Pergamon

Atmospheric Environment Vol. 30, No. 12, pp. 2307–2316, 1996
Copyright © 1996 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
1352-2310/96 $15.00 + 0.00

1352-2310(95)00005-4

METHOD COMPARISONS OF VEHICLE EMISSIONS MEASUREMENTS IN THE FORT McHENRY AND TUSCARORA MOUNTAIN TUNNELS

GARY A. BISHOP,* SCOTT E. McLAREN and DONALD H. STEDMAN
Chemistry Department, University of Denver, Denver, CO 80208-0179, U.S.A.

WILLIAM R. PIERSON
Desert Research Institute, P.O. Box 60220, Reno, NV 89506, U.S.A.

and

ROY B. ZWEIDINGER and WILLIAM D. RAY
U.S. EPA, Mobile Source Emissions Research Branch, Mail Drop 48, Research Triangle Park, NC 27711, U.S.A.

(*First received* 2 *December* 1993 *and in final form* 10 *November* 1994)

Abstract—Experiments were conducted in the Fort McHenry Tunnel in Baltimore, MD, and in the Tuscarora Mountain Tunnel in Pennsylvania, during the summer of 1992 to evaluate real-world automotive emissions. Included in these experiments were the first reported measurements of individual vehicle exhaust in tunnels by a remote sensing device (RSD). Results are compared to integrated emission measurements carried out by analysis of concurrent collections of tunnel air into bags, canisters, and adsorbent traps and by conventional Fourier transform infrared (FTIR) spectroscopy. The vehicles using these highway tunnels proved to be lower emitting than vehicles usually measured by remote sensing in urban areas.

At Fort McHenry the RSD-measured CO/CO_2 ratios were, on average, high compared to either the bag or FTIR measurements (by a factor of 1.4 ± 0.2) for the four runs monitored. RSD hydrocarbon data were obtained only at the uphill location (+ 3.76% grade). RSD HC/CO_2 ratios were lower on average, but statistically indistinguishable when compared with either the FTIR or the integrated uphill measurements.

At Tuscarora, the RSD-measured CO/CO_2 ratios were in agreement with the CO/CO_2 ratios in the tunnel bag measurements and FTIR measurements (within a factor of 1.00 ± 0.16 by one method and 0.82 ± 0.32 by a second, when traffic was dominated by light-duty spark-ignition vehicles). The RSD HC/CO_2 ratios were, however, higher than the light-duty vehicle estimates from the integrated (bag/canister/Tenax) tunnel measurements by a factor of 3, and higher than the FTIR $\Delta HC/\Delta CO_2$ ratios by an even higher factor, mostly owing to water vapor interferences in the low average RSD measurements. For the first time RSD measurements were collected from a small sample of heavy-duty diesels; comparisons to the heavy-duty emissions contributions for CO and HC were favorable.

Analysis of emissions data for vehicle variability at Fort McHenry revealed that low CO emitting vehicles tended to be consistently low but that the minority that were high emitters (> 2.5% CO) were more likely to be high only at the uphill location. Vehicle mileage information was collected at a toll booth in the case of Fort McHenry and at a service plaza in the case of Tuscarora for comparison against the RSD emissions measurements. This comparison showed little conventional deterioration of CO or HC emissions with mileage. The trend consisted of an increased frequency of high emitters with mileage, rather than an increase in emissions from all vehicles with increasing mileage. Copyright © 1996 Elsevier Science Ltd

Key word index: Automotive emissions, remote sensing, tunnel measurements, carbon monoxide, hydrocarbons.

INTRODUCTION

The National Academy of Sciences (1991) recently expressed a grave concern that serious errors exist in the current automotive emission inventories which are being used by the EPA and others. The importance of these inventories is compounded by the fact that future emission controls are being designed utilizing the current inventory estimates. The Academy felt that the current strategy depended too heavily on the assumption that the inventories were accurate, and that not enough checks and tests of these inventories were being conducted. Therefore the Academy recommended that independent tests of the inventories be conducted and in particular that tunnel studies

---

* Author to whom correspondence should be addressed.

and remote sensing of vehicle exhaust be included in those checks.

A large number of studies of vehicle emissions measured on dynamometers, in roadway tunnels, on open highways via inert tracer releases, and through the use of remote vehicle exhaust sensors have been conducted and have been reviewed by Pierson *et al.* (1990). Much of the roadway data obtained has contrasted sharply with the results from fleet dynamometer studies which typically have indicated lower tailpipe emissions. This suggests that one potentially large source of error in estimating vehicle emission inventories lies with the fundamental inputs of fleet emissions derived from dynamometer studies. Further verification through measurements of real-world vehicle emissions as compared with model predictions for the same fleet would be valuable for determining this and possibly other sources of error.

The work described here reports the first time that remote sensing devices (RSD) have been combined with traditional emissions sampling techniques to measure vehicle emissions in a roadway tunnel. The addition of the remote sensors allows direct comparisons of tailpipe measured emission ratios with those detected via other analytical techniques and, for the first time, allows a detailed analysis of tunnel measurements on a vehicle-by-vehicle basis and thereby leads to an explanation of an apparent outlier in one of the Tuscarora Mountain Tunnel measurements.

EXPERIMENTAL

Fort McHenry

The Fort McHenry Tunnel is a four-bore tunnel carrying the eight lanes of Interstate 95 under the Baltimore Harbor. It contains varying grades which range between -3.76% and $+3.76\%$ with no significant level portion (see Fig. 1). Eleven 1 h gas-sampling runs were conducted between 18 and 24 June 1992 wherein CO_2, CO, non-methane hydrocarbons (NMHC), NO, NO_2, NO_x and carbonyl compounds were measured by collection into bags, canisters, and sorbent traps for subsequent analysis. The experiments were conducted in bores 3 and 4 with heavy-duty traffic directed into bore 4. RSD measurements were made of CO/CO_2 and HC/CO_2 (including methane) during four of the 11 runs in bore 3 to concentrate on the light-duty-vehicle traffic. Companion measurements to the RSD ratios were made via an automated Fourier transform infrared (FTIR) spectrophotometer of CO/CO_2 and HC/CO_2. A complete description of the equipment locations and the analytical procedures is given elsewhere (Bishop *et al.*, 1994; Pierson *et al.*, 1995; Zielinska *et al.*, 1995); however, a brief overview follows.

