REAL-WORLD AUTOMOTIVE EMISSIONS—SUMMARY OF STUDIES IN THE FORT MchenRY AND TUSCARORA MOUNTAIN TUNNELS

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Abstract—Motor vehicle emission rates of CO, NO, NOx, and gas-phase speciated nonmethane hydrocarbons (NMHC) and carbonyl compounds were measured in 1992 in the Fort McHenry Tunnel under Baltimore Harbor and in the Tuscarora Mountain Tunnel of the Pennsylvania Turnpike, for comparison with emission-model predictions and for calculation of the reactivity of vehicle emissions with respect to O3 formation. Both tunnels represent a high-speed setting at relatively steady speed. The cars at both sites tended to be newer than elsewhere (median age was < 4 yr), and much better maintained as judged by low CO/CO2 ratios and other emissions characteristics. The Tuscarora Mountain Tunnel is flat, making it advantageous for testing automotive emission models, while in the underwater Fort McHenry Tunnel the impact of roadway grade can be evaluated.

MOBILE4.1 and MOBILE5 gave predictions within ± 50% of observation most of the time. There was a tendency to overpredict, especially with MOBILE5 and especially at Tuscarora. However, light-duty-vehicle CO, NMHC, and NOx all were underpredicted by MOBILE4.1 at Fort McHenry. Light-duty-vehicle CO/NO2 ratios and NMHC/NOx ratios were generally a little higher than predicted. The comparability of the predictions to the observations contrasts with a 1987 experiment in an urban tunnel (Van Nuys) where CO and HC, as well as CO/NOx and NMHC/NOx ratios, were grossly underpredicted.

The effect of roadway grade on gram per mile (g mi-1) emissions was substantial. Fuel-specific emissions (g g-1), however, was almost independent of roadway grade, which suggests a potential virtue in emissions models based on fuel-specific emissions rather than g mi-1 emissions.

Some 200 NMHC and carbonyl emissions species were quantified as to their light- and heavy-duty-vehicle emission rates. The heavy-duty-vehicle NMHC emissions were calculated to possess more reactivity, per vehicle-mile, with respect to O3 formation (g O3 per vehicle-mile) than did the light-duty-vehicle NMHC emissions. Per gallon of fuel consumed, the light-duty vehicles had the greater reactivity.

The division between light-duty-vehicle tailpipe and nontailpipe NMHC emissions was ~ 85% tailpipe and ~ 15% nontailpipe (evaporative running losses, etc.).

Measured CO/CO2 ratios agreed well with concurrent roadside infrared remote sensing measurements on light-duty vehicles, although remote sensing HC/CO2 ratio measurements were not successful at the low HC levels prevailing. Remote sensing measurements on heavy-duty diesels were obtained for the first time, and were roughly in agreement with the regular (bag sampling) tunnel measurements in both CO/CO2 and HC/CO2 ratios.

A number of recommendations for further experiments, measurement methodology development, and emissions model development and evaluation are offered. Copyright © 1996 Elsevier Science Ltd

Key word index: Real-world vehicle emissions, NMHC, MOBILE models, O3 formation, remote sensing.
among them the Southern California Air Quality Study (SCAQS; see Lawson, 1990) of 1987 and the Southern Oxidants Study (SOS).

Emissions inventories (e.g. U.S. Environmental Protection Agency, 1994) show motor vehicles as a leading source of NOx and gas-phase nonmethane hydrocarbon (NMHC), the main precursors of urban/ regional O3, in the U.S. Motor vehicles are also the main source of CO. However, it was not until an experiment in an urban tunnel in Van Nuys, California, in 1987 (Ingalls, 1989; Ingalls et al., 1989) as part of the SCAQS, that attention was drawn to the possibility that motor vehicle emissions of CO and HC (although not NOx) may be greater, by 2 times or more, than is stated by the emissions inventories—or than is predicted by the emissions models (the California EMFAC series or the Federal MOBILE series; see California Air Resources Board, 1986; U.S. Environmental Protection Agency, 1991, 1993) upon which the motor vehicle emissions inventories are based. Pierson et al. (1990) reviewed the Van Nuys experiment and concluded that the results were, in the main, correct. They concluded moreover that ample evidence of the same sort of discrepancy between actual and predicted emissions already existed in the published literature on earlier tunnel experiments, open-roadway experiments, discrepancies between ambient CO/NOx ratios and inventory CO/NOx ratios, and discrepancies between ambient and inventory HC/NOx ratios. Fujita et al. (1992) have further documented the ambient vs inventory CO/NOx and HC/NOx ratio discrepancies in the Los Angeles basin and have concluded that the automotive CO and HC emissions are underestimated. A review by Seinfeld (1989) similarly concluded that automotive emissions may be higher than has been generally believed, and recommends that “Emission factors for mobile sources must be verified, for example, by comprehensive monitoring in highway tunnels”.

