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Vehicular emissions and air quality assessment in roadway tunnels: the Salim Slam tunnel

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Abstract

Vehicle emissions constitute a serious environmental concern particularly in confined spaces such as tunnels and underground parking garages. These emissions are characterized with the presence of various pollutants, which, at high concentrations, can cause adverse health effects. This paper presents an assessment of vehicle-induced emissions and air quality in a heavily traveled tunnel located in urban metropolitan Beirut. For this purpose, common modeling theories were reviewed, relevant air quality standards were defined, existing conditions were characterized, an air-sampling program was implemented, and mathematical modeling to simulate field measurements was conducted. Impact significance was evaluated by comparing measured and simulated pollutant concentrations with air quality standards. Model simulations were also used to evaluate vehicle-induced pollutant emission factors. Finally, mitigation measures are proposed to insure proper air quality management inside the tunnel. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Vehicle emissions; Tunnel modeling; Air quality

Abbreviations

AAQS	ambient air quality standards
BC	black carbon
CMB	chemical mass balance
CO	carbon monoxide
CO_2	carbon dioxide
EF	emission factor
EIVR	Flanders emissions inventory
EU	European Union

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FHWA	Federal Highway Administration
FS	Fuchs surface
HC	hydrocarbons
HDD	heavy-duty diesel
ICP-MS	inductively coupled plasma-mass spectrometer
IDLH	immediately dangerous to life or health concentrations
LDG	light-duty gasoline
MDG	medium-duty gasoline
NIOSH	national institute of occupational safety and health
NMHC	non-methane hydrocarbons
NMOC	non-methane organic compounds
NMVOC	non-methane volatile organic compounds
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NS	not specified
O_3	ozone
OSHA	Occupational Safety and Health Administration
Pb	lead
PM	particulate matter
PPAH	particle bound polycyclic aromatic hydrocarbons
QSSMB	quasi-steady-state mass balance
SF_6	sulfur hexafluoride
SMB	simple mass balance
SO_2	sulfur dioxide
TSP	total suspended particulate
USEPA	US Environmental Protection Agency
VOC	volatile organic compounds
WHO	World Health Organization

Nomenclatures

σ	standard deviation
ΔC	concentration difference (g/m^3)
α_i	inflow rate from ventilation (min^{-1})
α_o	outflow rate ventilation (min^{-1})
a	empirical constant (m/min)
A	tunnel cross-sectional area (m^2)
b	empirical constant (dimensionless)
$C_{(x)}$	pollutant concentration point x (mg/m^3)
$C_{i,\mathrm{in}}$	concentration of pollutant i entering the tunnel (g/m^3)
$C_{i,\mathrm{out}}$	concentration of pollutant i leaving the tunnel (g/m^3)
C_{iv}	pollutant concentration in the inlet ventilation air (mg/m^3)
C_0	pollutant concentration at $x=0$ (mg/m^3)
e	average vehicle emission rate (mg/m)
F	correction factor (dimensionless)

k	deposition rate (min^{-1})
L	tunnel length (km)
n	vehicle count rate (veh/min)
P	effective perimeter of the tunnel (m)
Q	air flow rate across the tunnel (m^3/s)
q	vehicular source strength (mg/min m^3)
R_i	removal rate of pollutant i out of the tunnel (g/s)
S_i	emission rate of pollutant i generated in the tunnel (g/s)
S_p	car spacing (m)
U	mean air flow velocity (m/min)
U_e	velocity at $x=0$ (m/min)
U_0	velocity resulting from natural ventilation (m/min)
v	deposition velocity (m/min)
W	pollutant produced per vehicle depending on velocity (g/min)

1. Introduction

Tunnels are usually constructed due to topographic constraints or in order to minimize traffic congestion in urban areas. Their inadequate ventilation combined with high traffic flow result in elevated concentrations of vehicle-induced air pollutants, which can pose serious health hazards. As a result, tunnel air quality and ventilation have been the subject of recent studies which focused primarily on: (1) measuring vehicular emission factors; or (2) characterizing corresponding emissions in tunnels and the compliance with applicable air quality standards. The majority of these studies fall under the first category with the purpose of obtaining representative emission factors using mass balance techniques (Gofa et al., 1998; Ingalls, 1989; Ingalls et al., 1989; Okamoto et al., 1998; Rogak et al., 1997, Sjödin et al., 1998; Staehelin et al., 1997, 1998; Tsai et al., 1998). Some work focused on the characterization of tunnel atmosphere although the impacts of polluted tunnels can be significant (Barrefors, 1996; Chan et al., 1996; Defre et al., 1994; Fraser et al., 1998; Gertler et al., 1996; McLaren et al., 1996; Pucher and Zweiner, 1997).