The Fort McHenry Tunnel was equipped with three sampling stations per bore. Collected bag samples were analyzed for CO_2 by non-dispersive infrared (NDIR) absorption spectroscopy, for CO by a gas filter correlation analyzer, and for $NO/NO_2/NO_x$ via a chemiluminescence analyzer. Hydrocarbons (C_2–C_{20}) were collected in canisters and Tenax traps and were analyzed using high resolution gas chromatographic separation and FTIR/mass spectrometric detection for qualitative identification and flame ionization detection for quantitation. Carbonyl compounds were collected in DNPH cartridges and analyzed by high performance liquid chromatography. Approximately 5% of the HC mass resides in compounds not identified.

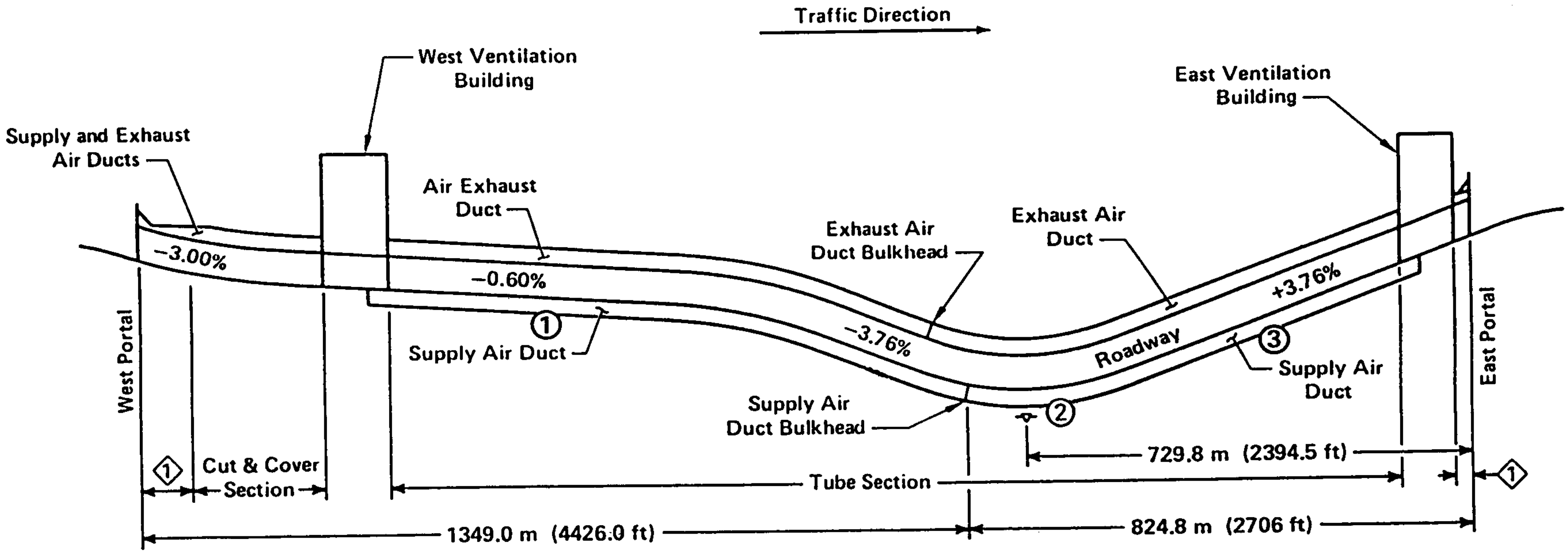
The lack of any roadway shoulders in the Fort McHenry Tunnel dictated that the remote sensing instrumentation be mounted on top of the two walkways located on either side of the roadway. A periscope assembly was designed and constructed for each of the three remote sensors to permit road-level measurements and is described in Bishop *et al.* (1994). Figure 1 shows the approximate locations of the three remote sensing stations. Data capture rates from the instrument located at station 2 were $< 50\%$ due to the light vehicle loads (minimum throttle) and therefore station 2 has been eliminated from the comparison.

Each RSD was continuously manned during data collection and was calibrated with a certified gas cylinder containing 1.99% CO, 10.00% CO_2 and 0.2% propane in nitrogen (Scott Specialty Gases) approximately every 10 min. A small amount of gas was released in front of each unit during calibration. The measured CO/CO_2 and HC/CO_2 ratios were then ratioed to the certified cylinder ratios. These factors were used to correct any shifts in the instruments' predetermined response curves due to changes such as altitude and/or ambient CO_2 concentrations. The frequency of calibration in a tunnel is necessarily higher (every 10 min vs once or twice a day when used outdoors) than when the devices are used outside, due to the changing background exhaust concentrations. The measurements from each station were recorded by computer along with video pictures of the backs of each vehicle. The video tapes were later viewed and the license plates transcribed for Connecticut, Delaware, Florida, Maryland, New Jersey, New York, Pennsylvania and the District of Columbia.

A fourth remote sensor was utilized in one lane at the toll plaza located just outside the exit of bore 3. The drivers of 220 randomly selected vehicles were queried as they entered the lane for their vehicles' odometer reading during three of the four runs that employed remote sensing (queries during one run, a late night run, were excluded for safety reasons). The reported mileages were recorded via a remote microphone onto the audio track of the remote sensing video tape and were manually transcribed after the experiment.

An FTIR spectrometer (MB-100 with 1 wavenumber resolution, Bomem Inc.) coupled to a Beckman white cell with a pathlength of 20 m was installed to sample tunnel air just inside the east (exit) portal of bore 3. Air was pumped at a flow rate of $10\ \ell\ min^{-1}$ through a 1/4″ Tygon tube lowered through the ceiling into bore 3. To prevent water condensation on the salt windows, the entire assembly, including the IR source and power supply, was enclosed. The instrument was calibrated at the site with NBS traceable standards supplied by the EPA for CO, CO_2 and propane. The CO and CO_2 values were determined by averaging calculated concentrations determined by relative peak height for CO at $2172\ cm^{-1}$ and for CO_2 at $2385\ cm^{-1}$.

