CHARACTERIZATION OF VEHICLE EMISSIONS IN VANCOUVER BC DURING THE 1993 LOWER FRASER VALLEY OXIDANTS STUDY

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Abstract—As part of the 1993 Lower Fraser Valley Oxidants Study, measurements of mobile source emission factors were performed in the Cassiar Tunnel on the Trans-Canada Highway to measure the on-road contribution to the ozone-forming precursors (NO_x and speciated hydrocarbons) along with CO. Observed emission factors were compared to the Canadian versions of the U.S. Environmental Protection Agency's MOBILE models, MOBILE4.1C and MOBILE5C, to assess uncertainty in the predicted mobile source contributions to the Vancouver emissions inventory.

A total of 16 1-h runs were made. The timing of the individual runs was designed to encompass different traffic volumes, driving conditions, and times of day. A total of 24,513 vehicles traversed the tunnel during the study, with approximately 91% light-duty vehicles, 4% heavy-duty spark ignition vehicles, and 5% heavy-duty diesel vehicles. MOBILE5C overpredicted the observed value of CO by ~2%, NMHC by 24%, and NO_x by 13%, while MOBILE4.1C underpredicted the observed values by 36, 29, and 23% for CO, NMHC, and NO_x, respectively.

Key word index: Ozone, vehicle emissions, emission models, speciated organics.

INTRODUCTION

The relatively high levels of ambient ozone in Vancouver have led to the need to better understand the sources of the ozone-forming precursors, NO_x and nonmethane hydrocarbons (NMHC), in the Lower Fraser Valley (LFV). Emissions inventories (e.g. U.S. Environmental Protection Agency, 1992) show motor vehicles as a leading source of NO_x and gas-phase hydrocarbons (HC), the main precursors of urban/regional O_3. Similarly, the 1990 Vancouver emission inventory assigns 77.3% of the total NO_x emissions to mobile sources (GVRD, 1994). Motor vehicles are also the main source of CO. However, it was not until the experiment by Ingalls (1989) and Ingalls *et al.* (1989) in an urban tunnel in Van Nuys, California during the 1987 Southern California Air Quality Study (SCAQS) that attention was drawn to the possibility that motor vehicle emissions of CO and HC (though not NO_x) may be underestimated by a factor of 2 or more. The Van Nuys study raised serious questions regarding the predicted importance of mobile sources toward ozone formation, since mobile sources are the largest contributor to CO and HC emissions in urban areas (Pierson *et al.*, 1990).

Recently, a number of experiments have been conducted in highway tunnels to measure, in an on-road setting, the emissions from mobile sources, and compare these results with model/inventory predictions in order to understand why the present O_3 strategies are not working (Pierson *et al.*, 1996). Concerns raised by these studies prompted Environment Canada to sponsor a tunnel study by the Desert Research Institute (DRI) in Vancouver's Cassiar Tunnel to assess on-road emissions in the LFV during the 1993 Lower Fraser Valley Oxidants Study (LFVOS).

The objectives of this study were:

- To provide a real-world comparison of observed CO, nonmethane hydrocarbons (NMHC), and NO_x against automobile emission models, MOBILE4.1C and MOBILE5C (the "Canadianized" version of the U.S. EPA MOBILE model).
- To provide real-world emission rates of NO_x and speciated gas-phase NMHC as input for calculating the O_3-forming potential of automotive emissions.
- To provide a real-world emission rate for CO.

Table 1. Summary of run times, average speed ($km\,h^{-1}$), vehicle counts, and vehicle fraction

