans and moving vehicles. Based on the results of this study we conclude the following.

1. Traffic volume on weekends was approximately 50% higher than that on weekdays in each direction. Traffic condition was generally satisfactory, with traffic speeds largely exceeding 60 km/hr during the survey period.
2. Measurements indicate that pollutant concentrations of CO, NO, NO_2 and NO_x on weekends exceeded those on weekdays, and were good correlated with traffic volume, but negatively correlated with traffic speed. Additionally, measured concentrations of CO at the two tunnel outlets (14.45–22.77 ppm) were approximately three times higher than those at the two tunnel inlets (3.17–7.33 ppm). Meanwhile, concentrations of NO_x at the two

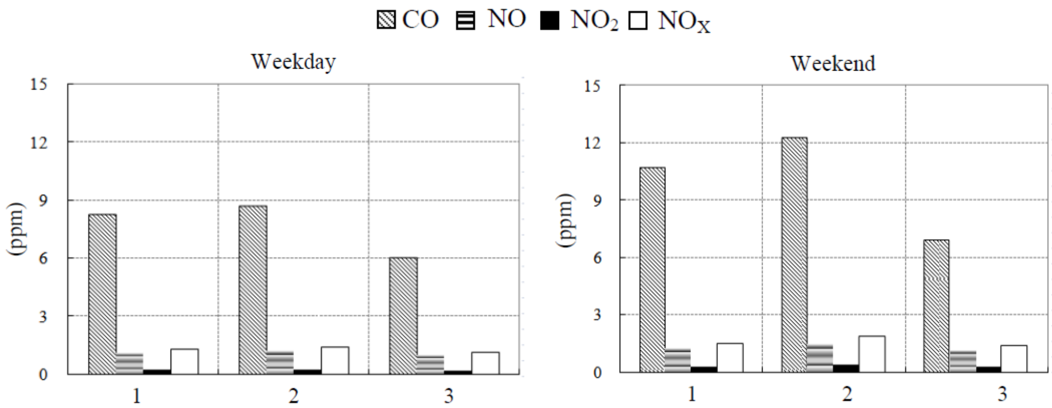

Fig. 7. Concentrations of CO NO, NO_2 and NO_x at the outlets of vertical shaft 1 (*x* = 2400 m), vertical draft 2 (*x* = 5900 m), and vertical draft 3 (*x* = 9300 m) on weekdays and weekends in the Hsuehshan Tunnel.

Table 2. Emission factors (g/km-veh) of CO, NO, NO_2 and NO_x from this and other studies.

Tunnel	NO	NO_2	NO_x	CO
Hsuehshan Tunnel [a]				
Eastward	0.213 ± 0.028	0.046 ± 0.009	0.259 ± 0.028	1.45 ± 0.13
Westward	0.309 ± 0.049	0.071 ± 0.020	0.379 ± 0.066	1.90 ± 0.43
Chung-Liao Tunnel [b]	–[i]	–	0.73 ± 0.15	1.89 ± 0.56
Zhongzheng Tunnel [c]	–	–	1.02	6.25
Tauern Tunnel [d]	–	–	0.359 ± 0.061	1.543 ± 0.315
Taipei Tunnel [e]	–	–	0.9 ± 0.18	3.64 ± 0.26
Salim slam Tunnel [f]	–	–	1.11	11.24
Tuscarora Tunnel [g]	–	–	0.422 ± 0.068	1.93 ± 0.68
Gubrist Tunnel [h]	–	–	1.053 ± 0.092	4.173 ± 0.375

[a] This study; [b] Chiang *et al.* (2007); [c] Hsu *et al.* (2001); [d] Schmid *et al.* (2001); [e] Hwa *et al.* (2002); [f] El-Fadel and Hashisho (2000); [g] Grosjean *et al.* (2001); [h] John *et al.* (1999); [i] No data.

Table 3. Correlation coefficient, *R*, between emission factors and traffic conditions.

	CO	NO	NO_2	NO_x
Westward				
Traffic volume	–0.84**	–0.96**	–0.75*	–0.97**
Traffic speed	0.75*	0.82**	0.70*	0.78**
Eastward				
Traffic volume	–0.65*	–0.80**	–0.62*	–0.75**
Traffic speed	0.70*	0.87**	0.65*	0.83**

* $p < 0.05$; ** $p < 0.01$

outlets (NO: 0.3–0.41 ppm; NO_2: 0.03–0.04 ppm) were about four to five times higher than those at the two inlets (NO: 1.75–2.59 ppm; NO_2: 0.17–0.29 ppm). Averaged pollutant concentrations in the eastward upslope lanes exceeded those in the westward down-slope lanes.

3. The outlet of vertical draft 2 had the highest pollutant concentrations (CO = 12.27 ppm; NO = 1.47; NO_2 = 0.38), followed by vertical drafts 1 and 3, which had comparable or slightly low concentrations than those inside the tunnel.
4. The emission factors for the upslope, west-ward lanes (CO = 1.90 ± 0.43 g/km-veh; NO = 0.31 ± 0.05; NO_2 = 0.07 ± 0.02; NO_x = 0.38 ± 0.07 g/km-veh) are higher than those for the down-slope, eastward lanes (CO = 1.45 ± 0.13 g/km-veh; NO = 0.21 ± 0.03; NO_2 = 0.05 ± 0.009; NO_x = 0.26 ± 0.03 g/km-veh).
5. Traffic volume and traffic speed affect the air quality in the tunnel significantly. High traffic volume and low traffic speed result in high concentrations and emission factors of pollutants in the tunnel; and vice versa.

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