Hydrocarbon absorption occurs between 2750 and $3100\ cm^{-1}$. Water peaks also occur in this region, and thus the total IR integral includes water vapor and hydrocarbons. An approximate method to eliminate the water vapor interference assumes that the water content is constant over the 1 h time period and that the time variability of the integral is all caused by HC changes. This method eliminates the water contribution but absolute HC data are not available; however, the correlation slope $\Delta HC/\Delta CO_2$ determined from a regression of 5 min averages for each 1 h run is a measure of the HC/CO_2 ratio. This method was used throughout. A test of this method was made using data collected at Fort McHenry on 21 June 1992. In the process of preparing the tunnel for single-lane traffic and restoring two-lane traffic, the Fort McHenry Tunnel authorities closed the tunnel to traffic before and after this measurement run. This allowed us to obtain true I_0 spectra (entrance air at the exit since traffic was eliminated) before and after the data collection



◇1 This cut & cover section does not have supply or exhaust duct.

Fig. 1. Fort McHenry Tunnel general profile, northbound bores and ventilation system. For the June 1992 experiment the remote sensors were located at grades − 0.61%, 0% (bottom of the uphill portion), and 3.76%, labeled 1, 2, and 3, respectively.

period. Water is contributed by the vehicles in roughly the same amount as their CO_2 contribution, i.e. 300–500 ppm at the exit portal, which is a negligible addition to the ambient concentrations of approximately 10,000 ppm for reference purposes. FTIR analyses were carried out using the background data and using the method described above. Both methods resulted in a $\Delta HC/\Delta CO_2$ value of 0.003 ± 0.001.

The vehicle fleet at Fort McHenry was characterized for age by two separate methods. The first involved one of us (WDR) visually identifying the vehicles by model year as they exited the tunnel bore. The second utilized the freeze-frame video pictures obtained by the remote sensors inside of the tunnel. Transcribed license plates were matched with department of motor vehicle records from Maryland, New York and Pennsylvania.

Tuscarora Mountain

The Tuscarora Mountain Tunnel is located on the Pennsylvania Turnpike (Interstate 76) approximately 70 miles west of Harrisburg, Pennsylvania at an elevation of 310 m. It is a flat and level tunnel with a length of 1623.2 m and two 2-lane bores oriented approximately east–west. Experiments were conducted in the bore carrying the eastbound traffic. Two sensors were used; one was placed just outside each portal. The RSD's were aligned across the two eastbound lanes (~6.5 m combined width) and underneath a guard railing. Plastic tents were constructed over each detector unit to allow them to remain in place for the entire experiment.

Eleven 1 h gas-sampling runs were carried out between 2 and 11 September 1992 with data collected for all of the previously listed species at the entrance and exit portals. Species analysis was conducted as previously described. Remote sensing was conducted during all of the measurement periods at Tuscarora Mountain. Experimental difficulties encountered with the RSD located at the west or entrance portal (the west-portal RSD was not shielded properly from the wind buffets from the passing traffic producing excessive instrument noise) eliminated all entrance-portal data from runs 1–9. RSD calibrations were performed as before, using the same certified cylinders. The FTIR system was located at the east portal.

A vehicle mileage survey was conducted in conjunction with the collection of emissions data at Tuscarora. This survey was carried out during six of the 11 data collection periods (runs 2, 4, 5, 6, 7 and 9). Motorists were questioned in the eastbound parking lot of a limited access service plaza at Sideling Hill which is located 22 km west of the Tuscarora Mountain Tunnel. Since time was not a limiting factor, the vehicle odometer, make, model year and license plate were all recorded manually for 318 vehicles. The license plates were later used to compare with the video tapes to relate mileage accumulation, etc., to emission rates of vehicles that traversed the tunnel during the hour-long runs.

We report here the first attempts at remote sensing of heavy-duty diesels. During run 11 a detector unit was temporarily mounted on a small wooden platform dug into the hillside at the entrance to the tunnel. An infrared source was positioned opposite it atop a medium sized cube truck. This allowed the beam to traverse the highway approximately 5 m above the roadway just clearing the tops of the trucks. At this height manual blockage of the beam was necessary to initiate the measurement sequence. As a truck approached the sensor the beam was blocked using a piece of cardboard which was removed as the cab of the truck passed under the beam. One second of data was then collected and analyzed according to established methods. Calibrations were performed before and after the 1 h period.

RESULTS

Table 1 provides a complete listing of the data collected by the various methods at Fort McHenry. The average percent of spark ignition vehicles in bore 3 for the four runs was 99.05%. One-hour average mole ratios are reported for each method with the number of individual exhaust measurements (*n*) reported for each RSD. All hydrocarbon data are reported as moles of carbon and the NMHC data are combined canister and Tenax cartridge samples (Zielinska *et al.*, 1995). The HC/CO_2 ratios from the remote sensors are reported only for the uphill RSD. The downhill instrument located at station 1 failed to measure an instrumented vehicle successfully for HC and its data have been excluded (Bishop *et al.*, 1994).

The CO and CO_2 concentrations determined by the FTIR were compared against the bag averaged concentrations for 10 of the 11 sampling runs resulting in good agreement for CO and excellent agreement for CO_2($\langle FTIR_{CO}/Bag_{CO}\rangle = 0.89 \pm 0.1$; $\langle FTIR_{CO_2}/Bag_{CO_2}\rangle = 1.03 \pm 0.03$). FTIR data were not obtained on 20 June.

Average light-duty-vehicle model years for the four runs were determined as 1987.8 (2383 vehicles) by visual means and 1987.9 (1068 vehicles) through license plate records. The reported odometer readings at Fort McHenry averaged 60,600 miles with a run to run variability in the mean of ± 4%.

The Tuscarora Mountain Tunnel data for light and heavy-duty vehicles are provided in Table 2. The FTIR data from 6 September are not available. Unlike Fort McHenry where most of the heavy-duty truck traffic avoided the bore in which remote sensing was being conducted, at Tuscarora Mountain all types of vehicles utilized the same bore. For this reason Table 2 lists the percentage of light-duty vehicles (determined by visual counts) present during each sampling period. Comparison between methods must make allowances for the makeup of the vehicle fleet, since the remote sensor monitors only the light-duty vehicles or, at the entrance for run 11, only the heavy-duty ones.

At Tuscarora Mountain as at Fort McHenry the FTIR overall averages agreed better with the collocated (east portal) bag data in the case of CO_2 than for CO. Zero calibration of the FTIR revealed a − 0.25 ppm offset for CO which has been added back into each of the FTIR CO measurements. Even with this correction the FTIR values for CO were consistently lower than the bag averages. The comparison, not corrected for inlet concentrations, for CO was $\langle FTIR_{CO}/Bag_{CO}\rangle = 0.84 \pm 0.08$ and for CO_2 was $\langle FTIR_{CO_2}/Bag_{CO_2}\rangle = 1.00 \pm 0.03$.