Run #	Date	Run time	Avg. spd.	Total vehicles	LDSI	HDSI	HDD	F-LD	F-HD
1	8/13/93	0200–0300	93.2	125	111	4	10	0.888	0.112
2	8/13/93	0600–0700	95.1	1678	1532	58	88	0.913	0.087
3	8/13/93	1000–1100	91.0	1821	1607	79	135	0.882	0.118
4	8/13/93	1500–1600	91.7	2502	2354	81	67	0.941	0.059
5	8/14/93	0900–1000	93.2	1470	1356	52	62	0.922	0.078
6	8/15/93	0900–1000	92.4	948	897	39	12	0.946	0.054
7	8/16/93	0200–0300	94.6	93	75	4	14	0.806	0.194
8	8/16/93	0600–0700	96.1	1622	1434	86	102	0.884	0.116
9	8/16/93	0800–0900	92.1	1859	1605	121	133	0.863	0.137
10	8/18/93	0200–0300	91.7	100	90	2	8	0.900	0.100
11	8/18/93	0600–0700	96.6	1650	1471	76	103	0.892	0.108
12	8/18/93	0800–0900	91.4	2074	1837	108	129	0.886	0.114
13	8/18/93	1000–1100	89.6	1769	1546	110	113	0.874	0.126
14	8/18/93	1200–1300	89.9	1850	1638	99	113	0.885	0.115
15	8/18/93	1400–1500	90.2	1977	1800	67	110	0.910	0.090
16	8/18/93	1600–1700	89.6	2975	2866	66	43	0.963	0.037

- To evaluate the relative contributions of light-duty (LD) and heavy-duty (HD) vehicle emissions in the LFV.
- To evaluate the relative importance of tailpipe and nontailpipe NMHC from mobile sources (see McLaren *et al.*, 1996).

EXPERIMENTAL METHODS

Measurement of emissions in tunnels

The method of measuring mobile source emissions in tunnels has been described in detail by Pierson *et al.* (1996). Briefly, the mass of any given constituent produced by vehicles in the tunnel is given by

$$M = \sum_i (C_{out} V_{out})_i - \sum_j (C_{in} V_{in})_j \qquad (1)$$

where $(C_{out} V_{out})_i$ is the product of concentration C_{out}($\mu g\,m^{-3}$) and volume of air V_{out} (m^3) for each of the i exit channels (exhaust ducts, exit portal), and similarly for $(C_{in} V_{in})_j$. For the case of the Cassiar Tunnel, there is only one entrance and one exit; thus $i = j = 1$.

Concentrations in ppb or ppm were converted to mass concentrations assuming standard temperature and pressure. The total vehicle counts and the vehicle class distributions of those counts were obtained by recording the traffic flow during the sampling period and reviewing video tapes of the runs to obtain both the total vehicle count and the class-specific vehicle counts. Given the total traffic count N, and the known length Ln of the tunnel, the average emission rate EMF in g veh-mile^{-1} is given by

$$\mathrm{EMF} = \frac{M}{N * \mathrm{Ln}}. \qquad (2)$$

For this study, the motor vehicle fleet was divided into three major classes. The light-duty spark ignition, LDSI, heavy-duty spark ignition, HDSI, and heavy-duty diesel, HDD. In order to separate mathematically HD and LD emissions, the HDSI and HDD vehicle classes were combined to form a heavy-duty (HD) class and the LDSI vehicles was termed the light-duty (LD) class.

Tunnel description

The Cassiar Tunnel is an urban two-bore tunnel, 730 m in length, with two lanes of traffic per bore. It is situated on the Trans-Canada Highway, Highway 1, in Vancouver, BC. Traffic is generally heavy during the day. Speeds ranged between 89.6 and 96.6 $km\,h^{-1}$. Hourly traffic counts ranged from approximately 100 vehicles during the early morning hours to almost 3000 vehicles during the afternoon rush hours (see Table 1). The grade within the tunnel varies from + 1.66% at the south end to − 1.29% at the north end. The nearest entrance ramps before the tunnel are over 1000 m to the south and connect with major arteries. Cold-start operation should therefore be minimal in the tunnel.

Ventilation for the tunnel is achieved from the piston effect of the vehicles traversing it and from fans positioned along the ceiling throughout the tunnel. The fans were used only when high levels of CO were present in the tunnel. They were not activated throughout the course of this study. The surrounding area is primarily residential, with one major urban street located over the middle of the tunnel. Contamination from background sources is eliminated using the emissions calculation methodology outlined in the previous section.

Measurement protocol

A total of 16 1-h runs were conducted at various times of the day beginning at 0200 h on 13 August 1993 and ending at 1700 h on 18 August 1993. Table 1 lists the dates and time periods for the sampling runs. For all runs, the average model year was 1988.5 for cars and 1989.3 for sport utilities/pickups. Overall, the average model year for the LD vehicle class was 1988.8.

