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Real-world vehicle emissions and VOCs profile in the Taipei tunnel located at Taiwan Taipei area

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Abstract

An in situ field experiment was conducted in a highway road tunnel in the Taipei City to determine the motor vehicle emission factors (EF) of different kinds of air pollution species. These are carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane hydrocarbons (NMHC) and VOCs species. About 56 species of VOCs were sampled by canister sampler and followed by the GC-MS analyzing. Furthermore, the tunnel-drafting rate was determined by SF_6 tracer method.

The EF for the highway vehicles determined from this experiment are 3.64, 0.90, 0.44 and 0.24 gm km^{-1} veh^{-1} for CO, NO_x, NMHC and the totally measured VOCs, respectively. A comparison of the EFs from the road tunnel experiment to the estimates by the USEPA MOBILE5b (M5b) and the modified Taiwan EPA MOBILE-TAIWAN2.0 (MT2.0) provides a first-hand evaluation of the model characteristics. M5b and MT2.0 both tend to underpredict CO by 10% and 20%, respectively. While M5b overpredicts NO_x and NMHC by 40% and 20%, respectively; MT2.0 has fairly good predictions for these two species. From the GC-MS analysis of the canister samples, it was found that the most abundant species from the traffic-emitted VOCs in Taipei road tunnel are toluene, ethene and 1,2,4-trimethylbenzene (1,2,4-TMB) by the weight basis. However, ethene, acetylene and toluene are the most abundant in VOCs based on volume. The VOCs' weight composition in terms of the carbon bond classification is 28% by the paraffins, 33% by the olefins and 39% by the aromatics, respectively. In order to evaluate the ozone formation potential from the typical road emission in Taipei area, the maximum increment reactivity is calculated. It was found that about 1015 mg of O_3 is induced by per vehicle per kilometer traveled emission. Among them, ethene, 1,2,4-TMB and propene from the road vehicle's emission contribute most to the ozone-formation reactivity.

Keywords: Emission factor; Tunnel study; VOC profile; Taiwan; MIR

1. Introduction

Ozone pollution attains a serious air quality issue in several urban areas over Taiwan. In recent years, the number of days with ozone hourly concentration exceeding the National ambient air quality standard (NAAQS) (120 ppb) has replaced PM_{10} to be the major contributor for air quality episodes in Taiwan. Ozone is not emitted directly into air; it is formed in the troposphere as a result of complex photochemical reactions that involve VOCs and NO_x as its precursors. The anthropogenetic VOCs exhibit a wide range of variation in reactivity with respect to ozone formation (NRC, 1991). Several VOC reactivity-scaling methods have been introduced and proposed in the articles. For example, the California Air Resource Board (CARB,

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1990) has adopted the maximum incremental reactivity (MIR) introduced by Carter (1994) to evaluate the VOC reactivity of alternative motor vehicle fuels (CARB, 1990). NRC (1991) defined the propylene-equivalent concentration, Propy-Equiv (j), for each VOC species "j" to account for the combined effect of OH-radical in ambient air and the VOCs' concentration.

Mobile source becomes a significant origin of the VOCs and NO_x in the urban area of Taiwan. The emission inventory was compiled by CTCI (1999), which indicated that mobile sources contribute 92% of COs total emission, 37% of NMHCs total emission, and 69% of NO_xs total emission in Taipei metropolitan area. In order to figure out an adequate mitigation strategy concerning the ozone problem in Taiwan, it is necessary to obtain a reliable mobile source emission profile. Many emission factor (EF) models have been widely used to do the job. Examples are the MOBILE5, the EMission FACtor (EMFAC7) (CARB, 1996) and the COmputer program to calculate emissions from road transport (COPERT II) (Ahlvik et al., 1997; Winther, 1998) and so on. However, the reliability of a mobile source emission model can be affected by many factors that vary from place to place and traffic fleet by fleet. Thus, the design and implementation of an adequate in situ mobile source emission study become necessary in order to serve as a first-hand comparison and evaluation. Highway and/or road tunnel studies have been used to measure the real-world emissions of motor vehicles. The method, compared to the method of the individual test of vehicle on a dynamometer, has the advantage on their simplicity, cost-effectiveness and sufficiency in statistical sample size. The important findings from the results of Van Nuys Tunnel study (Ingalls, 1989) revealed that motor vehicle emissions of CO and NMHC were about a factor 2 higher than the predictions by EMFAC7C. Similar road tunnel studies conducted in different places can be found in the articles, such as Gubrist Tunnel experiment of Switzerland (Staehelin et al., 1995, 1997, 1998; John et al., 1999), Fort McHenry Tunnel experiment of Baltimore Harbor, Maryland (Pierson et al., 1996) and Tuscarora Mountain Tunnel of Pennsylvania (Sagebiel et al., 1996). All these kinds of activities contribute significantly to the improvement of the development of traffic emission models. In Taiwan, the tunnel study was first conducted in southern Taiwan area by Tsai et al. (1998) for the Chung–Cheng tunnel in the Kao-Hsiung city (Tsai et al., 1998; Hsu et al., 2001). However, the tunnel is relatively short and thus the entrance effect becomes a major concern. Later on, an experiment was carried out in the Lishin and Zefun tunnel of Taipei county for the emissions of volatile aromatic compounds from the combined traffic composed by motorcycles and light-duty (LD) vehicles (Hsieh et al., 1999).