The average age of the vehicle fleet at Tuscarora was determined visually for the eleven runs as 1987.5 (4521 vehicles). From license plate matching, the average was 1987.8 (1636 vehicles which traversed the tunnel during the 11 1 h runs). Mileages and model years obtained from the Sideling Hill service plaza resulted in an average mileage of 52,700 miles with a 1988.5 model year average. A subset of the Fort McHenry data (132 vehicles which had both model year and odometer reading) is combined with the data from the Sideling Hill survey in Fig. 2.

Table 1. Data from measurement runs at Fort McHenry Tunnel which included remote sensing; ratios are carbon-atom ratios

Run no. date start time	Downhill[a] RSD CO/CO_2 (n) HC/CO_2^{b}	Uphill[c] RSD CO/CO_2 (n) $HC/CO_2^{d,e}$ (*n*)	FTIR[f] data CO/CO_2 $\Delta HC/\Delta CO_2^{d}$	Downhill integrated measurements CO/CO_2 $NMHC/CO_2$	Uphill integrated measurements CO/CO_2 $NMHC/CO_2$
1 6–18 12:30	0.046 (272)	0.047 (302) *0.001* (272)	0.027 *0.007*	0.028 *0.0041*	0.033 *0.005*
2 6–19 03:00	0.045 (132)	0.041 (144) *0.002* (*123*)	0.031 *0.007*	0.035 *0.0053*	0.031 *0.0045*
4 6–20 12:00	0.041 (667)	0.038 (839) *0.003* (*806*)		0.030 *0.0066*	0.029 *0.0047*
5 6–21 12:00	0.043 (772)	0.045 (905) *0.003* (*865*)	0.026 *0.003*	0.027 *0.0062*	0.028 *0.0017*
Averages	0.045 ± 0.004	0.043 ± 0.004 *0.002 ± 0.001*	0.028 ± 0.002 *0.006 ± 0.002*	0.03 ± 0.004 *0.006 ± 0.001*	0.03 ± 0.002 *0.004 ± 0.001*

[a] Station 1 in Fig. 1.

[b] Hydrocarbon data from this site were shown to be below the RSD's detection limits via comparisons with an instrumented vehicle (Bishop *et al.*, 1994).

[c] Station 3 in Fig. 1.

[d] Hydrocarbon measurement includes methane.

[e] Includes a zero offset correction of 285 ppm (as carbon) determined by comparisons with an instrumented vehicle (Bishop *et al.*, 1994).

[f] Sampling just inside the east (exit) portal of bore 3.

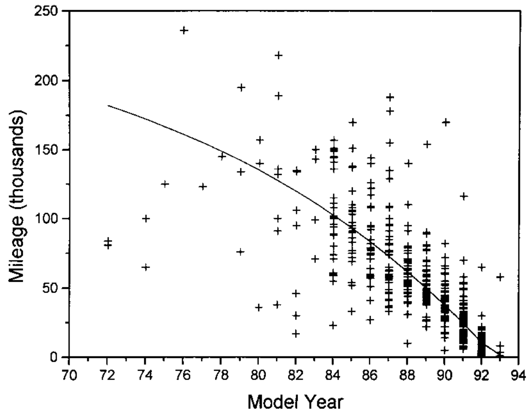


Fig. 2. Combined survey data for 450 vehicles from both tunnels for which vehicle model year and odometer readings were collected. The solid line represents the predicted mileage accumulations for MOBILE5 using a 1 January 1993 starting date.

During the last measurement run (run 11) a total of 60 heavy-duty diesels operating at highway speeds were measured by the RSD at the west end of the Tuscarora Mountain Tunnel. Mole ratios and standard errors of the means were determined to be 0.009 ± 0.001 for CO/CO_2 (~0.13% CO on a dry basis) and 0.002 ± 0.001 for HC/CO_2 in moles of carbon (~0.032% HC as carbon on a dry basis). These compare favorably to estimated heavy-duty ratios determined (by regression analysis as described in Pierson *et al.*, 1995) from the bag, canister and Tenax data of 0.006 ± 0.0016 for CO/CO_2 and 0.0014 ± 0.0004 for $NMHC/CO_2$.

The possibility of vehicles that have intermittent high emissions was evaluated at both tunnels. Table 3 compares CO/CO_2 ratios observed at sites 1 and 3 at Fort McHenry for 1182 vehicles identified by license plates. The percent of vehicles and their percent of total emissions are grouped into three CO/CO_2 mole-ratio categories. Thus 82.1% of the vehicles were low at both stations, 0.9% were intermediate at both and 1.4% were high at both stations. The rest, or 15.6%, changed; 3% went from low to high or vice versa. At Tuscarora 50 vehicles were compared during the only dual sensor period on the morning of 8th September (run 10). Of the 50 vehicles traced, one was a high emitter at both stations, seven were medium at the entrance and low at the exit, and the rest were low at both sensors.

DISCUSSION

At Fort McHenry the RSD CO/CO_2 ratios are high when compared to the bag ratios by average

Table 2. Tuscarora Mountain Tunnel data for RSD light-duty and heavy-duty measurements and integrated measurements of mixed traffic; ratios are carbon-atom ratios

