MEASURED ROAD TUNNEL AIR CONCENTRATIONS USED TO VERIFY MOBILE SOURCE EMISSION FACTORS EMBEDDED IN THE IPIECA TOOLKIT AND TO SPECIATE TOTAL HYDROCARBONS

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ABSTRACT
As we are moving towards an era of cleaner air, it is becoming increasingly necessary to rely upon scientific models for the prediction of air quality trends. One such emission inventory model is the IPIECA Toolkit. As a part of the Urban Air Quality Management (UAQM) programme, the International Petroleum Industry of Environmental Conservation Association (IPIECA) has developed the IPIECA Toolkit, a PC-based emission inventory model used to predict emissions of carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NOx) and particulate matter (PM) emissions with an acceptable level of confidence. The Toolkit is able to estimate emissions from both stationary and mobile sources and to integrate domestic, commercial, industrial and mobile (vehicular) sources into an overall inventory. The Toolkit is flexible as it allows for different scenarios thus allowing all sources of polluting emissions in a given area to be characterized [1]. The main objective in this study is to verify the mobile source emission factors embedded in the Toolkit, locally, using vehicle emissions from the Huguenot Tunnel. Vehicles emit various pollutants, such as, volatile organic compounds (VOC's), sulfur oxides (SOx's), carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NOx's) and lead, on a daily basis. This study will focus on the comparison between physically measured concentrations and estimated-predicted concentrations of VOC's, CO and PM emissions. The Huguenot tunnel has been chosen as the study area because it represents a real-world laboratory (i.e. a closed environment) within which the environmental factors (such as temperature and humidity) can be measured. Furthermore, the sampling medium (sorbent tubes) and analysis method (thermal desorption followed by GC/MS) to be used to measure the VOCs will result in a speciated list of hydrocarbons emitted from vehicles.

INTRODUCTION
Motor vehicles continue to be a major source of a wide range of air pollutants, namely, VOC's (methane and non-methane hydrocarbons (NMHC's)), lead and the nitrogen and sulphur oxides, etc. These pollutants have different impacts on human health and the environment. Many of the VOC's, such as tricholoroethylene and benzene are carcinogenic [1]; NMHC's and the nitrogen oxides are the main precursors to ozone production in the atmosphere [2].

The management of air quality, including the reduction or prevention of air pollution requires an accurate inventory of all emission sources, including vehicle emissions. Estimates of vehicular emissions are generated with the use of emission factor models, such as COPERT [EEA], MOBILE [EPA] and, more recently, the IPIECA Toolkit [EU], together with information on vehicle populations and activity rates [3]. The emission factors used in these models are based on

dynamometer studies performed in controlled environments. Dynamometer measurements may not represent real-world driving conditions and may not be fully representative of the vehicle fleet on the roads. For a mobile-source emission inventory to represent real-world driving conditions for a vehicle fleet, it has to consider vehicle age, maintenance, use of control technologies and type of fuel used. Ignoring the latter may lead to inaccurate emission estimates [4,5].

One feasible way in which to complement the results of dynamometer studies is to determine vehicle emissions from road tunnels and compare them to modeled results. Tunnel studies provide samples that represent tailpipe and non-tailpipe (evaporative) emissions during the transit time of a vehicle through the tunnel [3]. A large sample of vehicles can be screened during their normal operating conditions using local fuel [6]. Hydrocarbon species are not subjected to photochemical degradation and can thus be speciated accurately. Further advantages of using a tunnel include the fact that the measured concentrations of exhaust emissions are significantly higher than ambient levels, thus reducing the error introduced by ambient level pollutants. A tunnel also provides an appropriate environment in which vehicle fleet characteristics can be monitored. Tunnels provide a control volume with known dimensions, which facilitates the use of mass balances and any other calculations required during modeling [7].