In this study, the Taipei tunnel was selected to study the highway traffic emissions. It is on a connecting freeway that provides the channel to access the turnpike No. 3, an artery freeway of Taiwan Island, from southeastern Taipei urban area. Most of the traffic is commuters; they use the turnpike No. 3 to access their work places from towns within 100 km distance. The experiment was voted to determine the EF of CO, NO_x, NMHC and important VOCs species from motor vehicles that traveled through the tunnel with different congestion patterns in a daily cycle. Furthermore, a direct deduction from the dilution factor of a controlled release of tracer gas, SF_6, was used to determine the induced tunnel-drafting rate (the volumetric flow rate). It is believed that this method can significantly reduce the uncertainty in the determination of the traffic-induced drafting inside a highway tunnel.

2. In-situ measurement

2.1. Tunnel description

The Taipei tunnel is located on the connecting highway to the turnpike No. 3 that goes through the southeast corner of the great Taipei Metropolitan area. This area has inhabitants of more than 5 million. The tunnel facilitates a two-bored, no signal light control and divided highways for the eastbound and westbound traffics, which connect the city traffic to the major turnpike. There are two lanes on a one-way bore, and each bore has 60 m^2 in cross-section, and 800 m in length, 10.6 m in width, 6.8 m in height. Also, it facilitates a 1.1 m wide sidewalk on the right-hand side of the road and thus provides the mounting space for the instruments in our experiment. The measurement was carried out in the eastbound bore. The tunnel's orientation is rather straight and the grade is minimal. Since the traffic light control is located beyond 3 km from the entrance of the tunnel, the traffic speed within it is varied mainly by the congestion factor. All vehicles' operation can be safely assumed to be in the hot-stabilized mode. Four axial-type blowers mounted under the tunnel's ceiling are equipped to enhance the tunnel drafting. Two of them run automatically at 8:00 a.m. and 18:00 p.m. for each 1-h congestion period.

2.2. Run description

The sampling experiment was carried out from 7:00 a.m. to 17:00 p.m. on 1 July 2000 (Saturday, half-workday). It was a typical sunny and hot summer day in Taipei area. The averaged daytime ambient temperature outside the tunnel during the experiment period was recorded as 32.0°C, while the temperature inside the tunnel was about 0.4°C higher. Each sampling that

sampled the concentrations inside the tunnel lasted for 60 min. Two types of vehicles were classified, namely the LD vehicle and the heavy-duty vehicle (HD). Since, the highway regulation in Taiwan does not allow the two-wheel motorcycle to access the normal highway, the LD contains only passenger cars and small gasoline-fueled or diesel-fueled pick-ups. While, the HD contains those buses and HD trucks used for cargo transport. All of them are powered by the diesel-fueled engine. The traffic volumes and traffic speeds were detected and recorded by the inductance sensors originally mounted by the freeway control center. Serving as a back-up record in our experiment, a video camera (SONY DCR-TRV-310) was used to tape-record the traffic status within the tunnel.

2.3. Instrumentation

Air samplers were located over the sidewalk space in the tunnel. Array of sampling racks was allocated at a distance of 100, 400 and 700 m, respectively, from the entrance point of the tunnel. Each sampling rack has 4 sampling inlet ports, and was located at 1.0, 2.0, 3.0 and 4.5 m heights above the tunnel floor, respectively. Fig. 1 shows the sampling system layout. This arrangement allowed a cross-sectional averaged concentration to be obtained. Air samples contaminated by traffic emissions were collected by either Tedler bags or stainless-steel canisters (61 in size) located at the aforementioned positions, respectively. Either the Tedler bag or the canister was controlled by floating flow meters at a flow rate of about 100 ml min^{-1} level continuous for 60 min. The tracer gas, SF_6, was released at the 100 m down the entrance position from a near floor port, the total mass released in the 1-h period was controlled and recorded.

Tedler bag samples were analyzed immediately after each run by automatic monitors for their concentrations of CO, NO_x, and SF_6. The specifications of analyzers used are API-300 NDIR CO analyzer, API-200 chemiluminescence NO–NO_2/NO_x analyzer and the HP-5890 GC-ECD SF_6 analyzer. The GC-ECD was equipped with a stainless steel column (Porapak Q 80/100, 2 m × 4 mm ID), and the oven temperature was set to 80°C, the injector's and detector's temperature were set to 220°C and 250°C, according to the operation manual. 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 canister samples were brought back to the laboratory to analyze its NMHC concentration by GC-FID method and the speciated composition of VOCs by the GC-MS method. The US EPA Method 15 (TO-15, USEPA, 1997) provides the guidance of GC-MS analysis. The VOCs standard (Enviro-Mat Ozone Precursor Mixture, Matheson Gas Products, Georgia, USA) was prepared and served as the standard. Canister content was injected into a 500 ml pre-conditioning system for thermal conditioning (Entech Instrument, Inc., model 7100, CA). After that, the sample was injected into the gas-chromatograph (GC) (HP 5890 Series-II plus coupled with a HP 5972 MS). The mass-spectrometer (MS) scanned the range of m/z from 40 to 150 using SCAN mode. A non-polar HP-1, 60 m × 0.25 mm ID × 1.8-μm film thickness capillary column was used to separate individual compound in the sample. NMHC were analyzed by capillary GC-FID (Shimadzu GC-14B). The column used in this GC-FID is a 15 m × 0.53 mm ID silica steel capillary with the 1 m × 0.53 mm ID molecular sieve 5A (60–80 mesh). The oven temperature of GC was set to 150°C.