Run no.	Date\location start time	Number of RSD measurements CO and HC % Spark ignition	RSD[a] CO/CO_2 HC/CO_2^b	FTIR data[c] CO/CO_2 $\Delta HC/\Delta CO_2^b$	Integrated[c] measurements CO/CO_2 $NMHC/CO_2$
1	9–2\Exit	54 and 38	0.016	0.004	0.0048
	03:00	24.2%	*0.012*	*0.0004*	*0.00054*
2	9–2\Exit	293 and 255	0.02	0.011	0.0134
	15:00	73.6%	*0.012*	*– 0.0024*	*0.00217*
3	9–3\Exit	36 and 26	0.031	0.006	0.0077
	04:00	20%	*0.009*	*0.0007*	*0.00073*
4	9–4\Exit	533 and 476	0.025	0.021	0.0262
	17:00	90.9%	*0.012*	*0.0004*	*0.00283*
5	9–5\Exit	442 and 393	0.018	0.017	0.0207
	11:30	92%	*0.009*	*0.0007*	*0.00179*
6	9–6\Exit	395 and 349	0.027		0.0219
	11:30	91.6%	*0.009*		*0.00216*
7	9–6\Exit	448 and 420	0.018		0.0209
	13:00	92.1%	*0.012*		*0.00208*
8	9–7\Exit	48 and 45	0.054	0.028	0.0277
	02:00	73.4%	*0.011*	*0.0001*	*0.00496*
9	9–7\Exit	760 and 656	0.025	0.022	0.0227
	13:00	94%	*0.012*	*0.0003*	*0.00210*
10	9–8\Entrance	272 and 267	0.033	0.011	0.0144
	08:00	70.3%	*0.015*	*0.0009*	*0.00135*
10	9–8\Exit	216 and 183	0.03	0.011	0.0144
	08:00	70.3%	*0.012*	*0.0009*	*0.00135*
11	**9–8\Entrance**	**60 and 60**	**0.009**	0.011	0.0105
	20:10	**59%**	***0.002***	*– 0.0001*	*0.00110*
11	9–8\Exit	145 and 122	0.028	0.011	0.0105
	20:10	59%	*0.015*	*– 0.0001*	*0.00110*

[a] The RSD measurements are confined to light-duty vehicles except for run 11 at the entrance which is entirely composed of heavy-duty diesel powered vehicle measurements.

[b] Hydrocarbon measurement includes methane.

[c] The integrated measurements reported for the FTIR, Bag, Canister and Tenax cartridges represent values for mixed (light- and heavy-duty) vehicle traffic. Comparisons among the various methods must make allowance for the traffic composition.

factors of 1.5 for the downhill station and 1.4 at the uphill station (see Table 1). However, the fact that the RSD measured ratios are similar at the two stations, despite grade, is in agreement with the bag measurements. Both methods show that fuel-specific CO emissions (as opposed to mile-specific emissions) are unaffected by the grades.

Possible explanations for the over-prediction are instrument error, inadequate calibration or too infrequent calibrations resulting in an under-correction of the data, and/or the influence of the changing roadway grades on the weighting procedures used to derive the respective ratios. The comparison between the two methods is inherently non-rigorous in a situation of changing grades since the RSD measures only at a point along the tunnel traverse while the bags collect emissions from whole ensemble of grades. Instrument error and any fundamental problems with the calibration methods can be ruled out as possible explanations, as comparisons with an instrumented vehicle during the experiment were good (Bishop *et al.*, 1994). Since many of the instrumented vehicle passes were made during data collection any overestimation caused by these situations would have resulted in overestimations for the instrumented vehicles emissions which was not found. We know from the difficulties encountered with making measurements at station 2 that exhaust volumes change with changing grades. Since the RSD weights all of the determined ratios equally while the bag averaged values are weighted by volume, i.e. by the size and load on the engine ($\langle CO/CO_2\rangle_{RSD}$ vs $\langle CO\rangle_{Bag}/\langle CO_2\rangle_{Bag}$), this could account for the observed difference.

The influence of grade can also be seen in the data shown in Table 3. Table 3 is not symmetric about the diagonal; high emissions uphill sometimes follow low emissions downhill, but high emissions downhill seldom precede low emissions uphill. If intermittent high

Table 3. Percent of 1182 vehicles, and total emission contributions in parentheses, for 3 mole ratio CO/CO_2 categories at site 1 (downhill) and at site 3 (uphill) at the Fort McHenry Tunnel

	Downhill		
Uphill	Low (< 0.07)	Medium (0.07–0.18)	High (> 0.18)
High (> 0.18)	2.7 (20.5)	1.4 (12.3)	1.4 (14.2)
Medium (0.07–0.18)	5.1 (16.3)	0.9 (3.2)	0.4 (1.6)
Low (< 0.07)	82.1 (28.9)	5.4 (2.5)	0.6 (0.5)

emissions were purely random and had nothing to do with driving conditions, Table 3 should be symmetric about the diagonal. These data therefore suggest that, in addition to a few consistently high emitters and an even smaller number of randomly intermittently high emitters, there are low emitters which become high emitters under moderate load.

At Tuscarora Mountain grade was not a problem since the tunnel is essentially flat (± 0.3%) its entire length. The only factor to be accounted for is the percentage of light-duty vehicles vs heavy-duty vehicles. The majority of heavy-duty vehicles are diesels with elevated exhaust pipes and as such are not measured by ground-level remote sensing. The RSD measured light-duty exhaust only (with the exception of the entrance in run 11) while the bag/canister/Tenax measurements include heavy-duty vehicles and also include non-tailpipe HC emissions. Therefore, confining our direct comparison to the five runs (runs 4, 5, 6, 7 and 9, Table 2) which have light-duty vehicle percentages in excess of 90% we find that

$$\left\langle \frac{\langle CO/CO_2 \rangle_{\mathrm{RSD}}}{\langle CO \rangle / \langle CO_2 \rangle_{\mathrm{Bag}}} \right\rangle = 1.00 \pm 0.16$$

in excellent agreement with one another. A validity test using the Student's *t* distribution shows that this agreement is significant at the 95% confidence level.

Alternatively, we can consider the CO and CO_2 emission rates determined for light-duty vehicles alone, by regression analysis of the tunnel bag data (Pierson *et al.*, 1995) at Tuscarora. The light-duty-vehicle CO/CO_2 emission-rate mole ratio determined in this way (0.033 ± 0.004) , compared to the remote sensing average CO/CO_2 ratio (0.027 ± 0.01) , gives

$$\frac{\langle CO/CO_2 \rangle_{\mathrm{RSD}}}{\langle CO \rangle / \langle CO_2 \rangle_{\mathrm{Light-duty}}} = 0.82 \pm 0.32$$

again in good agreement.

The comparison is more complicated for the hydrocarbon case as the two methods for determining total carbon are different. The NDIR method employed by the RSD and emulated with the FTIR are spectroscopic methods with selectivity and water vapor sensitivity determined by the interference filter peak wavelength and bandwidth. (Two RSD's utilizing different interference filters were used for the measurements. The instrument located at station 1 at Fort McHenry and at the exit portal at Tuscarora utilized a filter centered at 3030 cm^{-1} with a bandwidth of 140 cm^{-1} and has an average response to water vapor in excess of 600 ppm C (Guenther *et al.*, 1995), while the instrument used at station 3 at Fort McHenry and at the entrance portal at Tuscarora utilized a filter centered at 2941 cm^{-1} and a bandwidth of 180 cm^{-1} and is an order of magnitude less responsive to water vapor.) Conversion to equivalent carbon for the RSD data assumes an instrument response that is proportional to the carbon content of the species and includes any methane measured. Analysis of the canisters and Tenax cartridges includes calibrations which insure a direct measure of the non-methane carbon content (Zielinska *et al.*, 1995).