Simple or quasi-steady state mass balance (SMB and QSSMB, respectively) models are typically used, in conjunction with tunnel air quality measurements, to estimate emission factors. These models are based on the following assumptions [6]:

- There is no deposition, destruction or reaction of pollutants in the tunnel atmosphere.
- Movement of air and vehicles cause uniform mixing and distribution of pollutants throughout the tunnel.
- Pollutant emission and wind velocity rates are constant.

Tunnel studies have limitations that have to be considered when evaluating models inside tunnels. The most important being that the operating speeds inside tunnels tend to be constant, thus not reflecting the stop and go and decelerations and accelerations experienced by the whole fleet. Furthermore, the actual mix (ratio) of light- and heavy-duty vehicles, operating in urban areas may not be sufficiently represented. Tunnel grades are also not, currently, reflected in models. Hence the importance of performing a complementary evaluation of on-road driving conditions, choosing a variety of speeds, vehicle age, traffic composition and grade.

Several tunnel studies have been conducted to compare measured pollutant concentrations in tunnels to emission factor model predictions (e.g. Pierson et al., 1997; Gertler et al., 1997; Rogak et al., 1997). Many of these studies were also used to define the detailed chemical composition of mobile source NMHC emissions (e.g. Rogak et al., 1997; Lonneman et al., 1986; Kirchestetter et al., 1996; Sagebiel et al., 1996) [3]. These and other tunnel studies have been summarized in a literature review table (Table 1).

No.	Reference	Description
1	Weingartner et al., 1995	A field study was conducted in the Gubrist tunnel to investigate vehicle emission factors. Results indicated that particulate emissions were mainly due to diesel cars.
2	Staehelin et al., 1995	This paper presented the concept and first results of the Gubrist tunnel study that took place from the 20^{th} to the 26^{th} of September 1993. EF of a large number of individual VOC's, t-HC, CO, NO_x and SO_x were determined and are reported here at an average speed of 90km/h.
3	Pierson et al., 1995	The motor vehicle emission rates of CO, NO, NO_x and gas-phase speciated NMHCs and carbonyl compounds were measured in 1992 in the Fort McHenry and Tuscarora Mountain tunnel, for comparison with emission-model predictions and for the calculation of the reactivity of vehicle emission w.r.t O_3 formation. MOBILE4.1 and 5 gave predictions within ±50% of observations for most of the time.
4	Zielinska et al., 1995	This report focused on reporting differences between measurement methods for VOC up to C20 taken in the Fort McHenry and Tuscarora Mountain tunnels. The comparison of HC concentrations found in the Tenax and canister samples allowed an assessment of the contribution of semi-volatile HC (C_{10} to C_{20} derived from Tenax) to the total NMHC's (C_2 to C_{20} derived from Tenax and canisters). The study showed that HC in the range of C_{10} C_{20} are the important components of gas-phase HC emitted from HD diesel vehicles and that solid adsorbent sampling should be used in addition to canister sampling in measurements of motor vehicle emissions.
5	McLaren et al., 1996	This paper reports on real-world EF of deconvoluted exhaust and evaporative NMHC emissions and to compare them to EF calculated with the Canadian versions of the US EPA MOBILE 4.1 and 5C. the total measured NMHC EF, comprising of over 100 speciated HC's, are deconvoluted through the use of the chemical mass balance(CMB) model.
6	Gertler & Pierson, 1996	The objectives of this paper was to: -describe the methodology for measuring EF in tunnels; -summarize results from recent on-road emissions measurements performed in the Cassiar, Tuscarora, Fort McHenry and Caldecott tunnels; -compare the results of tunnel studies with model predictions; -define limitations of tunnel observations for mobile source EF model evaluation and inventory validation.
7	Weingartner et al., 1997	Continuous measurements of aerosol emissions assisted in the evaluation of how the characteristics of combustion aerosols change during the residence time in the tunnel. It was found that the respirable size range ($d < 3\mu m$) was mainly from tailpipe emissions with a very small amount of tire wear and road dust.
8	Bellasio, 1997	This paper presents 2 models for the description of air pollutant concentrations in road tunnels due to traffic. Emissions are calculated as a function of the position inside the tunnel and of the time. The equation of conservation of mass has been solved with the control volumes method. Sensitivity analysis was conducted to verify the model answer to different input parameters, such as initial concentration, boundary concentration and vehicle-induced turbulence.