The Southern Oxidants Study initiated measurements in the Fort McHenry Tunnel in 1991 to generate data needed for predicting and dealing with O3 levels in the southeastern U.S. (Pierson, 1992). It was soon acknowledged, however, that the national scope of the tropospheric O3 problem and the attendant need to evaluate automotive emissions models called for a broader approach. The work to be presented here and in companion papers was conducted in the Fort McHenry Tunnel in June 1992 and in the Tuscarora Mountain Tunnel in September 1992, with multiple sponsors (see Acknowledgements). The Tuscarora Mountain Tunnel, unlike Fort McHenry, is flat and therefore data from it can be compared directly with automotive emissions models (current models do not consider roadway grade).

Roadside infrared remote sensing (e.g. Peterson and Stedman, 1992) has generated a great deal of interest, and controversy, regarding its suitability as a means of measuring on-road emissions. A tunnel experiment with remote sensing affords a unique opportunity for direct comparison to evaluate the remote sensing technology.

The objectives of the Fort McHenry and Tuscarora experiments were:

- To provide real-world comparison against models of automotive CO, NMHC, and NOx emissions.
- To provide real-world emission rates of NO, NOx, and specified gas-phase NMHC as input for calculating the reactivity of automotive organic emissions with respect to O3 formation.
- To evaluate the separate contributions of light-duty (LD) and heavy-duty (HD) vehicles and compare with the models. (This was not done at Van Nuys, and therefore it is not known whether the model under-prediction pertains to one vehicle category or to more.)
- To evaluate the relative contributions of heavy-duty spark-ignition (HDSI) and heavy-duty diesel (HDD) vehicles. (There has been speculation that HDSI vehicles may be disproportionately heavy emitters.)
- To evaluate the effect of roadway grade upon emission rates.
- To evaluate the relative importance of tailpipe and non-tailpipe NMHC—the latter consisting of “resting losses” (leaks, permeation through plastic lines, missing fuel-tank cap) and evaporative running losses. (There is a common but poorly-substantiated belief—e.g. Quarles and Lewis, 1990—that evaporative losses constitute much, or even most, of the automotive NMHC emissions total; the tunnel experiments can evaluate the running-loss component.)
- To evaluate remote sensing of CO/CO2 and HC/CO2 ratios. (A tunnel offers the opportunity for a three-way test, comparing remote sensing with the other tunnel measurements and also with an instrumented drive-by car with prescribable emissions and on-board emissions readout.)

**EXPERIMENTAL**

The method of extracting emission rates from tunnel measurements has been explained elsewhere (e.g. Pierson et al., 1983, 1990): one samples simultaneously the tunnel outgoing air and the incoming air (the air coming in through the ventilation system, if any, and the air coming in at the tunnel entrance; the piston effect of the traffic in a one-way tunnel normally assures that the exit end is the same for both the air and the traffic. One obtains by mass difference the mass of any given constituent produced by vehicles in the tunnel:

\[ M = \sum_i (C_{out}V_{out}) - \sum_j (C_{in}V_{in}) \quad (1) \]

where \((C_{out}V_{out})\) is the product of concentration \(C_{out}\) and volume of air \(V_{out}\) \((m^3)\) for each of the \(i\) exit channels (exhaust ducts, exit portal), and similarly for \((C_{in}V_{in})\).

Alternatively, if there is only one exit channel \((j = 1)\) then \(M\) can be determined by release of a known mass of inert gas (SF6) into the incoming air during a sampling run. The ratio between its concentration in the exit air and the...
inlet-corrected concentration of the species of interest immediately gives M. Both methods of determining M were employed, in both tunnels, and the results were averaged for a best estimate. Agreement on any given run was usually within 10%. The tracer method gave the lower results at Fort McHenry, by an average of 9%, and the higher at Tuscarora by an average of 12% (6–19%).

Given the traffic count N and the known length L of the tunnel, one obtains the average emission rate E for a given sampling period as

\[ E = \frac{M}{NL}. \]  

(2)

The emissions of the LD and HD vehicles are differentiated, and the respective emission rates are determined, as follows. For the nth sampling period, E can be written as

\[ E_n = x_n G + (1 - x_n) H \]  

(3)

where \( x_n \) is the fraction of the vehicles that are LD, \( 1 - x_n \) is the fraction that are HD, \( G \) is the average emission rate characteristic of the LD vehicles, and \( H \) is the average emission rate characteristic of the HD vehicles. Equation (3) is a straight line whose intercepts at \( x = 0 \) and \( x = 1 \) are the emission rates from, respectively, HD and LD vehicles:

\[ E = H(x = 0) \]  

(4a)

\[ E = G(x = 1) \]  

(4b)

as illustrated in Fig. 1. Equations (4) are not rigorously true, since \( E \) is not strictly a single-valued function of \( x \); for example, \( H \) may comprise different HD/HD ratios for different runs with the same \( x \). Also, emission rates \( G \) and \( H \) are affected slightly by traffic speed, ambient temperature, dewpoint, etc.

Correlations on the visual counts showed that the count rates of motorcycles, automobiles sport/utility vehicles, and pickup trucks tracked one another (0.8 < \( r \) < 0.99). Diesel buses were marginally associated with this category; there are so few diesel buses that it does not matter which category they are put into. The HDSI and HDD vehicles were not associated with anything else, including each other. From these results we concluded that the division into LD and HD vehicles was at least as discriminative as a division into spark-ignition (SI) and diesel vehicles. LD vehicles comprise motorcycles, automobiles, sport/utility vehicles, and pickup trucks; HD vehicles comprise HDSI and HDD trucks and buses.