The Fort McHenry measurements benefited from both segregated light/heavy-duty traffic (light- and heavy-duty vehicles have CO/CO_2 and HC/CO_2 ratios that differ by a factor of three or more) and numerically larger traffic volumes, but the comparisons suffer due to the small sample size. The averages for the uphill RSD HC/CO_2, the FTIR $\Delta HC/\Delta CO_2$, and the uphill integrated bag $NMHC/CO_2$ measurements agree within overlapping standard deviations. The Student's *t* test shows that the mean RSD HC/CO_2 ratio is statistically equal to the integrated $NMHC/CO_2$ ratio at the 95% confidence limit. The HC/CO_2 ratios were tiny in part due to the age of the fleet and in part due to the loaded uphill driving conditions (Ashbaugh *et al.*, 1993; Zhang *et al.*, 1993).

The RSD hydrocarbon data collected at Tuscarora Mountain (see Table 2) reveal a large overestimation and constancy across all of the runs. The RSD HC/CO_2 ratios are (0.011 ± 0.002) a factor of three higher than the ratio derived for light-duty vehicles from the canister and Tenax $\Sigma NMHC$/bag CO_2 ratio (0.004 ± 0.0016). The previously reported positive water vapor interference is responsible for much of the large difference measured from this new and low emitting fleet. The water interference and noise limited the RSD to an equivalent end-of tunnel concentration sensitivity of 1 ppm HC as C. The observed variations in end-of-tunnel canister/Tenax HC concentrations were well below this limit and therefore with the noise of the RSD for average HC/CO_2 measurements (Pierson *et al.*, 1995). However, when sufficient quantities of hydrocarbons were present the instrument was capable of making distinctions. Table 4 shows the average RSD HC/CO_2 ratios increase with increasing fleet age. Since age and RSD data are uncorrelated when measured, this observation can arise only if the effect is real and is correctly measured by the RSD hydrocarbon channel. The instrument was also capable of measuring individual high-emitting vehicles (see later discussion of run 8 and Fig. 5) which are verified by FTIR measurements.

Table 4. Mean emissions data by model year groupings from the exit of the Tuscarora Mountain Tunnel; ratios are carbon-atom ratios

Model years	CO vehicle count[a]	Mean RSD CO/CO_2	HD vehicle count[a]	Mean RSD HC/CO_2
Pre 75	12	0.095	11	0.056
75–80	75	0.061	69	0.02
81–82	49	0.031	43	0.017
83–93	1578	0.0189	1408	0.011
All years	1714	0.0216	1531	0.012

[a] Data set includes 78 vehicles which were measured outside the time bounds of the 11 1 h runs.

One of several firsts in these studies was the successful measurement of the heavy-duty diesels with elevated exhaust systems. The RSD CO/CO_2 ratio for the heavy-duty diesels (0.009 ± 0.001) was close to the estimated bag ratio (0.0059 ± 0.0016), though only a small number of trucks were measured by RSD. The comparison with the estimated $NMHC/CO_2$ ratios for the heavy-duty vehicles again finds the RSD value high, but within estimated errors ($0.002_{RSD} \pm 0.001$ vs $0.0014_{Bag} \pm 0.0004$). The few high emitting trucks have a much larger weighting in the smaller RSD data sample.

While the configuration was makeshift, several important observations were made which will have a bearing on future measurements. The CO/CO_2 and HC/CO_2 ratios for these vehicles were very low, with averages being a factor of three or more lower than for the light-duty fleet. These very low exhaust concentrations, which result in weak instrument responses, are offset by the larger quantity of exhaust from these engines. As in automobile fleets, gross emitters also appear in the heavy-duty diesel fleets. One truck accounted for 38% of the total measured HC/CO_2 ratio (fleet average HC/CO_2 of 0.002 ± 0.001 including this vehicle vs 0.0013 ± 0.0007 excluding it). Excessive HC emissions from diesel trucks has also been observed in dynamometer studies (Clark, 1994).

The plume dynamics from trucks appear to differ markedly in several ways from automobiles. For example, at the speeds observed (55–65 mph) the optimum sampling height is higher for a truck which has an air deflector on the tractor than for a truck which does not. In the latter case, the exhaust stays at the height of the exhaust stack from which it is released. This means careful beam alignment will be necessary to sample these heavy-duty vehicles successfully. Also, because the air above the trucks is not stirred by moving vehicles as it would be at ground level, when the exhaust is released the dilution process appears to be slower. This can result in smaller measured changes in path-integrated concentration for each species during the half- to one-second RSD measurement.

The data obtained from the mileage surveys at both Fort McHenry and Tuscarora Mountain were an attempt to characterize the usage levels and the related emissions for the vehicles traversing the tunnel. In both cases the vehicles were newer than the national median, < 4 yr vs 6.7 nationally, with reported mileages of 60,600 miles at Fort McHenry and 52,700 miles at Tuscarora. Figure 2 shows MOBILE5 average mileage accumulations, as a solid line, assuming a 1 January 1993 model start date. MOBILE5 consistently under-predicts the average mileage accumulations (even with the late starting date) for model years 1985–1991 and 1993. This means that modeled emission estimates at either tunnel will be higher when actual mileage accumulation data are used. The MOBILE5 assumption that no 1988 vehicles have lower mileage than any 1989 vehicles is clearly incorrect and leads directly to one modeling error. When *a* and *b* are actually distributed variables, $\sum \bar{a} \times \bar{b} \neq \sum \overline{a \times b}$. In other words the fact that some 1990 vehicles have accumulated 120,000 miles and drive 40,000 miles yr^{-1} causes them to contribute more emissions than is obtained if only the average (30,000 miles and 12,000 miles yr^{-1}) are used. Figure 3 shows CO emissions as a function of mileage for 289 vehicles from the combined Fort McHenry and Tuscarora surveys. The Tuscarora measurements were made at highway speeds while the measurements from Fort McHenry (toll booth) were made at idle. The figure shows an increased frequency of high emitters rather than an across-the-board deterioration in CO emissions. Data for hydrocarbons give a very similar picture.