HP5972 MS and the data processing software (HP G1034C Chemstation Software) were used for measuring and analyzing species in VOCs. Quality control and assurance requirements include establishing GC retention times, calibration R2, method detection limit (MDL) and the study of reproducibility for all analyzing compounds. An internal standard (toluene-d8) was used for each analysis to confirm the stability of the MS. Additionally, cyclohexanal-d12 was analyzed daily as an instrument performance reference standard. For VOCs collected by canisters, method detection limits were between 0.1 and 0.7 ppbv for GC-MS used. The RSD is between 2.2% and 6.5%, which is well within the limit of

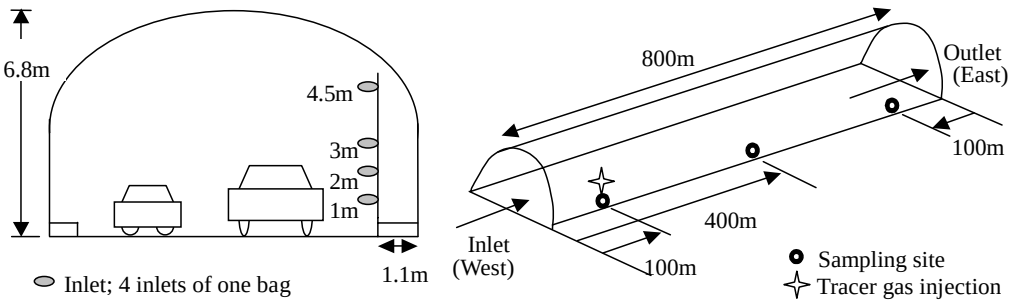

Fig. 1. Sampling locations and placement of equipments of Taipei Tunnel experiment.

±25%. The precision in this analyzing routine was between 7% and 8% that is less than the required ±30%.

2.4. Determination of the tunnel ventilation flux

The tunnel ventilation flux was determined by tracer gas method. A fixed mass emission rate of SF_6 was maintained and recorded at the release point. In the pre-run test, the cross-sectional averaged concentration of SF_6 at several downwind sections were sampled and analyzed to check the mixing status of SF_6 in the tunnel. It was found that the assumption of complete mixing over the cross-sectional area of the released SF_6 can be adopted at the distance of 75 hydraulic diameters down the releasing point. In the real run period, the averaged concentration of SF_6 sampled through 5 different ports located at the last instrument array (100 m before the tunnel exit) was used to infer the drafting rate (ventilation volume flow rate) in the tunnel. Since the vehicle's body movement induces the draft in the tunnel, the high-intensity turbulence within the drafting flow renders the direct measurement by anemometer method to be extremely difficult and unreliable. With the known SF_6 concentration at the near exit section and the pre-known mass emission rate of SF_6, the effective drafting rate can be determined by the mass conservation principle.

2.5. Determination of the vehicle's EF

The total mass emission rate from the passing vehicles between two cross-sections in the tunnel can be inferred by the mass conservation principle.

$$M/t = Q \times (\bar{C}_{\text{out}} - \bar{C}_{\text{in}}). \quad (1)$$

Here, M (μg) is the total pollutant's mass emitted by passing traffic vehicles in-between two cross-sections in the period of time "t". Q is ventilation flux (air flow volume per unit time); $\bar{C}_{\text{in}}$ and $\bar{C}_{\text{out}}$ represent the cross-sectional averaged concentration at the upwind cross-section and the downwind cross-section, respectively. Giving the traffic volume counting, N (number of passing vehicles) within period "t"; and the known distance between two sampling cross-sections, L, the average emission factor, EF in $\text{gm veh}^{-1}\,\text{km}^{-1}$ for a given run can be obtained

$$\text{EF} = M \times (N \times L)^{-1}. \quad (2)$$

In this study, the difference between LD and HD vehicles are neglected, instead the overall fleet emission was calculated.