Several mathematical models, with varying degree of complexity, have been developed to simulate pollutant concentration inside tunnels (Bellasio, 1997; Chan et al., 1996; Chang and Rudy, 1990; Pursall, 1976; Rogak et al., 1998a,b). Conservation of mass constitutes the basic principle underlying the development of these models. Invariably, they are based on the assumption that pollutants are long-lived species with no deposition and no destruction or reaction and that movement of air and vehicles cause uniform mixing and distribution of pollutants throughout the tunnel. In addition, pollutant emission rates and wind velocity are assumed to be constant. At any time, a mass balance across a tunnel can be represented by Eq. (1) that reduces to Eq. (2) if the removal rate inside the tunnel is insignificant (Pierson et al., 1996):

$$Q(C_{i,\mathrm{out}} - C_{i,\mathrm{in}}) = S_i - R_i, \tag{1}$$

$$C_{\mathrm{out}} = C_0 + \frac{S_i}{Q} = C_{\mathrm{in}} + \frac{neL}{AU}, \tag{2}$$

where Q is the air flow rate across the tunnel (m^3/s), $C_{i,\mathrm{out}}$ the concentration of pollutant i leaving the tunnel (g/m^3), $C_{i,\mathrm{in}}$ the concentration of pollutant i entering the tunnel (g/m^3), S_i the emission rate of pollutant i generated in the tunnel (g/s), R_i the removal rate of pollutant i out of the tunnel (g/s), L the tunnel length (km), e the average vehicle emission rate (mg/m), n the vehicle count rate (veh/min), A the tunnel cross-sectional area (m^2) and U is the mean air flow velocity (m/min).

Better estimates are reportedly obtained by introducing a correction factor in the denominator of Eq. (2) to account for velocity and concentration non-uniformities in the tunnel (Rogak et al., 1997, 1998a,b). The magnitude of the correction factor differs from one tunnel to another and is reported to be inversely proportional to the air velocity inside the tunnel (Eq. (3)).

$$F = \frac{a}{U} + b, \tag{3}$$

where F is the correction factor (dimensionless), a the empirical constant (m/min) and b is the empirical constant (dimensionless).

A modified version of the overall mass balance model, referred to as the quasi-steady-state analytic air quality model, accounts for pollutant deposition and can be applied to determine the spatial variation of pollutant concentrations in tunnels. Following this approach, the tunnel is subdivided into infinitesimal elements, and the mass balance across each element is expressed in Eqs. (4a)–(4c) (Chang and Rudy, 1990).

$$\frac{\mathrm{d}(UC)}{\mathrm{d}x} = q + \alpha_{\mathrm{i}} C_{\mathrm{iv}} - \alpha_{\mathrm{o}} C - kC, \tag{4a}$$

$$q = \frac{ne}{A}, \tag{4b}$$

$$k = \frac{vP}{A}, \tag{4c}$$

where C_{iv} is the pollutant concentration in the inlet ventilation air (mg/m^3), C the pollutant concentration at x (mg/m^3), α_{i} the inflow rate from the ventilation system (min^{-1}), α_{o} the outflow rate from the ventilation system (min^{-1}), q the vehicular source strength (mg/min m^3), k the pollutant deposition rate (min^{-1}), v the deposition velocity (m/min) and P is the effective perimeter of the tunnel (m).

In the case of natural/longitudinal ventilation, the solution for Eq. (4a) can be expressed by Eq. (5a) that reduces to Eq. (5b) in case of negligible deposition.

$$C_{(x)} = \frac{q}{k} + \left(C_0 - \frac{q}{k}\right) e^{-kx/U_0}, \tag{5a}$$

$$C_{(x)} = C_0 + \frac{qx}{U_0} = C_0 + \frac{nex}{AU_0}. \tag{5b}$$

Although it seems similar to Eq. (2), Eq. (5b) is quite different. In fact, Eq. (2) is based on the concept that the concentration C is independent of the distance along the tunnel (x), thus it is the same throughout the tunnel. However, Eq. (5b) assumes that C varies with x or $C_{(x)}$ is the concentration at point $x + \mathrm{d}x$. In other terms, Eq. (2) gives the average pollutant concentration in the whole volume of the tunnel, whereas Eq. (5b) gives the concentration in the volume element $A\,dx$ at point x.

The average concentration is better represented by integrating Eq. (5b) along the length of the tunnel (L) and dividing the value over L as expressed in Eq. (6a) that reduces to Eq. (6b) in the case of natural ventilation with negligible deposition.

$$C_{\mathrm{avg}} = \frac{1}{L}\int_0^L C_{(x)}\,\mathrm{d}x, \tag{6a}$$

$$C_{\mathrm{avg}} = C_0 + \frac{nLe}{2AU}. \tag{6b}$$

In a study conducted in the Cassiar Tunnel, sulfur hexafluoride (SF_6) was used as a tracer gas for the calibration of the mass balance model (as expressed in Eq. (2)). The correction factor was found to be close to 2 especially at low wind speeds (Rogak et al., 1998a,b). This suggests that Eq. (6b) predicts the average concentration better than Eq. (2), thus it is more appropriate to use the former in the estimation of pollutant concentrations and emission factors.

This paper presents an assessment of vehicle emissions and air quality in an urban tunnel recently constructed to reduce traffic congestion along a major corridor in urban metropolitan Beirut. For this purpose, air samples were collected and analyzed for the presence of primary air pollutants, priority metals, and non-methane volatile organic compounds. Pollutant emissions and air quality modeling was conducted to estimate vehicle-induced emission factors and simulate pollutant concentration profiles along the tunnel. Field measurements and mathematical simulations form the basis for developing a strategy for proper air quality management in tunnels.