Sampling sites were set up at the north and south ends of the tunnel. At each location, a metal framework of angle iron was set up to position the sample lines over the edge of the concrete buttress above and to hang below the ventilation fans and into the top of the tunnel. Attached to the angle iron were propeller anemometers lined up parallel to the roadway to measure the total volumetric air flow through the tunnel. There were no walkways within the tunnel on which to locate additional sampling stations which would have reduced the uncertainty in the observed air flows and emissions. (In order to reduce the possible uncertainty in air flow measurements, SF_6 should be used in future experiments as a check of the air flow in the tunnel.) Power for the samplers was supplied by using 20A gasoline generators set back

Table 2. Total fleet (HD + LD) run observed and MOBILE predicted emission factors and vehicle weighted average emission factors for the 15 valid runs

		Measured emission factors (g veh-mile^{-1})			MOBILE4.1C/MOBILE5C emission factors (g veh-mile^{-1})		
Date	Run	CO	NMHC	NO_x	CO	NMHC	NO_x
8/13/93	1	6.40	1.82	2.88	5.68/8.96	0.38/0.64	2.43/3.42
8/13/93	2	12.5	0.70	4.00	8.29/14.5	0.50/0.91	2.46/3.59
8/13/93	3	8.98	0.58	2.70	6.19/9.25	0.43/0.71	2.53/3.45
8/13/93	4	8.52	0.45	1.81	6.11/9.21	0.39/0.73	1.52/2.51
8/14/93	5	6.56	0.36	1.63	7.47/10.7	0.44/0.73	1.88/2.80
8/15/93	6	7.16	0.37	1.54	5.89/9.89	0.36/0.69	1.16/2.15
8/16/93	7	9.35	0.49	3.41	7.40/11.9	0.52/0.85	4.59/5.65
8/16/93	8	11.8	0.61	3.93	9.32/15.9	0.54/0.99	2.73/3.87
8/16/93	9	14.3	0.85	4.06	6.36/9.92	0.41/0.72	2.44/3.40
8/18/93	10	8.88	0.54	2.85	6.23/9.31	0.42/0.69	2.58/3.51
8/18/93	11	11.4	0.75	3.84	10.5/18.8	0.60/1.11	2.85/4.09
8/18/93	12	14.1	0.77	3.85	5.68/8.80	0.40/0.68	2.21/3.11
8/18/93	13	7.89	0.48	2.07	5.04/7.25	0.38/0.63	2.14/2.96
8/18/93	14	6.83	0.39	1.75	6.07/8.47	0.44/0.73	2.21/3.10
8/18/93	15	5.62	0.33	1.36	4.46/6.75	0.34/0.59	1.94/2.74
8/18/93	16	11.2	0.83	2.16	4.09/5.95	0.30/0.53	1.02/1.79
Weighted average[a]		9.91	0.59	2.66	6.38/10.1	0.42/0.73	2.05/3.00

[a] Without run #1 (8/13/93, 0200–0300).

approximately 18 m from the sampling locations, and out of the airflow of the sampling inlets.

One-hour samples were collected using Tedlar bag samplers. The bags were analyzed immediately following collection for CO, total hydrocarbon (THC), and NO_x using a TECO model 48 gas filter correlation CO analyzer, a Baseline Model 15 THC analyzer, and a TECO model 42A chemiluminescence $NO/NO_2/NO_x$ analyzer. Before reuse, the Tedlar bags were evacuated, filled with zero air, and then reevacuated.

Differences between inlet and outlet THC values were small. The uncertainty present in the THC analysis precluded use of these data and these values are not reported. Instead, the sum of the NMHC species (C_2–C_{10}) obtained from canister sampling was used in the calculation of emission factors. Laboratory analysis of the canisters was carried out by Environment Canada at River Road Labs in Ottawa, Ontario (Dann *et al.*, 1994).

RESULTS

On-road emission factors

The total fleet (HD + LD) emission factors for each individual run were calculated using the methodology described earlier and are listed in Table 2. Emission factors are dependent on a number of variables, including traffic composition, distribution of emitters (i.e. were there a large fraction of like-emitting vehicles?), speed, temperature, etc. Vehicle class and age distributions do not account for all of the data scatter. The run on 13 August from 0200 to 0300 has an abnormally high NMHC emission factor, 1.82 g veh-mile^{-1}, which is more than double the next highest value (0.85 g veh-mile^{-1} on 18 August 1993, 0800–0900). There are a number of possible explanations. The sample may have been contaminated by operator-transferred gasoline used for the power generator, or by direct emission contamination from the on-site power generator. Alternatively, the run may have had an unusually high fraction of high-emitting vehicles. It is difficult to determine which explanation is correct and so this run was treated as an outlier and not used in the determination of the results.