The same emission factor can also be obtained from the model's computation. The applications of MOBILE5b (M5b) and Mobile-Taiwan2.0 (MT2.0) are such examples. MT2.0 is a modified version of MOBILE4.1, with a minor modification with parameters pertinent to Taiwan's specific vehicle, fuel and driving pattern characteristics. However, these characteristics appear to be reflected in the so-called "the zero miles emission rate" and the "deterioration rate" factors used in the model. Due to the insufficient sample size in performing the test for MT2.0, we regard that the determination of these parameters might be a significant concern. Furthermore, the hot summer climate in Taiwan causing the "hot soak" emission becomes an unknown effect. All these uncertainties need to be solved by the real road test of traffic emission. As for the purpose of model evaluation and comparison, we did not alter the model parameters except those of in situ road fleet vehicle composition and the traveling speed as measured. Both models and tunnel experiments provide the EF of CO, NO_x and NMHC in the unit of $\text{gm km}^{-1}\,\text{veh}^{-1}$ to reflect the emissions on an averaged freeway traffic condition during summer in Taiwan climate.

3. Results and discussion

3.1. Traffic flow

The hourly traffic volume ranged from 1643 (7–8 a.m.) to 2819 (1–2 p.m.) with an average of $2296\,\text{veh}^{-1}\,\text{h}^{-1}$ on the experiment day. Among 94–98% of the traffic volume were LD vehicles, in which 4–10% was diesel-fueled. The experimentally averaged speed of LD in the tunnel was recorded at $67\,\text{km h}^{-1}$, the variations were from 64 (1–2 p.m. on Saturday, half-working-day rush hour) to 71 (7–8 a.m.) km h^{-1}. The average speed of HD vehicles ranged from 60 (1–2 p.m.) to $69\,\text{km h}^{-1}$ (11–12 p.m.), the experimentally averaged speed was $65\,\text{km h}^{-1}$.

3.2. Tunnel ventilation flux

The ventilation flux in a tunnel is vital in controlling the pollution level inside it. Concerning our experiment in the determination of the EFs of on-road vehicles' emission from tunnel measurement, accurate measurement of the effective ventilation flux is key to determine the emission rate inferred from concentration measurement. The drafting effect inside a tunnel is mainly caused by the aerodynamic drag force from the moving vehicles. The shape factor of the car, its moving speed and the sparsity among vehicles determine the effective drafting flow. However, due to the nature of turbulence and intermittency in the induced drafting flow, the point measurement by a traditional anemometer becomes difficult and even unreliable.

The result from the SF_6 tracer method is presented in Fig. 2. Interesting features are revealed by the figure. The tunnel cross-section averaged ventilation velocity is

seen to be inversely proportional to the vehicle's speed, although with a rather large scatter from the regression line. The drafting speed is seen to increase as the in-tunnel traffic volume (the number of passing vehicles per time) increases. This makes sense that traffic volume may affect the total number of the dragging bodies in the tunnel. The ventilation flux from our experiments ranged from 250 $m^3 s^{-1}$ at 7–8 a.m. to 290 $m^3 s^{-1}$ at 1–3 p.m., with an average of 272 $m^3 s^{-1}$.

3.3. Emission factors

Due to the insignificant variation of the HD/LD traffic volume ratio in our experimental runs, the attempt to differentiate the EF of LD vehicle and the HD vehicle by multi-regression method has failed. Thus, only the composite EF for all the on-road vehicles is reported in this paper. Table 1 provides the comparison of our EFs for CO, NO_x and NMHC to EFs obtained from other domestic experiments and experiments in other regions. The EF of CO obtained in this experiment ranges from 3.27 to 4.08 gm km^{-1} veh^{-1} with an average of 3.64 gm km^{-1} veh^{-1}. The EF for NO_x ranges from 0.67 to 1.21, with an average of 0.90 gm km^{-1} veh^{-1}. The EF of NMHC (obtained by GC-FID measurement) and the EF of total sum of 56 VOC species (obtained by GC-MS measurement) are 0.44 and 0.24 gm km^{-1} veh^{-1}, respectively. Compared with the EFs from the Chung–Cheng tunnel experiments, their EFs of CO and NMHC are higher by factors of 1.8 and 3.4, respectively, while the EFs for NO_x from both the experiments are about the same. Reasons for these discrepancies are discussed as follows. Since the Chung–Cheng road tunnel is located at Kao-Hsiung city of southern Taiwan, it passes under a surface railway with a length of about 100 m. Thus the sloping effect (with road grade of about $\pm 6\%$) becomes significant. Furthermore, the entrance of Chung–Cheng tunnel is only about 30 m from a cross-road signal. We expect that the acceleration–deceleration driving modes of the passing vehicles may significantly increase the emissions of CO and NMHC. On the other hand, the inauguration of more stringent new car emission standard effective by 1999 might be another minor effect (Chung–Cheng tunnel experiment was carried out in 1997). All these may contribute to

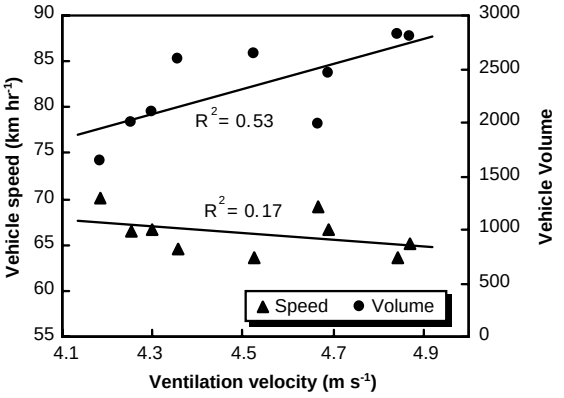

Fig. 2. Ventilation velocity and vehicle volume vs. speed.