2. Existing conditions

The subject tunnel, which is locally referred to as Salim Slam tunnel, is located in a residential and commercial area with little to no industrial activities thus limiting the sources of air pollution to vehicle emissions. It has been in service since 1994 in order to link the Beirut Central Business District to the Beirut International Airport and densely populated provinces. While data on air quality within the tunnel are not available, visual observations coupled with chronic public complaints suggest the presence of elevated concentrations of various air pollutants, particularly TSP which, combined with inefficient lighting, result in low visibility and driving safety. The tunnel has a slight upgrade at the entrance and a slight downgrade at the exit. It consists of four lanes, two shoulders and a longitudinal ventilation system with five fans. Fig. 1 depicts the approximate layout and geometric dimensions of the tunnel.

3. Air sampling program

Measurements of pollutant concentrations including CO, NO_2, SO_2, non-methane volatile organic carbons (NMVOC), total suspended particulate (TSP), Lead, and priority metals were

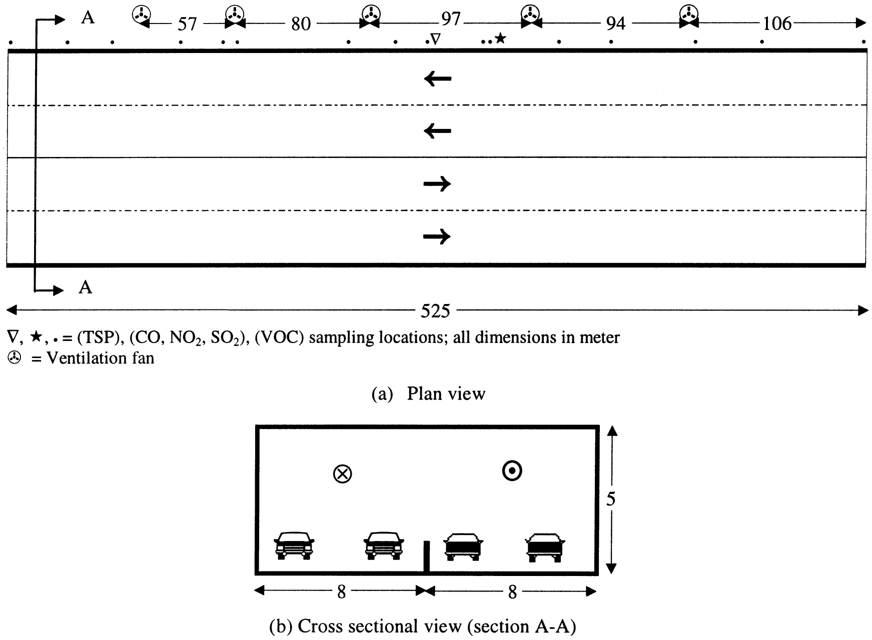

Fig. 1. Layout and geometric dimensions of the tunnel.

conducted at several locations inside the tunnel. Sampling procedures and results are presented below.

3.1. Sampling procedures

Concentrations of CO, NO_2, and SO_2 were measured inside the tunnel using a manual air sampling analyzer. Due to limited space along the side of the tunnel, the measurements were conducted at one location at tunnel midpoint (Fig. 1). The measurements are 30-min average concentrations for CO and SO_2, and 10-min average concentrations for NO_2.

NMVOC were measured inside and outside the tunnel using an organic vapor analyzer. Measurements were conducted at fixed locations at the entrance, midpoint and exit of the tunnel. Additional measurements were taken while moving between the entrance and the middle of the tunnel, and between the middle of the tunnel and its exit. This procedure provided an approximate NMVOC concentration profile along the tunnel. A replicate of this profile was recorded with corresponding vehicle flow and distribution. In addition, two series of time varying measurements at specific locations were conducted (Fig. 1).

Air samples were also collected at tunnel midpoint during peak traffic volume using a portable high volume air sampler equipped with a non-hygroscopic glass fiber filter. The filters (which were digested with 1–4 concentrated nitric and perchloric acids) were pre- and post-weighed for particulate matter determination, and then they were analyzed on an inductively coupled plasma-mass spectrometer (ICP-MS), using NIOSH method 7300, for the presence in the air of priority metals including beryllium, chromium, manganese, iron, cobalt, nickel, copper, zinc, arsenic, molybdenum, cadmium, tin, mercury, and lead.

3.2. Sampling results

The results of SO_2, NO_2, and CO measurements as well as particulate matter and priority metal analysis are presented in Tables 1 and 2. While TSP, NO_2, CO, lead and beryllium concentrations were several times higher than international standards, levels of SO_2 and other priority metals were lower which is consistent with the fact that leaded gasoline with low sulfur content is the main fuel used in the country. TSP concentrations were alarmingly high. In fact, within a 7-min sampling period, the sample filter turned dark black.