9	Staehelin et al., 1997	Multiple regression models have been used to calculate the EF of NO_x, CO and t-HC (26 individual HC's) based on data obtained in study number 2 above. The authors concluded that several models might be needed if calculated EF are to be compared to results of other studies.
10	John et al., 1999	EF of NO_x, VOC and CO of the Gubrist tunnel study were compared with results of emissions calculations based on dynamometric test measurements. Except for NO_x EF, there was no discrepancy between the results of the tunnel study and emission modeling. Measured EF of individual HC of LDV were in good agreement with expectations for most components.
11	Touaty & Bonsang, 2000	The aim of this study was to determine the HC speciation of vehicle emissions and to measure the emission rates of NMHC's and CO. results were compared to other tunnel studies. CO and NMHC EF tended to be more than 2 times higher, possibly due to differences in catalyst equipped fleets.
12	El-Fadel & Hashisho, 2000	An assessment of vehicle emissions and urban air quality was conducted in a recently constructed urban tunnel in Beirut. Air samples were analysed for primary air pollutants, priority metals and NMVOC's. The pollutant emissions together with air quality monitoring was used to estimate vehicle-induced emission factors and to simulate pollutant concentration profiles along the tunnel. Concentrations of CO, SO_2, NO_2, PM and lead were above international and proposed local standards.
13	Hsu et al., 2001	A tunnel test in Chung-Cheng tunnel located in Kashsiung city was designed to investigate the on-road vehicle emissions of CO and NMVOC's. The results were compared to predictions from the MOBILE Taiwan 2.0 model (MT2.0). MT2.0 predicted values that closely matched observed data.
14	Hwa et al., 2002	A field experiment was conducted in a highway road tunnel in the Taipei City to determine the motor vehicle EF of CO, NO_x's, NMHC and VOC species. Approximately 56 species of VOC's were sampled. EF from the tunnel was compared to modeled results using MOBILE5b and EPA MOBILE-Taiwan2.0. Thus evaluating the performance of these models. M5b overpredicted NO_x and NMHC by 40 and 20%, respectively, where as MT2.0 had good predictions. Further findings included the most abundant species of VOC present, i.e. toluene, ethane and 1,2,4-trimethylbenzene by weight. It was also found that ethane, 1,2,4-TMB and propene, from road vehicle emissions, contribute most to O_3 formation reactivity.
15	Chen et al., 2002	Concentrations of CO, NO_x and t-HC; at three axial locations in the tunnel, together with traffic flow rate, traffic speed and types of vehicle; were measured in an attempt to understand the spatial distribution of air pollutants caused by traffic emissions. Results revealed that cross-sectional concentrations are nonuniformly distributed and the concentrations rise with downstream distance.
16	McGaughey et al., in Press	In this study measurements from a Houston tunnel were used to develop fuel consumption-based EF for CO, NO_x and NMOC for on-road gasoline vehicles. The NO_x EF were found to be at a lower range than those reported in pre 1996 tunnel studies, whereas NMOC EF were slightly higher.

Table 1: Literature Reviewed

This paper reports the pilot test results of measured tunnel concentrations for the pilot-test sampling period.

METHODOLOGY

Tunnel Description

The 3.75 kilometer long Huguenot tunnel is situated on the N1 between Cape Town and Worcester in the Western Cape, South Africa. It currently accommodates two-way traffic flow in a single bore and utilizes a fully transverse ventilation system as is required for a tunnel of this length [6]. Two fresh air fans, situated at each end of the tunnel, sucks ambient air from the surroundings which is vented into the tunnel by means of ventilation slits on one side of the tunnel wall as indicated by Figure1.