One very interesting piece of data concerns the explanation of outliers in the 1 h tunnel measurements. At both Fort McHenry bore 3 and Tuscarora Mountain the eighth measurement run exceeded the other emission runs in CO/CO_2 and $NMHC/CO_2$ by factors of 2.5–4. Both of these samples were late night runs with few vehicles. Since remote sensing was not utilized during run 8 at Fort McHenry, the suspected explanation for that anomaly could not be confirmed. However, at Tuscarora the remote sensing and FTIR data revealed that a few high-emitting vehicles were responsible for the elevated measurements there.

At Tuscarora 3 out of the 48 spark-ignition vehicles in run 8 had %CO values greater than 5%. They were, in order of appearance, a 1968 Chrysler sedan (measured at 2:27:33 with 5.10% CO and 1.335% HC), a 1972 Dodge van (measured at 2:29:45 with 5.31%

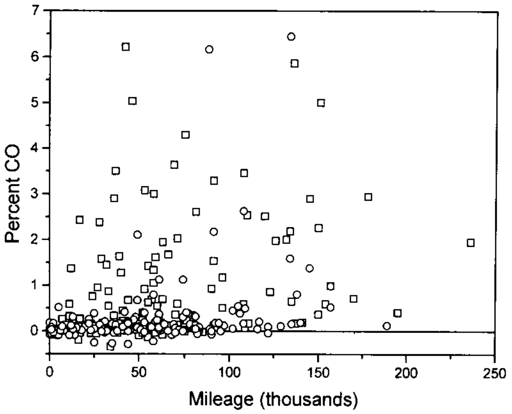


Fig. 3. Combined remote sensing CO emissions data for 289 vehicles measured during data collection runs at a Fort McHenry Tunnel toll booth (□) and at the Tuscarora Mountain (○) Tunnel.

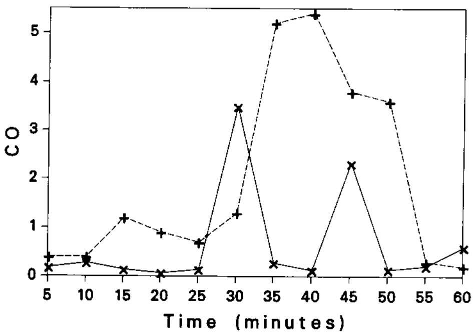


Fig. 4. Five-minute-averaged CO data for the remote sensor (X, solid line) as percent CO compared with data collected by the FTIR (+ , dashed line) reported in ppm from run 8 at Tuscarora conducted during the morning of 7 September. A 5 min lag exists between the remote sensor and the FTIR due to the residence time of the air in the tunnel. A high-emitting 1968 Chrysler sedan and a 1972 Dodge van were measured at the 30 min mark and a high emitting 1990 Ford F350 truck was observed at the 45 min mark.

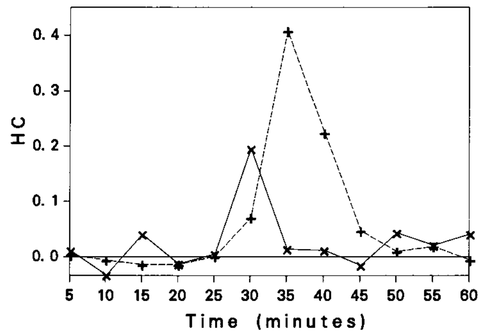


Fig. 5. Five-minute-averaged HC data for the RSD (X, solid line) as percent HC compared with data collected by the FTIR (+ , dashed line) reported in ppm from run 8 at Tuscarora conducted during the morning of 7 September. The 1990 Ford F350 truck (which passed at the 45 min mark) was measured as a low HC emitting vehicle on both instruments. The Chrysler and Dodge were both very high in HC.

CO and 0.615% HC) and a 1990 Ford F350 truck (measured at 2:40: 38 with 8.89% CO and 0.093% HC) (carbon on a dry basis). These three vehicles while representing only 6.25% of the remotely sensed light-duty fleet during the hour, accounted for 73% of the remotely sensed CO/CO_2 emissions in the run. Figure 4 shows the remote sensing data plotted as ending 5 min averages (with the 0–5 min average plotted at the 5 min mark) compared to the 5 min averaged FTIR data. Because traffic at this hour was light the FTIR response only includes a few vehicles in each 5 min average. The FTIR data are plotted in ppm CO while the remote sensing data are plotted as percent CO. The 1968 Chrysler and 1972 Dodge van pass the RSD during the 5 min average which ends at the 30 min mark separated by 2 min and 15 s. While the FTIR shows a small response to the 1968 Chrysler at the 30 min mark the full response is delayed until the next 5 min average in keeping with the tunnel air flow time lag (Pierson *et al.*, 1995). The elevated measurement continues through the 40 min mark in the FTIR plot as exhaust from the 1972 Dodge Van dissipates. Also the slightly higher FTIR average at 40 min is consistent with the RSD-measured %CO's for the two vehicles. The 1990 Ford truck passes the RSD 15 min after the first two at the 45 min mark. The double peak again is believed to be due to the vehicle exhaust influencing both FTIR 5 min averages. The excess emissions of these three vehicles (using the average CO/CO_2 ratio of 0.024 as determined from the 10 other Tuscarora runs) account for 126% of the difference between run 8 and the Tuscarora average.

The RSD HC/CO_2 ratio for run 8 was, however, not dissimilar from the other RSD hourly averages even though chromatographic analysis strongly suggests that the excess NMHC emissions originated with light-duty vehicles (Pierson *et al.*, 1995). Possible explanations for this discrepancy are that the variation in the canister/Tenax data is wholly contained within the interference/noise limits of the RSD as previously discussed or that the remote sensor did not successfully measure one or more high emitting HC vehicles. Data from the FTIR and the RSD video record cannot completely rule out either explanation. Figure 5 displays the HC data from both instruments (%HC for the RSD and ΔHC in ppm for the FTIR) and shows that the only pulse in HC concentration in the tunnel occurred during a 15 min interval. During this time 16 light-duty and four heavy-duty vehicles traveled through the tunnel and 11 of the 16 light-duty vehicle HC/CO_2 ratios were determined by the RSD. It is therefore possible that one of the five light-duty vehicles not measured by the RSD could have been a high HC emitter. The RSD does register a large increase in HC emissions at the 30 min mark which coincides with the passing of the 1968 Chrysler and the 1972 Dodge Van. The fact that the Ford truck (which passed at the 45 min mark) is a late model vehicle equipped with a catalytic converter (assuming it has not been tampered with) probably accounts for its low HC emissions. The 36% increase in the RSD average HC/CO_2 ratio (HC/CO_2 ratio for all 45 vehicles is 0.011 ± 0.003) attributable to the 1968 Chrysler and the 1972 Dodge Van was, however, still within the standard error of the mean for the 43 low HC emitting vehicles (HC/CO_2 of 0.007 ± 0.002). The source of excess HC emission in run 8 includes at least two high emitting vehicles identified by the RSD.