Temporal and spatial variations of NMVOC concentrations are depicted in Fig. 2. The results suggest that the ventilation system effect appears to be localized and not effective in reducing pollutant concentrations in the tunnel. VOC spatial variation continued to increase along the tunnel in the direction of traffic, which can be attributed to the piston effect resulting from vehicular movement. Vehicle movement along the tunnel roadway leads to an overpressure in the front and a partial pressure in the back. Thus air is both pushed and dragged out of the tunnel along the direction of the traffic and as a result the concentration of contaminants increases from

Table 1
Measured pollutant concentrations inside the tunnel

Constituent	Averaging period (min)	Average	Range	Standards	
				WHO (1997)	USEPA (1997)
SO_2 (ppm)	30	0.15	0.13–0.16	0.13	0.14
CO (ppm)	30	50	40–80	27	9
NO_2 (ppm)	10	0.49	0.28–0.70	0.212	0.053
TSP (μg/m^3)	7	2525	2495–2555	150–230	260
Lead (μg/m^3)	7	31	29–32	0.5–1	1.5

Table 2
Summary of priority metal analysis

Constituent	Sample 1		Sample 2		NIOSH
	μg/m^3	μg/g PM	μg/m^3	μg/g PM	μg/m^3
Arsenic	0.03	0.01	0.03	0.01	2
Beryllium	3.20	1.35	3.90	1.66	0.5
Cadmium	0.03	0.01	0.10	0.04	–
Chromium	0.03	0.01	0.03	0.01	500
Cobalt	0.09	0.04	0.95	0.40	50
Copper	1.30	0.55	1.30	0.55	1000
Iron	68.00	28.83	360.00	153.37	NS[a]
Manganese	0.65	0.28	6.60	2.82	1000
Mercury	0.30	0.13	0.23	0.09	15
Molybdenum	0.11	0.05	0.09	0.04	10,000
Nickel	0.27	0.12	0.23	0.10	15
Tin	0.14	0.06	0.17	0.07	100
Zinc	11.00	4.79	11.00	4.72	NS

[a] NS = Not specified.

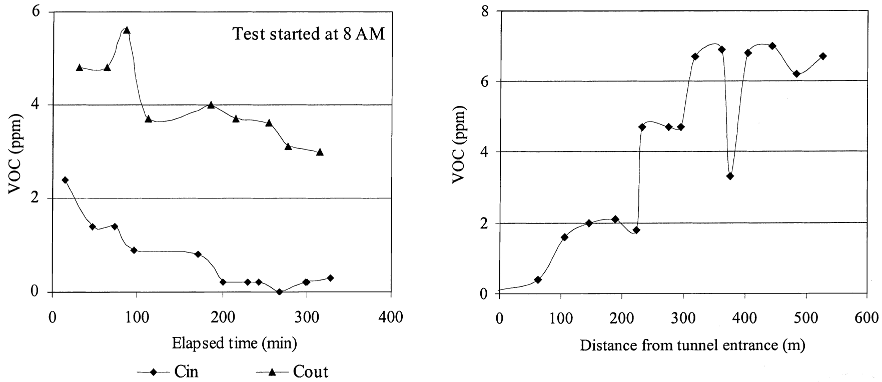

Fig. 2. Temporal and spatial variation of NMVOC concentration.

ambient levels to a maximum at the exist portal. In addition, the absence of a barrier wall between the two-way tunnel traffic coupled with the presence of congested side roads at tunnel portals, would inevitably result in different concentration profiles along the tunnel depending on traffic distribution.

4. Air quality modeling

Air quality modeling was performed in order to evaluate pollutant emission factors, simulate field measurements, and predict pollutant concentration profiles and average concentrations along the tunnel. For this purpose, vehicle fleet mix was characterized, model input parameters were estimated, and a sensitivity analysis was conducted. Fig. 3 presents a flow diagram of the modeling methodology and the parameters typically evaluated during this process.

4.1. Vehicle mix and age

The Lebanese vehicle fleet is comprised mainly of passenger cars and characterized by relatively old (14 yr average age), deteriorated and poorly maintained vehicles resulting in high pollutant emission rates. In fact, 70% of the private car fleet are model 1984 or older (Dar Al-Handassah, 1995; Kaysi and Salvucci, 1993). Since the share of unleaded gasoline is relatively small (<10%) (Mahmassani, 1997), it is expected that only a small fraction of the fleet is equipped with catalytic converters. Although predictions indicate a decrease in passenger car usage and an increase in bus trips as a result of introducing a mass transit system (TEAM, 1994), it is unlikely that this will occur in the near future because of: (1) socio-cultural stigma associated with bus riding; (2) weak urban planning practices; (3) lack of enforcement of traffic regulations; and (4) absence of an inspection and maintenance program.