The Fort McHenry Tunnel

Description. The Fort McHenry Tunnel (Fig. 2) is a four-bore tunnel, two lanes per bore, carrying Interstate 95 east–west under the Baltimore Harbor. The downgrade reaches -3.76% and the upgrade reaches +3.76%, with no significant level portion. Average grade from west portal to bottom is -1.8% and, from bottom to east portal, +3.3%. The four tunnel bores are designated 1 and 2 westbound (towards Washington, DC), and 3 and 4 eastbound (towards Philadelphia). Our work was conducted in Bores 3 and 4, the eastbound bores (length 2174 m), measuring in the two bores simultaneously.

LD vehicles are allowed in both bores. Trucks are directed into Bore 4, the right-hand bore; all but 3% of them complied in the June 1992 experiment, with the result that the traffic in the light-duty-only Bore 3 contained only 0.8% HD vehicles, comprising 0.45% SI and 0.32% diesel.

Traffic composition and volume were determined by visual count. On the average, 17% of the traffic in the right-hand bore was HD vehicles, with strong diurnal and hebdomadal patterns between hourly-average extremes of 4 and 73%. Within the HD classes the distribution between SI and diesel varied from 69 to 94% diesel, with an average

![Fig. 1. Weighted regression analysis of CO₂ emissions in the Tuscarora Mountain Tunnel, September 1992 experiment; plot of emission rate vs traffic composition. The intercept at 0% light-duty vehicles (x = 0) is the emission rate average from heavy-duty vehicles; the intercept at 100% light-duty vehicles (x = 1) is the emission rate average for light-duty vehicles.](image-url)
of 80% diesel. Only 3.6% of the HD diesels were buses. Maximum hourly-average traffic eastbound was 4970 vehicles per hour. Total eastbound traffic during the 11 1-h periods of sampling was 26,665 vehicles (12,460 in Bore 3 and 14,205 in Bore 4).

Vehicles were classified visually throughout each run, in each bore, into 15 categories, namely, automobiles, motorcycles, three categories of LDSI trucks (utility vehicles, pickup trucks, others), four categories of HDSI trucks/buses (2-, 3-, 4-, 5-axle), diesel buses, and five categories of HDD trucks (2-, 3-, 4-, 5-, > 5-axle). By utility vehicles we mean vans and all-terrain vehicles. It was not possible to distinguish reliably between SI and diesel automobiles; the diesel fraction in the automobiles was estimated from sales fractions for each model year as provided by Birch (1992); the number varies from run to run but is small—only 0.6% of all automobiles (0.7% at Tuscarora).

There is a toll plaza 470 m east of the east portal. Toll-plaza records of hourly vehicle totals, classified according to axles per vehicle, were consistent with our visual totals.

Fig. 2. The Fort McHenry Tunnel. General profile—eastbound roadways and ventilation system.

![Fort McHenry Vehicle Model Year Distribution](image_url)

Fig. 3. Model-year distributions of light-duty vehicles in the Fort McHenry Tunnel during the June 1992 experiment—all runs combined, both bores combined. Utility vehicles consist of vans and all-terrain vehicles. Model-year 1993 vehicles are included with 1992. The distributions at Tuscarora were very similar to these.
(except that we consistently got lower numbers for 4-axle vehicles). Counts were also obtained from induction loops in the pavement. Agreement with the visual counts was ±1.2% (e).

The median age of the LD vehicles was under 4 yr (Fig. 3). The median model year was 1989.0 for automobiles, 1988.9 for vans, 1990.2 for all-terrain vehicles, and 1988.5 for pickup trucks. This was determined by looking at the vehicles as they came through the tunnel during sampling, and also by later inspection of videotapes recorded during sampling in both bores. Concurrently, license plates obtained on videotape during remote sensing were used to ascertain vehicle ages and other information from state records on the vehicles from the eight leading states including Maryland; overall the two methods differed by only 0.1 yr, with a run-by-run average deviation |Δ| = 0.4 yr. Of the motorists interrogated at the toll plaza, the median model year (all LD types) was 1988.

Posted speed was 50 mi h\(^{-1}\) in the tunnel, 55 outside. Traffic flowed freely except for sporadic light braking/slowdown at the exit at rush hour during a few sampling runs. On the last or 11th run a vehicle breakdown in Bore 4 resulted in all traffic—LD and HD—being routed into Bore 3 for 15 min. The actual average speed for the 11 runs, obtained by measuring the time it took most induction loops to record all vehicles—LD and HD—being routed into Bore 3 for 15 min, was 49 mi h\(^{-1}\), with ±4 mi h\(^{-1}\) run-to-run variability (ε). There was, however, a slowdown of ~7 mi h\(^{-1}\) in the uphill portion of the tunnel—from 51 mi h\(^{-1}\) upon entering and in the downhill portion, to 43 mi h\(^{-1}\) at the exit. The speeds from the induction loop pairs were checked against a hand-held calibrated radar which in turn was field-checked against a test vehicle with a calibrated speedometer.