Figure 1: Top view of fully transverse ventilation system in Huguenot tunnel

Since the fans were operational during the sampling period, forced ventilation is likely to dominate airflow because of the two-way traffic flow. The piston effect, air flow induced by the motion of vehicles, is significantly reduced when traffic flow is in opposite directions in the same tunnel bore [3]. External wind speeds were 7 – 10 m/s during the sampling period; tunnel air speeds fluctuated between –0.24 – 3.2m/s (refer to Figure 2).

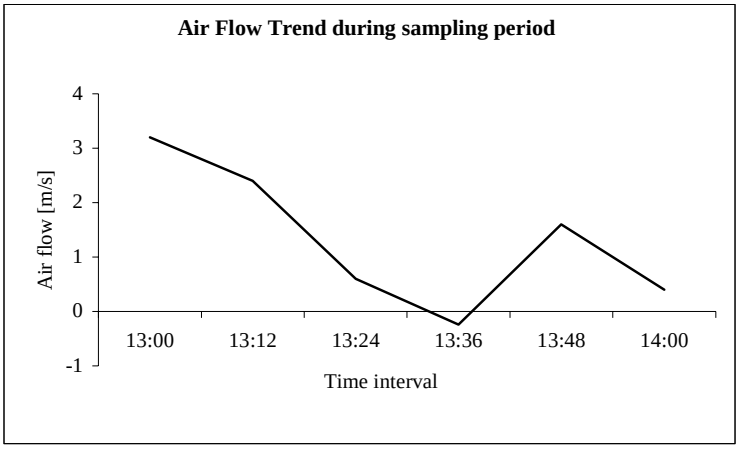

Figure 2: Air flow trend during 1-hour sampling period [Data supplied by CONCOR]

A lunch hour was used for the pilot test. The average speed for this time of day is approximately 70km/h and the fleet composition mainly consists of light-duty vehicles (refer to Figure 3). Measurements were collected for 2 hours (from 13:30 to 14:30) on the 21st of June 2004.

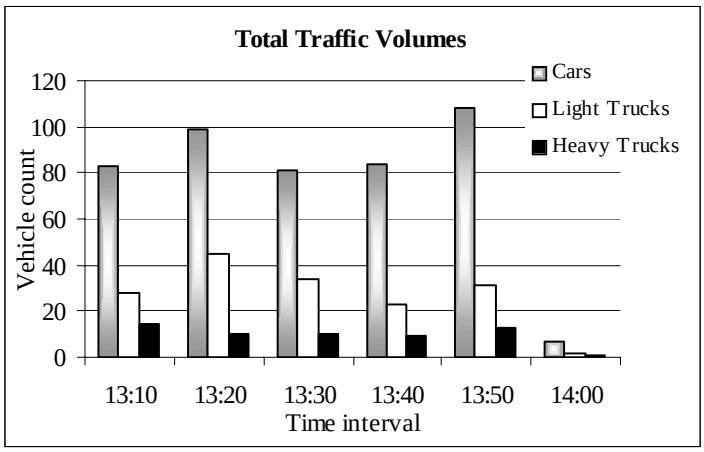

Figure 3: Traffic volumes during sampling period

Traffic Monitoring

Vehicle count data was obtained from the tunnel monitoring system. This data classifies vehicles into light vehicles (motorcycles, small- and large cars and caravans), heavy-duty (HD) vehicles with 2 axles (small HD trucks and buses), HD vehicles with 3 or 4 axles (medium trucks and big buses) and HD vehicles with 5 or more axles (large HD trucks). The dominating wind direction during the sampling period was from West to East.

Pollutant Measurements

Measurements of CO, relative humidity (RH), $PM_{2.5}$ and individual hydrocarbons were collected during the sampling period. One sampling station was situated at the halfway mark, approximately 1.9 kilometers from either entrance. The second sampling station, which lacked a PM monitor, was based outside the CONCOR [Tunnel management] control room, more than 2kms from tunnel. Table 2 summarizes the equipment and analysis methods used.