Vehicle count at the tunnel entrance showed that the majority of vehicles passing through the tunnel consists of light-duty gasoline (LDG) vehicles followed by heavy-duty diesel (HDD) vehicles and medium-duty gasoline (MDG) trucks (Table 3), which is consistent with previous

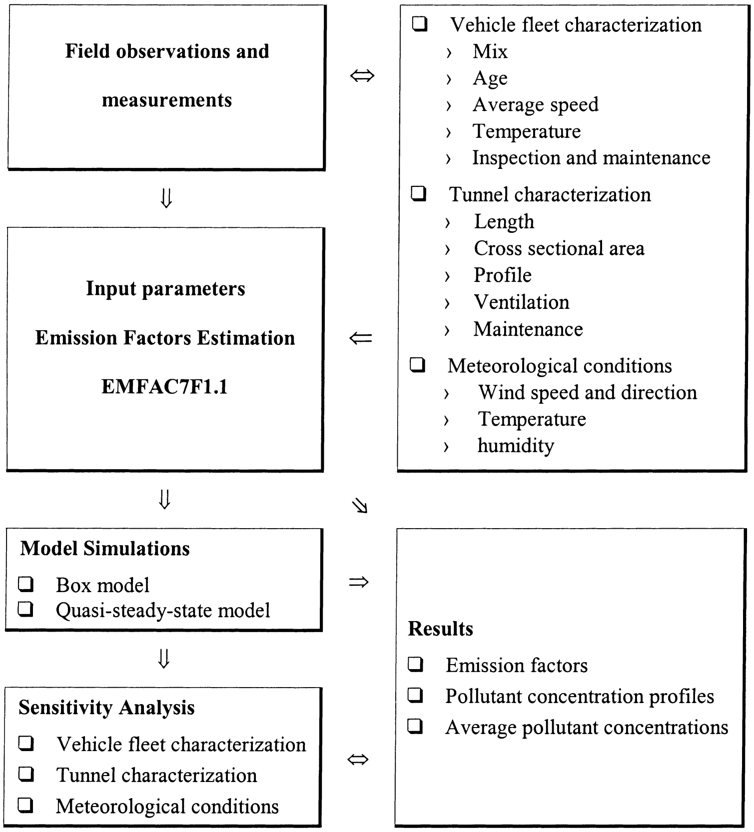

Fig. 3. Air quality-modeling flow diagram.

overall area surveys that reported greater than 90% share of passenger cars (TEAM, 1994). Note that motorcycles, small gasoline pick-ups and mini-buses were included in the LDG vehicle fraction.

4.2. Emission factors

The emission factor is an estimated average emission rate of a certain pollutant for a class of vehicles. Emission factors for CO, NO_x, VOC, and PM were determined using the EMFAC7F1.1

Table 3
Vehicular mix of traffic fleet

Vehicle type	LDG vehicles	MDG trucks	HDD vehicles
Fleet (%)	95.7	1.3	3
Average occupancy[a]	1.5	3	1
Average age (yr)[b]	14	14	16

[a] TEAM (1994).
[b] Dar Al-Handassah (1995).

model, for the winter of 1999 and the fleet distribution presented in Table 3 assuming that all vehicles are in the hot stabilized mode. EMFAC is one module of the MVEI model which was developed by the California Air Resources Board to estimate the total amount of pollutants released into the atmosphere by road transportation vehicles using statistical relationships based on emission tests for new and used vehicles (ARB, 1996). The model accounts for vehicle mix; percent cold and hot starts; existence and application of an inspection and maintenance program; fraction of vehicles using catalytic converters; and fraction of vehicles using gasoline or diesel. In the context of this study, MVEI was calibrated and used to determine emission factors for the Lebanese fleet (El-Fadel and Bou Zeid, 1999).

Emission factors for CO, NO_x, VOC vary with speed and temperature reaching a maximum at low temperatures and speeds, decreasing at medium values and increasing again as temperature and speed increase. Since EMFAC7F does not estimate NO_2 emission factors, it was assumed that NO_2 constitutes 15% of NO_x emissions (Gorse, 1984; Pucher and Zwiener, 1997).

Several studies comparing pollutant emission factors derived from tunnel measurements and from the EMFAC7F model showed that while the latter provides reasonable estimation of NO_x emissions, it underpredicts CO and VOC emission rates by up to a factor of 4 (Gofa et al., 1998; Kirchstetter et al., 1996; McLaren et al., 1996). On the other hand stop-and-go traffic pattern, which is frequent at the subject tunnel, increases vehicle emissions by 5–10 times because of acceleration and deceleration processes (Faiz et al., 1996). Those two factors, in combination with high emissions characterizing the Lebanese fleet, will increase further the discrepancy between actual and simulated values. Therefore, it was imperative to use a correction factor, which allows the simulation of measured concentrations and validate the modeling results.