Table 1
Comparison of emission factors (g km^{-1} veh^{-1}) with other tunnel experiments

Tunnel		CO	NO_x	NMHC
Taipei	(All vehicles)	3.64 ± 0.26	0.90 ± 0.18	0.44 ± 0.06
Chung–Cheng	(All vehicles)	6.25	1.02	1.51
		6.5 ± 1.5(sp[a] < 60)	1.9	± 0.5[b] (sp[a] < 60)
		6.0 ± 1.8(sp[a] > 60)		1.0 ± 0.5[b] (sp[a] > 60)
Gubrist	(LD)	4.18 ± 0.38	1.05 ± 0.09	0.46 ± 0.04[c]
	(HD)	1.18 ± 2.33	15.56 ± 0.79	0.29 ± 0.27[c]
	(All vehicles)	3.89 ± 0.64	2.45 ± 1.59	0.44 ± 0.06
Fort McHenry	(LD)	3.95 ± 0.34	0.50 ± 0.06	0.39 ± 0.06[d]
	(HD)	6.11 ± 1.75	8.97 ± 0.28	0.96 ± 0.28[d]
	(All vehicles)	4.63	2.060.48	
Tuscarora	(LD)	3.04 ± 0.30	0.24 ± 0.16	0.18 ± 0.04[d]
	(HD)	3.75 ± 1.00	12.09 ± 0.53	0.42 ± 0.12[d]
	(All vehicles)	3.63	3.81	0.30

[a] Speed of vehicle (km h^{-1}).
[b] 21 Species of NMVOC.
[c] *t*-VOC, to be calculated by regression.
[d] Calculated by weighted regression (by the number of vehicles).

smaller EF for CO and NMHC from our experiment. Compared to EFs by Gubrist tunnel experiment (Switzerland), the values of CO and NMHC from our experiment are quite similar, while their EF of NO_x is a factor of 2.7 higher than the result from the Taipei tunnel experiment. The comparison to the results from the Tuscarora Tunnel experiment on the Pennsylvania Turnpike and the Fort McHenry Tunnel experiment in Baltimore finds a similar conclusion about EFs of CO and NMHC. The difference is concentrated on the values of EF of NO_x from different regions. To explore the reason, it is found that the fraction of HD vehicles (diesel-fueled) on the experimental day's traffic was extremely low. It only occupied 2–6% of the total traffic volume. The fraction of HD vehicles in the total traffic volume, by the Gubrist experiment was averaged as 24% (workday average), the Tuscarora experiment was 6–80% (average 18%), and the Fort McHenry experiment was 4–73% (average 17%), is significantly larger than ours. This fact causes a smaller NO_x emission factor of total on-road traffic volume from Taipei tunnel experiment. It is unclear, but is speculated that the special date we chose might be of bias concerning the on-road HD vehicle's population. Further study regarding the on-road fleet's characteristics is needed.

Table 2 shows the EF of different VOC compounds. On the mass basis, the top three abundant VOC in Taipei Tunnel are toluene, ethene and 1,2,4-TMB. The averaged EF for them are 29.02 ± 4.95, 26.23 ± 4.89 and $14.28 \pm 2.94\,mg\,km^{-1}\,veh^{-1}$, respectively. With little speculation, the characteristic VOCs emissions may directly reflect the specific formula of gasoline or diesel fuel provided by local refinery industry.

It can be seen that toluene's emission factor is significantly higher in Taipei tunnel than in Gubrist tunnel in Switzerland. The aromatic compounds like benzene, xylene and toluene, have been measured in significant concentrations by Hsieh et al. (1999). Other reasons like the hot-soak emission or the climate effect and so on, seem unlikely in explaining the measured VOCs spectrum in Taipei tunnel and other places in Taiwan. Concerning the EF of olefin compounds, they are recognized as the most reactive species in ozone

Table 2
Measurements of EF of Taipei tunnel and Gubrist tunnel study ($mg\,km^{-1}\,veh^{-1}$)