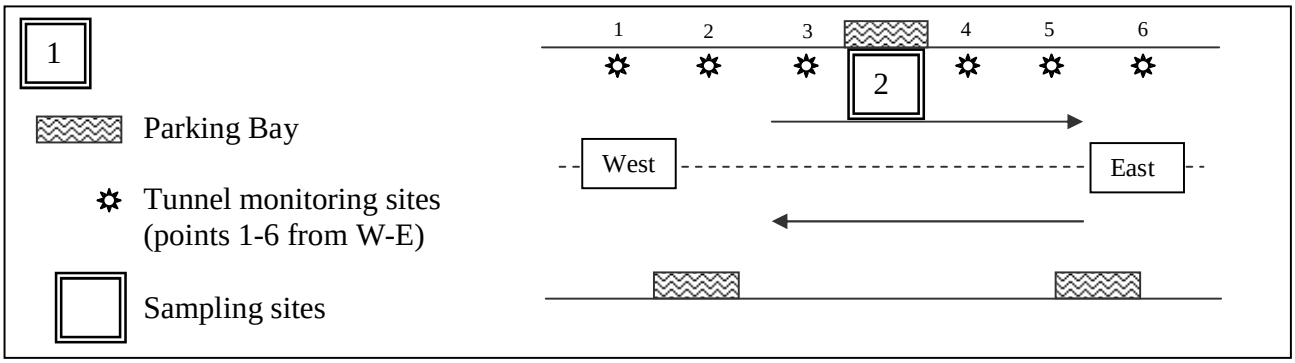

Figure 4: Huguenot Tunnel Schematic

Pollutant	Sampling	Analysis	Comments
CO	HOBO® CO Logger [Onset Cc.]	An electrochemical reaction is used to produce a current proportional to the ambient CO concentration	Additional CO data will be obtained from tunnel management monitoring.
PM	DustTrak Aerosol Monitor-Model 8520 [TSI Inc.]	Light scattering technology is used to determine mass concentration in real-time.	An Airmetrics minivol will be used in the main data collection in order to calibrate the DustTrak.
HC	Stainless steel sorbent tubes (packed with 70 & 160mg of Tenax & CS III, respectively) and SKC sampling pumps.	Short-path thermal desorption and cryogenic focusing followed by gas chromatography and mass spectrometry.	To obtain a sample of approx. 3 litres, a sampling flowrate of 50 – 60 ml/min was used for the one hour sampling period.

Table 2: Summary of equipment and analysis

Calibration of GC/MS

For the pilot test, the GC/MS was calibrated using a mixture of flourobenzene and p-bromofluorobenzene as the internal standards and 20 target compounds at 5 concentration levels (0.2, 3.0, 5, 15.0 and 40ng/µl). The temperature programs and additional instrument information used for calibration and field sample analysis are tabulated in Table 3. The first temperature program is not valid for the calibration since direct injections were performed during this task.

Site	Tube no.	Average Sampling flowrate [ml/min]	Standard Deviation	Start time	End time
Site 1:	C3577	57.20	0.6	13:00	14:00
Background	C4046	55.51	0.1	13:00	14:00
concentrations	C4036	Blank tube	Taken at 13:05		
Site 2: Inside	C4044	62.41	0.2	13:01	14:00
tunnel	C4065	56.8	0.1	13:01	14:00
	A4082	Blank tube	Taken at 13:05		

Table 3: Hydrocarbon sampling schedule

Program	Item	Description or Condition
ADS	Purge	40ml/min for 1min
	Inject time	1min
	Desorption	@200^{o}C, 10ml/min for 5min
	Cryo trap	Cryo-focusing @ -140^{o}C for 0.3min, heated to 250^{o}C for 5min.
	GC start	7min (count from thermal desorption system start)
GC	Carrier gas	High purity Helium
	Injector	SplitlessS, temperature at 230^{o}C
	Column	HP-5MM, 5% phenyl methyl Siloxane, 30m (length) x 0.25mm (ID), 0.25μm film thickness.
	Flow rate	1ml/min, velocity at 35cm/sec
	Temperature program	-10^{o}C hold for 3min 8^{o}C/min to 20^{o}C, hold for 3min 5^{o}C/min to 120^{o}C hold for 1min 15^{o}C/min to 200^{o}C hold for 1min Total run time 37.08 min.
MS	Mass type	Scan
	Low & High mass	20 & 270 AMU respectively
	MS quad temp	150^{o}C
	MS source	230^{o}C
	Scan rate	3 scan/sec
	Step size	0.1 AMU