4.3. Model simulations

The first objective for model simulations was to compare pollutant emission factors obtained from EMFAC7F with those estimated using the field measurements by applying both the simple mass balance (SMB, Eq. (2)) and the quasi-steady-state mass balance model (QSSMB) with and without deposition (Eqs. (5a) and (5b), respectively). The input parameters for Eqs. (2), (5a) and (5b) are summarized in Table 4 and the corresponding simulation results are presented in Table 5. Note that while the SMB model typically assumes that deposition is negligible, the deposition velocity can exhibit the highest uncertainty and may vary widely, particularly for PM, depending on the particle size distribution. While limited data have been reported in the literature regarding deposition velocity in a tunnel for SO_2 (0.07 cm/s) (Chang et al., 1981), no similar data are known for CO, NO_2 or VOC. As for PM, generally, vehicle-induced particulate emissions have a diameter less than 2.5 μm (Funasaka et al., 1998; Pierson et al., 1998; Rogak et al., 1997; Weingartner et al., 1997) which can result in a maximum settling velocity of 0.21 cm/s. For comparative assessment purposes, a deposition velocity of 0.07 cm/s was adopted in this study because traffic characteristics within the tunnel indicate an almost continuous flow of vehicles during the day. This would result in the inevitable entrainment and re-suspension of particulates due to vehicle-induced turbulence. In addition, neither the QSSMB or the SMB, nor EMFAC7F account for potential chemical decay of pollutants within the tunnel which may result in higher emission factors. In designing the air exchange rate of a tunnel ventilation system, overpredicting emissions in a tunnel would introduce a conservative safety factor.

Table 4
Model input parameters

Parameter	Average value
Average wind speed (m/s)	2
Average ambient temperature (°F)	60
Tunnel length (m)	526
Tunnel cross-sectional area (m^2)	38.3
Effective perimeter (m)	25.6
Vehicle flow (veh/min)	36
Average vehicle speed (mph)	25
Deposition velocity (cm/s)	0.07

Table 5
Estimated emission factors and comparisons with EMFAC7F predictions

Pollutant	Quasi-steady-state mass balance model				Simple mass balance	
	Without deposition		With deposition		EF (g/veh mile)	EF/EMFAC7F
	EF (g/veh mile)	EF/EMFAC7F	EF (g/veh mile)	EF/EMFAC7F		
CO	44.54	1.63	45.63	1.68	18.14	0.68
NO_x	4.26	2.12	4.47	2.19	1.79	0.88
NO_2	0.64	NE[a]	0.67	NE	0.27	NE
SO_2	0.21	NE	0.22	NE	0.09	NE
VOC[b]	8.58	3.91	9.24	4.20	4.62	2.10
PM	1.90	47.5	1.97	49.25	0.94	23.4

[a] NE = Not estimated by EMFAC7F.
[b] VOC = Emission factors were estimated by equating the slope of the QSSMB model simulation trendline with that of the measured VOC profile within the tunnel.

The small difference between the results of Eqs. (5a) and (5b) (less than 8%) suggests that deposition has limited effect on the dispersion and movement of gaseous pollutants in a tunnel. This is consistent with the fact that entrainment is likely to dominate because of the continuous movement of vehicles. Emission factors estimated by using the QSSMB model were generally higher than those using the SMB model or EMFAC7F predictions. With the exception of the SMB emission factors for CO and NO_x, EMFAC7F underpredicted emission factors in all other instances with highest underpredictions exhibited for particulates.

Table 6 compares pollutant emission rates and ratios from this study to measured values from other tunnel studies. As expected, pollutant emission factors are generally higher (depending on the model used) then those measured in other tunnels, which can be attributed to fleet and tunnel operations. However, CO/NO_x and VOC/NO_x ratios are within the range of reported values for other tunnels. Note that while the emission factors and ratios derived from the SMB model appear closer to values derived for other tunnels, they are unlikely to reflect the actual situation at the subject tunnel taking into consideration the vehicle fleet characteristics and the absence of inspection and maintenance.

Table 6
Summary of pollutant emission factors and ratios

Reference	Tunnel, location (yr)	CO (g/veh mile)		No_x (g/veh mile)		VOC (g/veh mile)		CO/NO_x		VOC/NO_x	
		QSSMB	SMB	QSSMB	SMB	QSSMB	SMB	QSSMB	SMB	QSSMB	SMB
This study	Salim Slam, Beirut, 1999	44.54	18.14	4.26	1.79	8.68	4.62	10.45	10.13	2.04	2.58
Gofa et al. (1998)	Van Nuys, Los Angeles, 1995	–	22.37	–	2.01	–	1.67	–	11.33	–	0.82
	Van Nuys, Los Angeles, 1995	–	37.01	–	2.41	–	4.46	–	15.83	–	1.95
Rogak et al. (1998b)	Cassiar, Vancouver, 1995	–	11.38	–	2.25	–	0.45	–	5.05	–	0.20
Sjödin et al. (1998)	Göteborg, Sweden., 1994–1995	–	9.33	–	1.77	–	1.21[a]	–	5.27	–	0.68
Gertler et al. (1997)	Cassiar, Vancouver, 1993	–	11.89	–	1.87	–	0.63	–	6.38	–	0.34
Staehelin et al. (1997)	Gubrist, Vancouver, 1993	–	10.22	–	2.85	–	1.08	–	3.59	–	0.38
Pierson et al. (1996)	Fort McHenry, MD, 1992[b]	–	14.66	–	2.04	–	1.27	–	7.17	–	0.62
	Fort McHenry, MD, 1992[c]	–	7.87	–	0.93	–	0.84	–	8.44	–	0.90
	Tuscarora, PA, 1992	–	7.77	–	0.63	–	0.47	–	12.5	–	0.74
Kirchstetter et al. (1996)	Caldecott, Berkely, 1994	–	–	–	–	–	–	–	10.3	–	0.55
Lonneman et al. (1986)	Lincoln, NJ, 1982	–	–	–	–	–	–	–	6.46	–	1.77
	Lincoln, NJ, 1970	–	–	–	–	–	–	–	10.46	–	2.63
Gorse (1984)	Allegheny, PA, 1981	–	14.32	–	<1.93	–	<1.61	–	>7.42	–	>0.83

[a] As CH_4.
[b] Uphill.
[c] Downhill.