Code	Species	Taipei (all)	Gubrist (GAV)[a]	Code	Species	Taipei	Gubrist
A	Ethane	4.27±0.96	4.29±0.89	AC	3-Hexene(*cis*)	0.36±0.11	—
B	Ethene	26.23±4.89	24.14±6.12	AD	Cyclopentane, methyl	2.64±0.93	—
C	Propane	2.40±0.77	0.15±1.15	AE	PENTANE,2,4-dimethyl	0.44±0.07	—
D	Propene	11.61±2.04	13.93±3.81	AF	Benzene	12.21±3.26	10.38±2.34
E	Acetylene	11.56±3.02	12.83±3.22	AG	Cyclohaxne	0.98±0.13	—
F	Isobutane	4.57±0.94	1.71±0.95	AH	Hexane,2-methyl	[b]	—
G	*n*-Butane	6.56±1.96	9.70±5.32	AI	Pentane,2,3-dimethyl	[b]	8.64±4.02
H	1-Butene	8.27±1.55	1.92±0.61	AJ	Hexane,3-methyl	2.94±0.43	—
I	trans-2-Butene	1.61±0.38	1.44±0.57	AK	2,2,4-Trimethyl-pentane	0.29±0.18	—
J	*cis*-2-Butene	1.84±0.46	1.26±0.53	AL	Heptane	1.46±0.24	0.93±0.44
K	3-Methyl-1-Butene	0.67±0.13	0.72±0.30	AM	Cyclohaxne, methyl	0.94±0.18	—
L	Isopentane	12.50±4.09	18.22±7.28	AN	Pentane,2,3,4-trimethyl	[b]	—
M	Pentene	1.61±0.38	0.61±0.39	AO	Toluene	29.02±4.95	16.02±4.84
N	Pentane	9.52±3.05	6.16±4.45	AP	Heptane,2-methyl	1.05±0.29	—
O	Isoprene	[b]	—	AQ	Heptane,3-methyl	1.02±0.33	—
P	*trans*-2-Pentene	2.76±0.77	1.22±0.75	AR	Octane	1.31±0.29	0.22±0.23
Q	*cis*-2-Pentene	1.59±0.43	0.78±0.48	AS	Ethylbenzene	5.88±1.55	3.6±0.91
R	2-Butene,2,2-dimethyl	3.09±1.05	—	AT	*m*,*p*-Xylene	8.95±2.38	10.78±3.01
S	Butane,2,2-dimethyl	1.32±0.25	4.53±2.14	AU	Styrene	4.81±1.33	—
T	Cyclopentene	0.47±0.12	—	AV	*o*-Xylene	7.88±2.14	4.77±0.56
U	1-Pentene,4-methyl	[b]	—	AW	Nonane	0.54±0.13	0.07±0.11
V	Cyclopentane	0.89±0.21	—	AX	Benzene,1-methyl-1-ethyl	1.09±0.44	—
W	Butane,2,3-dimethyl	1.33±0.69	—	AY	α-Pinene	[b]	—
X	Pentane,2-methyl	5.27±1.72	—	AZ	Benzene, propyl-	1.68±0.60	0.68±0.29
Y	Pentane,3-methyl	6.39±1.53	—	BA	β-Pinene	[b]	—
Z	1-Pentene,2-methyl	0.83±0.29	—	BB	Benzene,1,3,5-trimethyl	2.31±0.38	1.51±0.38
AA	Hexane	4.18±1.56	1.73±0.56	BC	Benzene, 1,2,4-trimethyl	14.28±2.94	4.59±1.09
AB	2-Hexene	0.93±0.10	—	BD	1,3-Butadiene	2.56±0.38	1.61±0.21

[a] Gasoline vehicles, were calculated by multi-regression model.
[b] Below the detection limit—not reported.

Table 3
Model-predicted emission rates ($g\,km^{-1}\,veh^{-1}$) and CO/NO_x, $NMHC/NO_x$ ratios from the Taipei tunnel

	CO	NMHC	NO_x	CO/NO_x	$NMHC/NO_x$
Observed	3.64±0.26	0.44±0.06	0.90±0.18	4.23±0.94	0.51±0.13
MOBILE5b	3.24±0.14	0.53±0.01	1.28±0.13	2.56±0.34	0.42±0.04
Mobile-Taiwan2.0	2.72±0.09	0.44±0.01	0.88±0.10	3.15±0.43	0.51±0.06

formation, and are in par with the findings in other tunnel experiments.

3.4. Comparison with EF models

EF as determined from our tunnel experiments at each run are listed in Table 3 in order to compare with the corresponding EFs obtained by M5b and MT2.0. The ratios of measured EF to that by the model are also plotted in Fig. 3. In general trend, the models tend to underestimate the CO emission, while they overestimate both the NO_x and NMHC emissions. On average, M5b underestimates the measured CO emission factor by 10%, while it overestimates the NO_x by 40%, and NMHC by 20%. The MT2.0 also underestimates the measured CO emission factor by 20%, while it fairly estimates the measured emission factor of NO_x and NMHC with slight run-to-run variations. Furthermore, the experiment run composite ratios of CO/NO_x and $NMHC/NO_x$ are also listed in Table 3. The same ratios calculated by M5b and MT2.0 with parameters pertinent with each run condition are also listed for comparison.

From the amplitude of deviations from its mean, the ratio provides the information of model sensitivity for their response to real condition. It can be seen that both models are of less sensitivity to respond to the real world change as compared to the measured ratios. We speculate that the changes like the driving pattern change due to traffic congestion and the on-road fleet composition change could alter the real EF to a larger extent. In short, it must be very careful in using the emission model to estimate the real world's traffic emission, especially when sitewise or diurnalwise traffic emissions are needed. We suggest that it might be an interesting topic when talking about the ozone episode. Whether it is caused by meteorology factors or the city traffic congestion factors needs to be explored.