At the toll plaza, 26% of the 2-axle vehicles paid from commuter-fare ticket books. Only 38% of the LD vehicles had Maryland license plates. The nearest entrance ramps before the tunnel eastbound, and carrying any significant amount of traffic, range upwards of 2200 m west of the entrance portal; all of these ramps connect with arteries, not local streets. From these three indicators—the fare records, the license plates, and the road layout—we conclude that essentially all vehicles were in hot stabilized operation.

The average mileage on the LD vehicles eastbound through the tunnel was 60,600 mi. This was ascertained by interrogating 220 motorists at the toll plaza. The average was 49.0 ± 6.4 mi (e).

The ventilation system of the Fort McHenry Tunnel comprises two sections. Ventilation air from above each end of the tunnel (Fig. 2) is supplied through ducts beneath the roadway, and tunnel air is removed through overhead exhaust ducts. The tracer method for determining emission rates requires that there be only one air exit pathway including the portals, so the exhaust fans were shut off. In this situation, typically 20% of the air might come in through the east supply duct (Fig. 2), 20% through the west supply duct, and 60% through the west portal, depending on traffic volume; the split was determined in each run from anemometer measurements and known cross-sections in the tunnel and supply ducts. The air displacements determined in the ducts were equal to the stated fan ratings, within experimental error. All of the air leaves through the tunnel exit portal, assisted by the traffic piston effect and, usually, by the prevailing wind. Flow balances (in vs out) were usually within ±9%. The average residence time of air in the tunnel without the exhaust fans running was 7 ± 2 min in Bore 3 and 4 ± 0.4 min in Bore 4, as calculated from the tunnel volumes and the air volumetric flow rates through the exit portal.

As depicted in Fig. 2, the dividing plane between the east and west supply ducts is 95 m before (i.e. west of) the low-grade section (3.76%) is essentially wholly contained in the west section.

Cross-contamination between the eastbound and westbound bores was evaluated carefully in this experiment and in the September 1991 pilot experiment (Pierson, 1992) since the bores are close together and the approaches are below grade. It was concluded that over- or under-correction for entrance-air concentrations (depending on whether the entrance-portal sampling points are in or out of the cross-contaminated airstream) resulting from cross-contamination could have affected the emission-rate estimates by ±10%.

The Fort McHenry Tunnel is situated in the midst of the third largest seaport facility on the East Coast, with many pollution sources to degrade the signal/background ratio; one would prefer the air coming into the tunnel to be cleaner. The roadway grades prevent rigorous comparison with the emissions in Bore 4 with strong time patterns in traffic composition, a wide range of traffic compositions would be available for regression analysis.

Sampling stations were set up in the east supply fan room (supplying air to both bores), the west supply fan room, the west portal of both bores (3 and 4), the “midtunnel” of each bore (near the bulkhead between east and west supply ducts, Fig. 2), and the east portal of each bore (near the bulkhead between east and west supply ducts). The rationale for the midtunnel stations was that the west section and the east section of a given bore could then be treated as two separate tunnels, affording emission rates downhill and emission rates uphill. The overall sampling error in an experiment of this type should be ~15% (Pierson and Brachaczek, 1983; Pierson et al., 1978), but in the case of the uphill rates the error is much larger because the already polluted midtunnel air is the “entrance portal” of the uphill “tunnel”.

Each of the eight sampling stations was equipped to collect CO\(_2\), CO, NO, NO\(_x\), gas-phase NMHC, and gas-phase carbonyl compounds (aldehydes and ketones) concurrently at constant rates for the same 60 min. At each of the six tunnel stations there was a propeller anemometer to measure airflow velocity along the tunnel. Flow balance meters were deployed in the exhaust ducts to monitor that the exhaust fans were not turned on by accident. Temperature and humidity were continuously monitored in the tunnel and in the east supply fan room. Barometric pressure for conversion purposes or ppb into mass concentrations was monitored in the east supply fan room. SF\(_6\) was released at a known constant rate inside the west portal of each bore and its concentration was measured inside the east portal.

The deployment of some of the sampling equipment at the east portal is depicted in Fig. 4. The East Portal Bore 3 (EP3) sampling station was ~128 m inside the portal. It
### Table 1. The Fort McHenry Tunnel June 1992 experiment; all runs were of 60 min duration

<table>
<thead>
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<th>Run no.</th>
<th>Bore no.</th>
<th>Start time (EDT)</th>
<th>Total vehicles</th>
<th>HD* (%)</th>
<th>( \langle \text{mi h}^{-1} \rangle_b )</th>
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* HD = heavy duty, both spark-ignition and diesel.

b Average speed for all vehicles, both bores combined.

Traffic control signs in Run 1 were improperly set. This influenced driver maneuvering and caused many vehicles to divert from Bore 3 into Bore 4.

Traffic was single-laned in Bore 3 in Runs 1, 4, and 5 for remote sensing.

Traffic was single-laned in Bore 3 in Runs 1, 4, and 5 for remote sensing.

Vehicle broke down in Bore 4 shortly before Run 4 commenced. The vehicle was cleared before 1200, but congestion continued past 1200 and was not completely gone until 1220.