The second objective of the modeling effort was to simulate pollutant concentration profiles as well as average concentrations along the tunnel. As previously mentioned, only the QSSMB model can simulate the spatial variation of pollutant concentrations. Fig. 4 depicts the basic simulation results of VOC field measurements. For other constituents, field measurements are limited to one location within the tunnel (219 m. from tunnel entrance). Simulated average pollutant concentrations are presented in Table 7. Recognizing the uncertainties associated with the estimation of model input parameters, the simulated VOC profile is relatively in good agreement with the measured concentrations profile in the tunnel and the present deviation of simulated average concentrations ranged from as low as 0% to as high as 16% depending on the pollutant.

4.4. Sensitivity analysis

According to the QSSMB model, C_{avg} is directly proportional to the tunnel length, the vehicle flow rate, the emission factor, the inverse of the cross-sectional area, and the wind speed. On the other hand, emission factors are highly dependent on vehicle speed and ambient temperature.

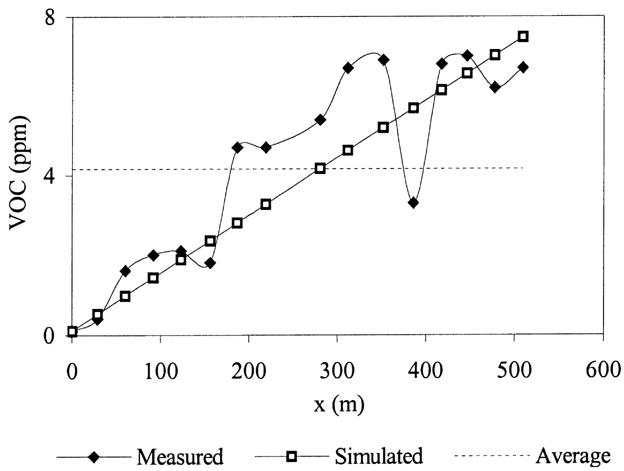

Fig. 4. QSSMB simulations of VOC field measurements.

Table 7
QSSMB model estimation of average pollutant concentrations

Pollutant	QSSMB without deposition	QSSMB with deposition	Measured	Percent deviation
CO (ppm)	58.2	56.9	50	13.8–16.4
NO_x (ppm)	3.73	3.00	3.27[a]	6.1–14.3
NO_2 (ppm)	0.56	0.45	0.49	6.1–14.3
SO_2 (ppm)	0.16	0.15	0.15	0–6.7
VOC (ppm)	3.88	3.64	4.15[b]	6.5–12.3
PM (μg/m^3)	2577	2507	2525	2–7

[a] Estimated as NO_2/0.15 (Gorse, 1984; Pucher and Zwiener, 1997).
[b] Based on direct averaging.

While some parameters are fixed (tunnel length and cross-sectional area), others may vary widely and can exhibit large fluctuations within a short period of time (wind speed, vehicle flow rate and speed, and emission factors).

The simplicity of the QSSMB model permits direct assessment of the sensitivity of the simulation results to variations in the input parameters. By varying those parameters within their uncertainty range, the variation in the basic results can be estimated. For this purpose, the variation in the emission factors can be considered as the most relevant indicator (Table 8). Once again, it can be observed that while the uncertainty in the emission factors is around 65%, the ratio of CO/NO_x and VOC/NO_x exhibit little variation which justifies their application as indices in assessing the consistency of air quality studies in tunnels.

4.5. Limitations

The discrepancy between measured and simulated results is due to several limitations. Although some of these limitations are intrinsic to the model used, others can be eliminated or at least minimized. Tunnel measurements have the advantage of screening a large number of vehicles in real operating conditions. However, they are only "snap shots" of vehicular emissions where several fluctuating parameters (such as wind speed and direction, vehicle speed, mix and age) are measured in a relatively short period of time. In addition, long term monitoring is seldom feasible inside tunnels (unless instrumentation is used at inception) due to elevated pollutant concentrations and absence of adequate space, which will render transport of bulky equipment difficult and risky.

Another limitation in this study is the absence of a dividing wall between the two traffic ways and the presence of a slight grade at both entrance and exit. It was assumed that exchange of air and pollutants between the two traffic ways is limited due to the presence of a wind shear wall created by the moving fleet. This assumption is questionable at low driving speed, in stop and go driving patterns or in the case of dissimilar driving pattern in the two ways.

While the simple mass balance model do not account for pollutant deposition, which may be substantial at low wind and vehicle speed, the quasi-steady-state mass balance model can incorporate deposition into its simulation based on the gaseous/particulate deposition velocity.