The LD and HD emission rates were calculated by weighted regression (Computing Resource Center, 1992), weighting each run by the total number of vehicles traversing the tunnel during the run. The rationale is that each run is heavily influenced by the total number of vehicles. Over the length of the study, the total number of vehicles per run ranged from 93 to 2975. A few high emitters can cause a low-traffic run to appear to be an outlier even though it may be quite valid.

Comparison with recent tunnel studies

Using the methodology described by Pierson *et al.* (1996), separation of the LD and HD contributions to the observed emissions can be achieved. There were a number of limitations in the experiment which precluded accurate separation of the LD and HD emissions components. These were:

- There was insufficient differences between the HDD and HDSI fractions to separate contributions from these vehicle classes.
- The HDD and HDSI fractions were combined. The rationale for this was to eliminate a high bias in the estimated LD from HDSI fraction. HDSI emissions are greater than LDSI emissions and more closely resemble those from the HDD fraction of the fleet.

Table 3. Light-duty emission factors for CO, NMHC, and NO_x, for the Cassiar, Tuscarora, and Fort McHenry tunnels (in g veh-mile^{-1})

	Cassiar	Tuscarora	Fort McHenry
CO	8.23 ± 2.27	4.89 ± 0.49	6.35 ± 0.54
NMHC	0.58 ± 0.16	0.29 ± 0.06	0.62 ± 0.10
NO_x	1.15 ± 0.73	0.39 ± 0.26	0.81 ± 0.09

- The combined HD fraction varied from 5.3 to 19.4%. The HDD fraction varied from 1.3 to 15.0%, with all but one run in the range of 5.4–13.7%. Extrapolating to 100% HD (or HDD) leads to large uncertainties in the HD (or HDD) estimates.

Given the uncertainty in the HD emission factors, only the LD results are listed in Table 3. These results are compared to two studies performed in the U.S. in 1992 at the Tuscarora Tunnel along the Pennsylvania Turnpike and the Fort McHenry Tunnel located in Baltimore, MD (Pierson *et al.*, 1996).

In reviewing Table 3, it is important to consider the differences among the tunnels. The Tuscarora Tunnel is rural interstate highway tunnel, approximately 1 mile long, with the nearest entrance to the parkway 10 km from the tunnel. The traffic through the tunnel is operating in a hot stabilized running condition, and there is essentially no grade throughout the length of this tunnel. The highest fractions of HD traffic occurred during the night, with the daytime traffic composed primarily of LD vehicles. The Fort McHenry Tunnel is situated on a major north–south interstate freeway in the middle of the third largest seaport on the east coast of the U.S. It is 2174 m long, has a grade which ranges from -3.76 to $+3.76\%$ throughout its length, and has its nearest on-ramps approximately 2200 m before the tunnel. The tunnel has a large number of HDD trucks traversing the tunnel. There are two bores in each direction, one carrying primarily LD traffic and the other composed of a mixture of LD and HD vehicles. The Cassiar Tunnel is similar to Tuscarora in that it is straight and flat; however, it is located in an urban area and there is little diurnal variation in vehicle fleet composition, which is mostly light-duty.

There are two other major differences between the U.S. tunnels and the Cassiar Tunnel. The first is that the type of fuel used in Canada can be significantly different from fuel used in the U.S.; the second is that the emissions restrictions for U.S. vehicles are stricter than those for Canadian vehicles in model years 1981–1988. The effect of differences in gasoline composition is unknown since the effect of regional differences in gasoline composition on emission factors in both the U.S. and Canada has been largely unexplored (apart from RVP effects). The effect of the differences in emissions control technology is that emission factors in Canada are higher than those in the U.S. for roadways that support a significant fraction of vehicles of model years 1981–1988. (Using the same input parameters, the U.S. version of MOBILE predicted approximately 3–10% lower emissions for the U.S. technology vehicles). These factors should lead to greater emission factors for a Canadian fleet similar in age to a U.S. fleet.