3.5. VOCs composition and fraction

The speciation of VOCs was obtained from the analysis of canister samples. Profiles of VOCs at the entrance and exit sampling sites are shown in Fig. 4. The most abundant three compounds observed, in both entrance and exit, were ethene, toluene and acetylene.

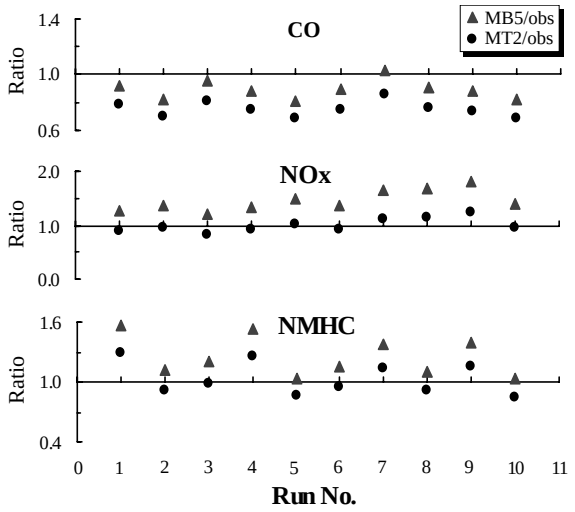

Fig. 3. Run ratios of model-predicted and observed emission factors for CO, NO_x and NHMC, (MB5: MOBILE5b, MT2: Mobile-Taiwan2.0).

Comparing the percentage of entrance with exit, ethene and acetylene were increased but toluene was decreased.

Observed VOCs emission profiles (as weight percentage of total VOCs) are shown in Table 2. The most abundant compounds were toluene, ethene, 1,2,4-TMB, isopentane, benzene, propene and acetylene; each of the former two compounds over 10%, each of the latter four compounds over 5%. The weight composition in terms of the carbon bond classifications is paraffins 28%, olefins 33% and aromatics 39%; with the number of carbon being C2–C4 34%, C5–C6 30% and C7–C9 36%.

The results showed that EF of CO, toluene and 1,2,4-TMB were less relative to vehicle speed, their correlation coefficient (R) was –0.259, 0.233 and –0.220, respectively. But that of 1,3-butadiene was 0.647; this means the EF of 1,3-butadiene increased with increasing vehicle speed. The R of NO_x and vehicle speed was 0.844, which means EF of NO_x increased with increasing vehicle speed.

The relations between CO and benzene were less relative ($R = 0.424$), or were CO and 1,3-butadiene

($R = -0.177$). But for benzene and toluene, they are more relative to each other ($R = 0.78$). However, the vehicle speed ranged from 63.6 to 70.2 km h^{-1}, more data should be collected to make the evidence clear.

3.6. Ozone formation potential

In order to evaluate the relative importance of individual VOC species concerning their ozone formation potential, the Maximum Incremental Reactivity (MIR) scale (Carter, 1994) for individual compound measured in Taipei tunnel is used. With the known VOCs profile measured by canister GC-MS method during this study, ozone formation potential is compiled to the form of ozone formed per vehicle per kilometer traveled. Their total is 1.02 gm O_3 km^{-1} veh^{-1}.

On the basis of 100 gm VOCs emitted, the ozone formation is 427 gm (from Section 3.3, average emission rate of total VOCs is 0.24 g km^{-1} veh^{-1}) which is similar to the LD fleet results of Tuscarora (409 gm) and of Ft. McHenry (403 gm). Also, individual species is grouped into paraffin, olefin and aromatic compounds to get the group lump-sum ozone formation potential. The results are shown in Table 4. It can be seen that the olefin compounds contribute most to the potential ozone formation, i.e. 53.9%. The aromatic compound group contributes in less but significant percentage, 38.7%. Paraffin is least in their contribution in ozone formation, regardless of their obvious amount of emission. The most important compounds and their reactivity to contribute ozone formation are listed in Table 5. Top three towere ethene, 1,2,4-TMB, and propene, each contributing over 100 mg O_3 km^{-1} veh^{-1}.

Due to the significant number of two-wheel motorcycles used by local commuters in almost every Taiwan urban areas, the emission difference needs to be explored. Furthermore, about half of the motorcycles

Table 4
Reactivity of VOCs (mg O_3 veh^{-1} km^{-1})

	Paraffins	Olefins	Aromatics	Overall
Max	91.3	661.5	494.5	1218.4
Min	57.8	425.4	280.4	812.4
Ave	75.2	547.6	392.7	1015.5
Std	12.0	87.9	61.6	143.9
%	7.4	53.9	38.7	100