CONCLUSIONS

It is difficult, but possible, to measure vehicle exhaust successfully using remote sensing in a tunnel environment. In general, excellent agreement can be obtained between remote sensing measured CO/CO_2 ratios and those obtained using more traditional bag integrated concentrations for light- and heavy-duty vehicles. The work at Fort McHenry demonstrated that for CO emissions, highway grades are unimportant in determining fuel-specific emission measurements, but grade can effect the vehicle emission distribution. At Tuscarora Mountain the first successful measurement of heavy-duty diesels opens new possible avenues for applying this technology.

The comparisons between the remote sensor HC/CO_2 and $NMHC/CO_2$ obtained by canisters, Tenax cartridges and bag samples were inconclusive. At Fort McHenry the RSD HC/CO_2 ratios are statistically in agreement with the companion techniques, but the small sample size limits conclusions. At Tuscarora Mountain the combination of experimental difficulties with the entrance portal RSD, the high water vapor/noise limits of the exit portal RSD's HC/CO_2 measurements and the low emitting nature of the fleet combine to prevent quantitative HC/CO_2 comparisons.

Vehicle information obtained from surveys of drivers illustrates the very broad distribution of mileage within a given model year, which has implications for the current vehicle emission models. In addition, the emissions as a function of mileage show little correlation with mileage. Finally, the remote sensor has been used, through the identification of high emitting vehicles, to help explain a CO and NMHC emissions anomaly.

Acknowledgements—The authors gratefully acknowledge the participation in this experiment by Dennis A. DeWitt, Richard T. Egami, Alan W. Gertler, Gregory J. Harshfield, Steven W. Schmidt, Laurence H. Sheetz, and Barbara Zielinska of the Desert Research Institute. We are indebted to Peter J. Groblicki of General Motors Corporation, to the U.S. EPA Mobile Source Emissions Research Branch under Kenneth T. Knapp, to the U.S. EPA Air Energy Engineering Research Laboratory/Emissions Modeling Branch, and to John W. Duncan and Alexander Q. McArver of Mantech Environmental Technology, Inc. for their extensive in-kind support. We are grateful to Robert C. Alter, Assistant Administrator-Tunnels, Maryland Transportation Authority; to the crew of the Fort McHenry Tunnel, especially Mike Darago and Loui Toalepai; to David P. Willis, Senior Environmental Scientist, and James B. Wilson, Associate Executive Director and Chief Engineer, of the Pennsylvania Turnpike Commission; to Kenneth Wilson and the crew at the Tuscarora Mountain Tunnel; and to many other Turnpike staff members; all of whom worked with us to make these experiments possible. The work was sponsored by the Coordinating Research Council, the Auto/Oil Air Quality Improvement Research Program, and the Department of Energy National Renewable Energy Laboratory under Contract VE-12-1-92 to the Desert Research Institute; by the U.S. EPA under Cooperative Agreement # CR818561 to the University of Denver; and by the Southern Oxidants Study through the University Corporation for Atmospheric Research, Contract # S9174. This document has been subjected to U.S. EPA agency review for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

Ashbaugh L. L., Lawson D. R., Bishop G. A., Guenther P. L., Stedman D. H., Stephens R. D., Groblicki P. J., Parikh J. S., Johnson B. J. and Huang S. C. (1993) On-road remote sensing of carbon monoxide and hydrocarbon emissions during several vehicle operating conditions. In *Transactions: PM_{10} Standards and Nontraditional Particulate Source Controls* (edited by Chow J. C. and Ono D.), A and WMA Trans. Ser. No. 22, pp. 885–898. Air and Waste Management Association, Pittsburgh, PA.

Bishop G. A., Zhang Y., McLaren S. E., Guenther P. L., Beaton S. P., Peterson J. E., Stedman D. H., Pierson W. R., Knapp K. T., Zweidinger R. B., Duncan J. W., McArver A. Q., Groblicki P. J. and Day J. F. (1994) Enhancements of remote sensing for vehicle emissions in tunnels. *J. Air Waste Man. Ass.* **44,** 169–175

Clark N. N. (1994) Private communication. West Virginia University.

Guenther P. L., Stedman D. H., Bishop G. A., Bean J. H. and Quine R. W. (1995) A hydrocarbon detector for the remote sensing of vehicle emissions. *Rev. Sci. Instr.* **66,** 3024–3029.

National Academy of Sciences, National Research Council Committee on Tropospheric Ozone Formation and Measurement (1991) *Rethinking the Ozone Problem in Urban and Regional Air Pollution*, pp. 7–8. National Academy Press, Washington, D.C.

Pierson W. R., Gertler A. W . and Bradow R. L. (1990) Comparison of the SCAQS tunnel study with other on-road vehicle emission data. *J. Air Waste Man. Ass.* **40,** 1495–1504.

Pierson W. R., Gertler A. W., Robinson N. F., Sagebiel J. C., Zielinska B., Bishop G. A., Stedman D. H., Zweidinger R. B. and Ray W. D. (1995) Real-world automotive emissions — summary of studies in the Fort McHenry and Tuscarora Mountain tunnels. *Atmospheric Environment* (submitted).

Zhang Y., Stedman D. H., Bishop G. A., Guenther P. L., Beaton S. P. and Peterson J. E. (1993) On-road hydrocarbon remote sensing in the Denver area. *Envir. Sci. Technol.* **27,** 1885-1891.

Zielinska B., Sagebiel J., Harshfield G., Gertler A. W. and Pierson W. R. (1995). Volatile organic compounds in the C_2–C_{20} range emitted from motor vehicles: Measurement methods. *Atmospheric Environment* (submitted).