Vehicle broke down in Bore 4. Bore 4 was closed from 1606 to 1619, with all traffic diverted into Bore 3. Traffic speed was affected.

had three bag samplers—left, right, overhead—for CO\(_2\), CO, NO, NO\(_x\), and SF\(_6\). Beside the right lane there was a canister sampler for light NMHC (\(\leq\text{C}_\text{10}\)), two Tenax adsorbent traps for heavy gas-phase NMHC (\(\geq\text{C}_\text{3}\)), and a DNPH (dinitrophenylhydrazine) cartridge sampler for carbonyl compounds. The concentrations of CO\(_2\), CO, NO, NO\(_x\), and SF\(_6\) were taken as the average of the three bags. Over the 11 runs the average of the root-mean-square deviations among the three bags was 3.5% for CO. All bags were 60°F Tedlar. Sampling lines were 1/4" i.d. FEP Teflon. Also overhead at EP3 a Fourier transform infrared (FTIR) spectrometer continuously measured CO\(_2\), CO, and HC; its main purpose was to measure HC/CO\(_2\) as a check of the remote sensing HC/CO\(_2\) measurements, the FTIR being the only other measurement method for HC which used the same principle (IR) as does the remote sensing. The East Portal Bore 4 (EP4) sampling station was similar, except that there was no FTIR and the inlets for the canister, Tenax, and DNPH cartridge samplers were beside the left lane rather than the right.

The Midtunnel Bore 3 (MT3) sampling station was set up just east of the supply-duct bulkhead, beside the right lane. It had a bag sampler, canister sampler, dual Tenax sampler, and DNPH sampler. The Midtunnel Bore 4 (MT4) sampling station was like MT3 except it was beside the left lane.

The West Portal Bore 3 (WP3) sampling station was located 55 m inside the portal, beside the right lane. There was a bag sampler, canister sampler, dual Tenax sampler, and DNPH sampler. The West Portal Bore 4 (WP4) sampling station was located 45 m inside the portal. It was equipped the same as the WP3 station but with sampling beside the left lane. SF\(_6\) releases at WP3 and WP4 were to begin 15 min before each run and to continue through the run.
The East Supply (ES) and West Supply (WS) fan room sampling stations were each equipped with a bag sampler, two canister samplers, a dual Tenax sampler, and two DNPH samplers. Sampling lines were not used at ES and WS.

The Tedlar bags were analyzed immediately after each run. The analyzers consisted of a NDIR CO2 analyzer, a gas filter correlation CO analyzer, a chemiluminescence NO/NO2/NOx analyzer, and a gas chromatograph with electron capture detector for SF6. Between runs the bags before re-use were evacuated, filled with CO2-free zero air, and then re-evacuated.

Laboratory analysis of the canisters, Tenax traps, and DNPH cartridges was carried out in the ensuing months at the Desert Research Institute's organic chemistry laboratory. These analyses were done together with the Tuscarora canister/Tenax/DNPH analyses as described by Zielinska et al. (1995). All of the Tuscarora canisters and 34 of the Fort McHenry canisters were sent after analysis to Kochy Fung at AtmAA, Inc. for CO2 analysis to confirm the bag CO2 analyses.

Roadside remote sensing was conducted in Bore 3 in Runs 1, 2, 4, and 5. For Runs 1, 4, and 5 the left lane was closed. For Run 2, traffic was light and single-laning was unnecessary. Three remote sensors were located in the tunnel—one at 739 m in from the west portal where the grade is −0.61%, one at 1468 m in from the west portal at the tunnel low point (grade 0), and one at 1974 m in from the west portal where the grade is +3.76% (Fig. 2). Video cameras recorded the license plates as the vehicles were measured. A fourth remote sensor was operated at one lane of the toll plaza, set to measure vehicles at idle waiting to pay toll; its results were used with the odometer information obtained at the same time.

Drive-by comparisons with the remote sensors during the experiment were provided by two vehicles, from General Motors and from the U.S. EPA, instrumented for on-board measurement of CO2, CO, and total HC. With these comparisons, one is able to evaluate the remote sensing technology by two ways simultaneously, i.e. against the drive-by vehicles and against the regular tunnel measurements (bag measurements, etc.). The GM vehicle was a 2.2 / 4-cylinder 1992 Corsica fitted with the instrumentation described by Lawson et al. (1990). The EPA vehicle was a 3.1 / 6-cylinder 1992 Corsica.

The possibility of power enrichment in the uphill part of the tunnel, and/or motoring (coasting) in the downhill part, was evaluated in the September 1991 pilot experiment (Pierson, 1992). Power enrichment is used under high-throttle conditions to provide more power and to protect the engine and catalytic converter from overheating. In closed-loop three-way-catalyst (TWC) systems, this is accomplished through computer controls which command rich air/fuel ratios (i.e. excess fuel) and open-loop operation (i.e. no control of the air/fuel ratio by feedback from the exhaust O2 sensor). Very high CO and HC emissions—especially CO—can result (e.g. CO 2500 times normal; Kelly and Grobicki, 1993). TWC vehicles generally comprise automobiles of model years 1983 and after. Such cars constituted 89% of the cars (and 67% of all LD vehicles) at Fort McHenry in the June 1992 experiment. Thus, evaluation of power enrichment was imperative. A laptop computer was attached in turn to the ALDL (assembly line diagnostic link) of several late-model GM rental cars chosen to span a range of power/weight ratios, from a 2.2 E Corsica to a 3.1 / Buick Regal—with various engine options and monitoring of commanded air/fuel ratio, speed, percent throttle, intake manifold vacuum, fuel economy, etc. None of the ALDL-instrumented cars went into power enrichment; in fact, very heavy throttle was not required on any of them.