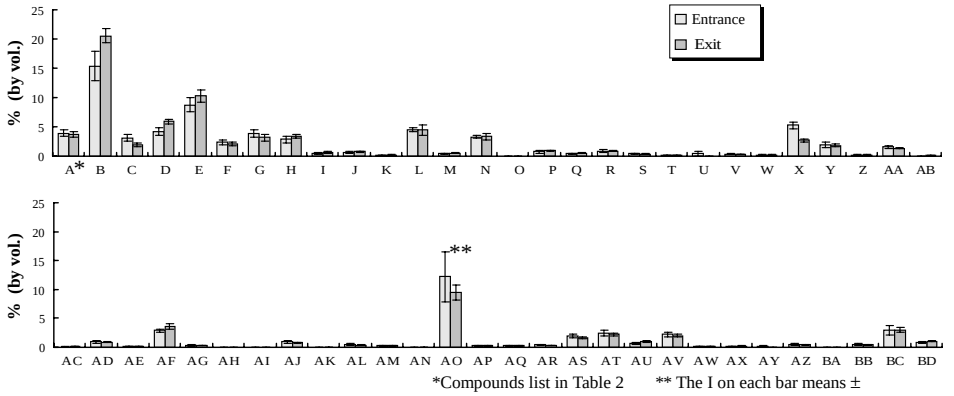

Fig. 4. Observed VOCs profiles of entrance- and exit-sampling site.

Table 5
Major VOCs compounds of ozone formation potential (per 100 g VOCs emitted)

Species	g O_3			Species	g O_3		
	Taipei[a]	Zefun[b]	Lishin[b]		Taipei[a]	Zefun[b]	Lishin[b]
Ethene	81.6	—	—	*o*-Xylene	21.5	29.3	51.3
1,2,4-TMB	52.8	14.4	34.5	1,3-Butadiene	11.7	—	—
Propene	45.9	—	—	*trans*-2-pentene	10.2	—	—
Toluene	32.9	126.1	98.7	1,3,5-TMB	9.8	115.5	170.2
1-Butene	30.9	—	—	Ethylbenzene	6.7	7.5	10.4
m, *p*-Xylene	27.9	58.8	81.6	Benzene	2.2	3.9	3.9

[a] Calculated from the EFs of this study.
[b] Calculated from each VOCs% (wt.) in NMHC (μg m^{-3} as C).

in Taiwan are powered by the two-stroke engine, which is notorious for its heavy VOCs emission. Table 5 also provides the comparison among the characterizing ozone potential by different aromatic compounds' emission profiles from highway and usual town-way traffic. Since the traffic fleets of Zefun tunnel and of Lishin tunnel are characterized by combined passenger cars and motorcycles, their emissions must reveal the distinct difference from the highway tunnel's emission. All the highways or freeway in Taiwan do not allow access by to two-wheeled vehicles. It can be seen that the significant differences in ozone formation are due to toluene, xylene and TMB.

4. Summary and conclusion

Real-world EF have been obtained for CO, NO_x, NMHC and individual VOC species from a tunnel experiment characterizing the usual highway emissions in northern Taiwan area. The results are compared with the traffic emission models like USEPA MOBILE5b (M5b), and the modified version MOBILE-TAIWAN2.0 (MT2.0), in order to evaluate their applicability in Taiwan. A comparison with the results from other prominent tunnel experiments carried out in a different region/country was also made and discussed. The presentation of VOCs-profile obtained in our experiment reveals the emission characteristics of on-the-highway traffic fleet of Taiwan. When compared to the town-way tunnel experiments in the same northern Taiwan, the VOC profile reveals distinct characteristics. The two-stroke engine used on motorcycles, which only allowed accessing the local town-way road, causes significant aromatic compounds' emission. Specific findings and conclusion are listed below.

- EF of CO and NMHC obtained from our freeway tunnel experiment are fairly close to the data by Gubrist tunnel Experiment, Fort McHenry tunnel Experiment and the Tuscarora tunnel Experiment. However, the emission factor of NO_x is at least of factor 2 less than other experiments. When the results from Chung–Cheng tunnel Experiment are compared, their EF for CO and NMHC are observed to be higher. This reveals that Taiwan town-way's driving pattern with more acceleration/deceleration mode may increase the CO and NMHC's emission.
- The emission factor model, MT2.0, predicts fairly well the real-world emissions in an overall average sense, although it underestimates the CO emission by 20%. Using the experimental run-to-run parameter input, both models become less sensitive in the output of emission amount, as compared to the experimental results. This fact suggests that MT2.0 or M5b might not be able to give a realistic emission change due to the city congestion effect or the on-road traffic fleet composition variation.
- The aromatic compounds are abundant in the Taipei Tunnel's emission in addition to the olefin species, ethene. Among them are toluene and 1,2,4-TMB, and their emissions are significantly higher than the findings from other regions/countries. It suggests that the aromatic compounds are actually the main gasoline additive or high fraction components in the fuel provided by local refinery industry.
- Using MIR scale for the ozone formation potential, different VOC species are rated for their ozone formation per vehicle per kilometer traveled. The average traffic emission of total VOCs from Taipei Tunnel Experiment produces 1.02 gm ozone per vehicle per kilometer traveled. Among this, ethene, 1.2,4-TMB and propene contribute over 100 mg O_3 per vehicle per kilometer traveled.

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