Table 4: Auto Thermal Desorption (ADS) and GC/MS Temperature Programs

RESULTS & DISCUSSION

The temperature and humidity, inside the tunnel, remained fairly constant at an average of 24±0.3 and 41±0.5, respectively. The background temperature was slightly lower at 20±0.2 and the humidity was slightly higher at 44±0.7. The data obtained from the tunnel CO monitors provides a concentration profile through the tunnel (refer to graph 3). The concentration increases from west to east, and then decreases as it reaches the east exit. This data will help improve the current understanding of the airflow behavior in the tunnel.

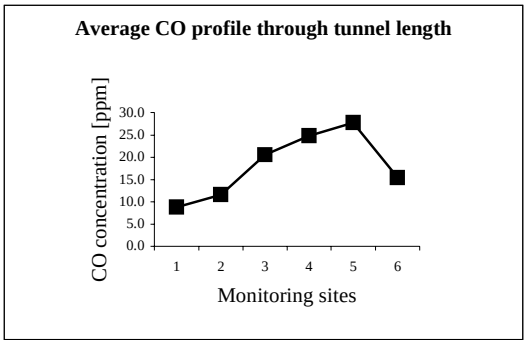

Figure 5: CO concentration profile from west to east through tunnel for sampling period

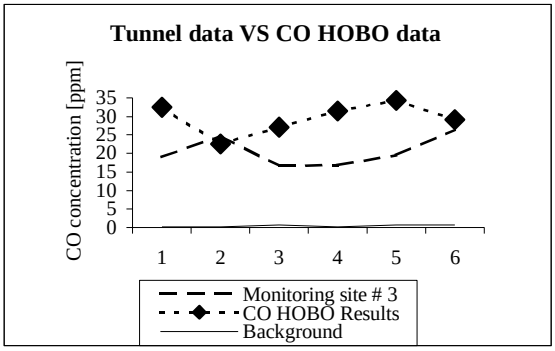

Figure 6: Comparison between tunnel monitors, HOBO tunnel and background measurements

Graph 4 indicates that the HOBO and Tunnel data correspond. The background levels of CO is well below the tunnel values with an average of 0.5ppm. This is an indication that background concentrations don't contribute significantly to the pollutants in the tunnel atmosphere. The HOBO average CO concentration is 30±4.3, compared to the tunnels' 4th sensor average of 25±4.5, which is fairly close. The sensor will be slightly more elevated in the main study in order to match vehicle height more closely.

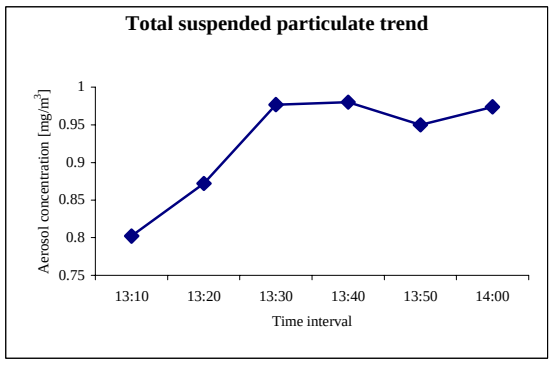

Figure 7: PM_{10} trend for sampling hour at site 2

CONCLUSION

The preliminary concentration profiles show the importance of airflow modeling, the basis of a pollutant mass balance and the estimation of emission factors. The airflow model has to account for the velocity and pollutant concentration profiles along the tunnel. This pilot study has formed the basis of future work, in which a 4-day sampling campaign will be undertaken to gather sufficient data to determine vehicle emission factors.

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