However, failure of closed-loop TWC cars to go into power enrichment says nothing about the rest of the cars, which are responsible for much of the emissions. To get an idea of what might happen at the Fort McHenry Tunnel with these other cars, chassis dynamometer tests on six automobiles with various emission control systems were conducted at highway speeds and at loads simulating a series of grades from −5.5% to +5.5% (Sigsby et al., 1991). NOx increased in most cases but not all, from near zero at −3.76% grade to as much as 5 times the level-road value at +3.76%. CO was at a maximum uphill in some cases, downhill in others, and similarly for HC. The highest HC
emissions occurred downhill, and the lowest HC tended to occur in level-road driving. Five brands of gasoline, all three grades in each, were collected during the experiment from service stations in the area. Speciated HC analyses were conducted by EPA/RTP on each of the fuels and on their headspaces, for use in apportioning the tunnel NMHC emissions into tailpipe emissions, resting losses, and evaporative running losses. RVP (Reid vapor pressure) was determined by the North Carolina Motor Fuels Laboratory on each fuel, to gauge what RVP to enter in the emission-model calculations. Baltimore lies in an ozone nonattainment area for which the 1990 Clean Air Act Amendments specify a maximum RVP of 7.8 as of the time of the experiment. The average found in our samples was 6.8 (range, 6.4–7.4).

The Tuscarora Mountain Tunnel

Description. The Tuscarora Mountain Tunnel (Fig. 5) is a two-bore tunnel, two lanes each bore, 1623.2 m (5325.4 ft) long, carrying the Pennsylvania Turnpike (Interstate 76) east–west through Tuscarora Mountain in south-central Pennsylvania at an altitude of ~305 m. The tunnel is flat (grades +0.30% towards the middle from either end) and straight. We did all of our work in the eastbound bore. The hourly-average HD component ranged from 6 to 80% with an overall average of 18%. Of the HD vehicles, 73–99% were diesel (average weight ~27 metric tons, according to Turnpike records). Only 2% of the HD diesels were buses. The maximum hourly-average traffic volume eastbound was 1329 vehicles per hour. The total eastbound traffic during the 11 1-h periods of emissions sampling was 5928 vehicles. These numbers are from visual counting; all vehicles traversing the tunnel eastbound were counted visually throughout each run and classified into the same 15 categories as at Fort McHenry. Traffic volume was checked by a road-tube axle counter. Weight-classified 24 h traffic totals through the tunnel were also obtained from the Turnpike Commission.

The median age of the LD vehicles at Tuscarora was under 4 yr. Median model years were 1988.7 for automobiles, 1988.6 for vans, 1990.2 for all-terrain vehicles, and 1989.1 for pickup trucks. The age distributions were

Fig. 5. The Tuscarora Mountain Tunnel. Crosses indicate the sampling locations. Overhead air supply ducts (not used) are indicated in the end view.
There were six sampling points (Fig. 5), namely, three within the west or entrance portal (left side, right side, overhead) and three within the east or exit portal (left, right, overhead). At each of the six sampling points there was a propeller anemometer and a bag sampler. At each of the four left- and right-side sampling points there was a canister sampler, a Tenax sampler, and a DNPH sampler. Sampling lines, when used, were 1/4" i.d. FEP Teflon. SF6 was released at a known constant rate beside the left lane 15 m inside the entrance portal remote sensor. In each run, using a gas filter correlation CO analyzer, a gas filter correlation CO analyzer, a chemiluminescence NO/NO2/NOX analyzer, and the same SF6 apparatus as for Fort McHenry. The treatment of bags for re-use was the same as at Fort McHenry. Laboratory analyses of the canisters, Tenax traps, and DNPH cartridges were done together with analysis of the Fort McHenry samples as described above and by Zielinska et al. (1995).

Roadside remote sensing was conducted at both ends of the tunnel throughout the Tuscarora experiment. There was no single-laning of traffic. A software modification on the apparatus at the east portal enabled us to cover both traffic lanes concurrently with the one sensor gaging two video cameras (one each lane). The cameras recorded license plates so that individual vehicles could be evaluated as to remote sensing emissions vs state records on each vehicle's model year, make and model, body type, and fuel type. Recording the license plates further allowed matching of remote sensing emissions measurements vs odometer readings from Sideling Hill. Finally, recording the license plates permitted an evaluation of the prevalence of vehicles that are high (low) emitters at the entrance portal but low (high) emitters at the exit portal. For the 11th run of the experiment, the entrance-portal remote sensor was raised to diesel-truck exhaust-stack height (about 5 m above the road), as a first-ever attempt to apply remote sensing technology to the measurement of emissions from HD diesels.