The average model year distributions for all three tunnels are very similar. For Tuscarora, the average model years were 1988.7 for cars, 1990.2 for sport utility vehicles, and 1989.1 for pickups. The overall average model year of LD vehicles was 1989.0. Fort McHenry was similar to Tuscarora; the average model years were 1989.0 for cars, 1990.2 for sport utility vehicles, 1988.5 for pickups, and 1989.0 for the LD vehicle class. These can be compared to the Cassiar values of 1988.5 for cars, 1989.3 for sport utility/pickups, and a light-duty vehicle average of 1988.8. (Since the Fort McHenry and Tuscarora experiments were performed in 1992 and Cassiar was performed in 1993, the Cassiar fleet was 1 yr older than the fleets in the earlier experiments.)

The LD emission factors for CO are significantly higher in the Cassiar Tunnel than those in either the Tuscarora or Fort McHenry Tunnels, although the uncertainty of the Cassiar value is large enough to encompass the Fort McHenry values. Both NMHC and NO_x emissions were lowest in Tuscarora and of similar value for Fort McHenry and Cassiar.

As discussed by Gertler *et al.* (1994), the increased emissions in Fort McHenry as opposed to Tuscarora may be due to the impact of grade on emissions. Cassiar, on the other hand, is flat and the results should be similar to those observed in Tuscarora. The increased emissions observed in Cassiar are likely to have resulted from three sources: (1) the difference in technology between the U.S. and Canadian fleets, (2) the urban and suspected to be more poorly maintained nature of the Vancouver fleet as opposed to the interstate and likely to be well maintained fleet observed in Tuscarora and Fort McHenry (the conjecture regarding the quality of maintenance has less to do with whether or not the fleets are part of an inspection and maintenance program but rather on the tendency to drive ones better car on long trips), and (3) the fleet is 1 yr older at Cassiar.

MOBILE4.1C AND MOBILE5C COMPARISON

Modeling methodology

Mobile emission factors were calculated using MOBILE4.1C (Terrillon, 1991) and MOBILE5C (Philpott, 1993), the Canadian versions of the EPA-developed on-road mobile emission factor models. Emission factors were calculated for the eight vehicle types in the models for each of the 16 runs. Average hourly conditions (temperature, speed, etc.) were used and on-road emission factors were calculated for CO, NMHC, NO_x by taking a vehicle count weighted average of the emission factors for each vehicle type.

Table 4. Observed and model-predicted emission factors for CO, NMHC, and NO_x

	CO	NMHC[a]	NO_x
Observed	9.91	0.59	2.66
MOBILE4.1C	6.38	0.42	2.05
MOBILE5C	10.09	0.73	3.00
Model performance (comparison to measurements)			
MOBILE4.1C	− 36%	− 29%	− 23%
MOBILE5C	+ 2%	+ 24%	+ 13%

[a] NMHC includes exhaust and running loss emissions for model predictions.

Table 5. CO/NO_x and $NMHC/NO_x$ mass ratios from the Cassiar Tunnel

	CO/NO_x	$NMHC/NO_x$
Observed	3.55 ± 1.67	0.207 ± 0.010
MOBILE4.1C	2.89 ± 1.71	0.217 ± 0.007
MOBILE5C	3.23 ± 1.98	0.244 ± 0.007

Speed measurements in the tunnel were supplied by the Ministry of Transportation and Highways Contractor, Capillano Highway Services Company, and averaged between 89.2 and 96.6 km h^{-1} (posted speed was 70 km h^{-1}). Temperatures were taken from nearby air-quality monitoring station readings and were relatively cool, ranging from 13 to 23°C (55° to 73°F) during the 16 runs. The Reid Vapor Pressure (RVP) of the gasoline was assumed to be equivalent to that sold in the Lower Fraser Valley. An average RVP, 8.6 psi, was calculated from data collected during August as part of the *Pacific* 93 field study (Steyn *et al.*, 1996). A grade split of 77% regular unleaded/10% midgrade unleaded/13% premium unleaded was used to weight the RVP data. Model year distributions were obtained from video tapes and diesel fractions specific to the Vancouver region were calculated from vehicle registration data provided by the Air Care Administration, the local vehicle inspection and maintenance (I/M) program in Vancouver.