Table 8
Variation in estimated emission factors (g/mile veh)[a]

Pollutant	Minimum EF	Mean EF	Maximum EF	Max EF/min EF
CO	37.53	44.54	60.29	1.61
NO_x	3.60	4.26	5.78	1.61
NO_2	0.54	0.64	0.87	1.61
SO_2	0.2	0.23	0.33	1.65
VOC	7.29	8.68	11.73	1.61
PM	1.58	1.90	2.59	1.64
CO/NO_x	10.42	10.20	10.43	
VOC/NO_x	2.02	2.03	2.04	
SO_2/NO_x	0.055	0.054	0.057	

[a] Based on variation in the vehicle flow, vehicle speed, temperature, and wind speed.

However, both models do not consider potential reactions between different pollutant species present in the tunnel. Furthermore, both models cannot directly simulate air intakes into the tunnel. This highlights the need for finite element/difference representations of flow and transport processes in the tunnel if detailed pollutant concentration profiles are required.

5. Impact significance and mitigation

Although the exposure time in tunnels is typically short, it could be outweighed by the elevated concentrations of pollutants. Unexpected increases in exposure time will inevitably aggravate the situation particularly in congested urban areas. In fact, several factors may increase the exposure time and hence increase potential health hazards. The most important of these factors is the traffic congestion that frequently occurs at peak hours (especially during the afternoon rush), which will result in several fold increase in pollutant levels beyond their corresponding standards as is the case. In addition, pollutant concentrations inside a vehicle compartment can reach levels exceeding those in the tunnel itself. [1] Car accidents and vehicle failure, which were observed in this study during tunnel air sampling, can increase the exposure time of vehicle occupants. Occupational exposure is generally limited to workers responsible for cleaning the tunnel.

In addition to their impacts on vehicle passengers, pollutants emitted from vehicles in the tunnel affect people in the vicinity of tunnel portals where people will be exposed continuously for longer periods (Matsumoto et al., 1998). On the other hand, inefficient lighting combined with high concentrations of TSP, and the lack of maintenance lead to significant reduction in visibility and driving safety. As the travel demand increases, vehicular flow will inevitably increase and pollutant concentrations inside the tunnel would also follow the same trend. Therefore, mitigation measures should be adopted to reduce pollution level in the tunnel and prevent further exacerbation of the problem. In the absence of adequate resources, the best solution consists of ensuring the proper operation of the existing ventilation system and constructing a dividing wall between the two ways to increase the piston effect and thus increase the dilution and flushing of pollutants. In addition, regular cleaning of dust and particulate deposited on the sides of the tunnel, coupled with restriction on the entrance of heavy-duty diesel trucks is expected to result in significant reduction in the concentration of TSP in the tunnel. Otherwise, more elaborate and expensive solutions, such as changing the type of the ventilation system, should be considered. Although longitudinal ventilation systems cost less than transverse systems, they are more prone to pollutant accumulation along the length of the tunnel.

6. Summary and conclusions

An assessment of vehicle-induced emissions and air quality in a highly traveled urban tunnel was conducted. Air samples were collected at normal and peak traffic conditions. The samples

[1] Vehicles leakiness to engine running loss emissions and tailpipe exhausts may increase in-vehicle pollutant concentrations beyond the tunnel air concentrations.

were analyzed for the presence of primary air pollutants, priority metals, and non-methane volatile organic compounds. Using EMFAC7F, the simple mass balance and the quasi-steady-state mass balance models, emission factors for CO, NO_x, NO_2, SO_2, VOC, and PM were estimated to simulate pollutant concentration profiles along the tunnel.

While the concentration of priority metals (except Beryllium) were below the corresponding standards set by the WHO and NIOSH, concentrations of CO, SO_2, NO_2, PM, and lead were above international and proposed local standards. Pollutant emission factors estimated using the QSSMB model were generally higher than those estimated using the SMB model, EMFAC7F predictions, and those reported in the literature. This can be attributed to tunnel characteristics, vehicle operations, and fleet characteristics. The small difference between the QSSMB model simulation with and without deposition in addition to the high ratio of QSSMB PM emission factors to those of the EMFAC7F suggest that dust accumulation (due primarily to inadequate ventilation and entrainment) is dominant in the tunnel. Comparison of the QSSMB model simulations with the SMB model and EMFAC7F simulations, and results from previous tunnel studies indicate that the QSSMB is more appropriate for estimating emission factors and pollutant concentrations in tunnels.

The sensitivity analysis of the QSSMB model revealed that while there is about 65% difference between the maximum and minimum CO, VOC, and NO_x emission factors, there was almost no difference for CO/NO_x and VOC/NO_x ratios. A better characterization of the tunnel fleet and ventilation system performance as well as the implementation of a more comprehensive sampling and chemical analysis program can minimize the uncertainty in emission factors. Adopting few initiatives, such as construction of a dividing wall and proper operation of the ventilation system will enhance air exchange rates and decrease pollutant concentrations in the tunnel. Further work in assessing tunnel impacts is recommended including the direct evaluation of passenger exposure inside vehicle compartments and assessment of potential exposure to pollutants at tunnel portal discharges.

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