Roadway grades on the last 1.2 km of the approach to the tunnel from the west ranged between +0.30% and +3.00%. Out of concern that power enrichment on the approach could have an after-effect on emissions in the tunnel, power enrichment on the approaches was evaluated with a closed-loop TWC-equipped 3.1 l 1992 Cor-sica instrumented as in the Fort McHenry experiment; on the average, closed-loop TWC cars, i.e. cars of model year 1983 and later, constituted 89% of the cars (and 64% of all LD vehicles) at Tuscarora. Power enrichment was not detected.

It is important to know whether the fuel economy and emissions are the same in the tunnel as they would be at the same speed outside. In the sampling arrangement described below would minimize any effect.

Ambient temperatures during the sampling periods are listed in Table 2. Run-average humidity ranged between 71 and 95% (average, 85%). Temperatures within the tunnel were 2°C above ambient temperature (20.0°C daytime, 28.8°C nighttime), and absolute humidity was marginally higher.

Extraction procedures. The sampling schedule (Table 2) at Tuscarora consisted of 11 1-h sampling periods chosen to span the range of traffic compositions. The strategy was to exploit the fact that LD vehicles preponderate during the day and especially over the Labor Day weekend, while HD vehicles preponderate on weekday nights.
Table 2. The Tuscarora Mountain Tunnel September 1992 experiment; all runs were of 60 min duration

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Start time (EDT)</th>
<th>Total vehicles</th>
<th>HD* (%)</th>
<th>( \langle \text{mi h}^{-1} \rangle_b )</th>
<th>( T^\circ C )</th>
<th>Remote sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0300 Wednesday 9/2</td>
<td>186</td>
<td>75.8</td>
<td>56</td>
<td>13</td>
<td>Yes*</td>
</tr>
<tr>
<td>2</td>
<td>1500 Wednesday 9/2</td>
<td>530</td>
<td>26.4</td>
<td>55</td>
<td>20.5</td>
<td>Yes*</td>
</tr>
<tr>
<td>3#</td>
<td>0400 Thursday 9/3</td>
<td>185</td>
<td>80.0</td>
<td>59</td>
<td>20.5</td>
<td>Yes*</td>
</tr>
<tr>
<td>4</td>
<td>1700 Friday 9/4</td>
<td>928</td>
<td>9.1</td>
<td>57</td>
<td>24</td>
<td>Yes*</td>
</tr>
<tr>
<td>5</td>
<td>1130 Saturday 9/5</td>
<td>661</td>
<td>8.0</td>
<td>58</td>
<td>21</td>
<td>Yes*</td>
</tr>
<tr>
<td>6</td>
<td>1130 Sunday 9/6</td>
<td>585</td>
<td>8.4</td>
<td>56</td>
<td>19#</td>
<td>Yes*</td>
</tr>
<tr>
<td>7#</td>
<td>1300 Sunday 9/6</td>
<td>659</td>
<td>7.9</td>
<td>58#</td>
<td>19b</td>
<td>Yes*</td>
</tr>
<tr>
<td>8</td>
<td>0200 Monday 9/7#</td>
<td>79</td>
<td>26.6</td>
<td>58</td>
<td>18.5</td>
<td>Yes*</td>
</tr>
<tr>
<td>9</td>
<td>1300 Monday 9/7#</td>
<td>1329</td>
<td>6.0</td>
<td>59</td>
<td>20.5</td>
<td>Yes*</td>
</tr>
<tr>
<td>10</td>
<td>0800 Tuesday 9/8</td>
<td>435</td>
<td>29.7</td>
<td>60</td>
<td>21</td>
<td>Yes#</td>
</tr>
<tr>
<td>11</td>
<td>2010 Tuesday 9/8</td>
<td>351</td>
<td>41.0</td>
<td>58</td>
<td>19.5</td>
<td>Yes*#</td>
</tr>
</tbody>
</table>

* HD = heavy duty, both spark-ignition and diesel.
\( b \) Average speed for all vehicles, both lanes.
\( c \) At exit only.
\( d \) Power failure, all circuits, at 0415 for 15 s. Tunnel lights and approach lights were off about 2 min.
\( e \) Rain throughout Run 6.
\( f \) Traffic was stopped 90 m west of the tunnel entrance at 1335 for 2 min to clear an obstruction; 24 vehicles, all LDSI, were affected.
\( g \) Not determined; assumed as the average of the similar Runs 5, 6, and 9.
\( h \) Rain stopped at 1315. Big pulse of HD diesels.
\( i \) Labor Day.
\( j \) At both entrance and exit.
\( k \) Remote sensor at entrance was elevated to measure HD diesel emissions.

RESULTS AND DISCUSSION

Concentrations

The pollutant concentrations encountered in these tunnels were lower than ambient-air concentrations in some cities. For example, the highest hourly CO

outside. For HD vehicles the result could have been quite different, however (Hampton et al., 1983; Gorse, 1984).