Comparison of observations emissions and model predictions

The calculated emission factors along with the observed emissions are shown in Table 4 for MOBILE4.1C and MOBILE5C. Emission factors are given for CO, NMHC (composed of exhaust + running loss estimates from the model), and NO_x. Run-weighted model performance results are presented in Table 4. MOBILE5C overpredicts the observed value of CO by ~2%, NMHC by 24%, and NO_x by 13%. This is compared to MOBILE4.1C, which underpredicts the observed values by approximately 36, 29, and 23% for CO, NMHC, and NO_x, respectively.

The run-weighted CO/NO_x and $NMHC/NO_x$ ratios for the 15 valid runs are given in Table 5. (The use of ratios reduces the uncertainty in the results since they are independent of the air flow in the tunnel.) The observed CO/NO_x ratio of 3.55 ± 1.67 has a large enough uncertainty to easily encompass the MOBILE4.1C and 5C values of 2.90 ± 1.31 and 3.23 ± 1.41, respectively. Here, the models are predicting the emissions ratios seen at the Cassiar Tunnel, with the discrepancies in the ratios possibly attributed to the uncertainties present in the model input, the composition of vehicles for each run, or in the sampling uncertainty.

The observed $NMHC/NO_x$ ratios are also relatively close to the predicted values (0.217 ± 0.086 and 0.244 ± 0.083, for MOBILE4.1C and 5C and 0.207 ± 0.102 observed). MOBILE5C overpredicts the ratio of the observed values by approximately 18%, but lies within the experimental uncertainty of the observed values, while MOBILE4.1C underpredicts the observed value, and also lies within the uncertainty range.

While MOBILE5C generally overpredicts and MOBILE4.1C generally underpredicts the emissions, they both appear to predict the CO/NO_x and $NMHC/NO_x$ ratios fairly well. Thus, even though the absolute values of the model predictions are off, with MOBILE4.1C regularly underpredicting and MOBILE5C regularly overpredicting, the ratios are in agreement.

Further improvements in the MOBILE models need to address the effects of commuting driving conditions, i.e. aggressive driving, and the possibility of the models underestimating the contributions of new vehicles, etc. These effects are seen in run #16, which has the greatest speed variability and youngest vehicle fleet, in addition to the largest differences between the MOBILE model predictions and the observed emission factors.

SUMMARY AND CONCLUSIONS

In order to understand the factors leading to high ozone in the Vancouver region, a limited study was undertaken in the Cassiar Tunnel on the Trans-Canada Highway to measure the on-road contribution to the ozone-forming precursors along with CO. The observed on-road emission factors were compared to MOBILE5C and MOBILE4.1C (the Canadian versions of the US Environmental Protection Agency's MOBILE models) to assess uncertainty in the predicted mobile source contributions to the Vancouver emissions inventory.

A total of 16 1-h runs were made at the Cassiar Tunnel beginning on 13 August 1993 and ending on 18 August 1993. The timing of the individual runs was made to encompass different traffic volumes, driving conditions, and times of day. During the 16 runs, a total of 24,513 vehicles traversed the tunnel, with approximately 91% light-duty vehicles, 4% heavy-duty spark ignition vehicles, and 5% heavy-duty diesel vehicles.

Taking into account traffic volume and weighting the results, MOBILE5C overpredicted the observed value of CO by ~2%, NMHC by 24%, and NO_x by 13% while MOBILE4.1C underpredicted the observed values by 36, 29 and 23 for CO, NMHC, and NO_x, respectively. It should be noted, however, that the tunnel measurements represent a best case scenario. The vehicles were operating under hot-stabilized conditions and at relatively constant speed. Under normal driving conditions with more variable speed and acceleration but with the average speed the same as for those vehicles traversing the tunnel, emissions would be expected to increase and the models are likely to underpredict the emissions.

The comparison of the MOBILE models to the observed emission factors demonstrates the limitations of the models. While there is run-to-run variability, MOBILE5C generally overpredicts the emissions of CO, NMHC, and NO_x while MOBILE4.1C regularly underpredicts the by-run emission factors. In spite of this, the ratios of CO/NO_x and $NMHC/NO_x$ are in good agreement.

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