All three grades of gasoline were sampled at the Sideling Hill service plaza; all Turnpike service plazas west of Tuscarora including Sideling Hill are Gulf stations. In addition all three grades were sampled at each of five off-Turnpike service stations located at interchanges west of Tuscarora. In all, there were 18 gasoline samples. RVP was determined (range, 7.7 to 8.4—again, by the North Carolina Motor Fuels Laboratory) on each sample. Each was analyzed for NMHC species composition, and its headspace was analyzed as well.

Sales-by-grade figures for the Turnpike service plazas were provided by the Pennsylvania Turnpike Commission. These figures were used in composing the analyses to derive a representative RVP (8.2) for use in MOBILE4.1 and MOBILE5, and to derive a composite fuel-composition profile and a composite headspace-composition profile for receptor-modeling tailpipe vs nontailpipe emissions.
Table 3. Emission rates in the Fort McHenry Tunnel, June 1992; Bores 3 and 4 data combined

<table>
<thead>
<tr>
<th></th>
<th>Light duty</th>
<th>Heavy duty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ g mi⁻¹</td>
<td>281 ± 1.5</td>
<td>1284 ± 78</td>
</tr>
<tr>
<td>CO g mi⁻¹</td>
<td>6.35 ± 0.54</td>
<td>9.84 ± 2.82</td>
</tr>
<tr>
<td>NMHC g mi⁻¹e,d</td>
<td>0.62 ± 0.10</td>
<td>1.54 ± 0.45</td>
</tr>
<tr>
<td>Formaldehyde g mi⁻¹</td>
<td>0.007 ± 0.002</td>
<td>0.053 ± 0.009</td>
</tr>
<tr>
<td>Acetaldehyde g mi⁻¹</td>
<td>0.0020 ± 0.0005</td>
<td>0.032 ± 0.003</td>
</tr>
<tr>
<td>Methylcyclopentane g mi⁻¹</td>
<td>0.0029 ± 0.0008</td>
<td>0.031 ± 0.004</td>
</tr>
<tr>
<td>NO g mi⁻¹ as NO₂</td>
<td>0.72 ± 0.09</td>
<td>12.99 ± 0.49</td>
</tr>
<tr>
<td>NOx g mi⁻¹ as NO₂</td>
<td>0.81 ± 0.09</td>
<td>14.43 ± 0.45</td>
</tr>
<tr>
<td>migal⁻¹f</td>
<td>30.4 ± 1.5</td>
<td>7.0 ± 0.4</td>
</tr>
</tbody>
</table>

* Light duty = motorcycles, automobiles, sport/utility vehicles, pickup trucks.
* Heavy duty = buses and heavy-duty trucks, mostly diesel.
* Probably 10–20% low. See text.
* Calculated on the assumption of empirical formula C₆H₁₂₂₅n.
* Calculated from mol mi⁻¹ with NO₂ molecular weight.
* Calculated from total carbon emission rate (ΣCO₂ + CO + organics), assuming empirical formula C₆H₁₂₂₅n for gasoline and C₆H₆ for diesel fuel, and assuming gasoline density 0.7406 g era⁻³ (national average test fuel; see Stump et al., 1992) and diesel fuel density 0.77331 (cetane).

Table 4. Emission rates in the Tuscarora Mountain Tunnel, September 1992

<table>
<thead>
<tr>
<th></th>
<th>Light duty</th>
<th>Heavy duty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ g mi⁻¹</td>
<td>232 ± 12</td>
<td>1596 ± 78</td>
</tr>
<tr>
<td>CO g mi⁻¹</td>
<td>4.89 ± 0.49</td>
<td>6.03 ± 1.61</td>
</tr>
<tr>
<td>NMHC g mi⁻¹e,d</td>
<td>0.29 ± 0.06</td>
<td>0.68 ± 0.20</td>
</tr>
<tr>
<td>Formaldehyde g mi⁻¹</td>
<td>0.006 ± 0.002</td>
<td>0.043 ± 0.007</td>
</tr>
<tr>
<td>NO g mi⁻¹ as NO₂</td>
<td>0.41 ± 0.23</td>
<td>18.27 ± 0.76</td>
</tr>
<tr>
<td>NOx g mi⁻¹ as NO₂</td>
<td>0.39 ± 0.26</td>
<td>19.46 ± 0.85</td>
</tr>
<tr>
<td>migal⁻¹f</td>
<td>37.0 ± 1.8</td>
<td>5.71 ± 0.14</td>
</tr>
</tbody>
</table>

* As in Table 3.

Emission rates

Table 3 lists the emission rates of CO₂, CO, NMHC (canister and Tenax merged), carbonyl compounds, NO, and NOₓ for LD and HD vehicles in the Fort McHenry Tunnel. Table 4 does the same for the Tuscarora Tunnel. (For comparison, the Federal standards for current automobiles on the Urban Dynamometer Driving Schedule are 3.4, 0.41, and 1.0 g mi⁻¹ for CO, HC, and NOₓ, respectively.) For the run-by-run emission rates, undifferentiated according to vehicle type, see the Appendix.

The emission rates were calculated by weighted regression (Computing Resource Center, 1992). Each run was weighted by the number of vehicles in it, since a few high emitters can cause a low-traffic run to be an outlier even though it is valid. (One high emitter can easily emit as much CO or HC as 20–50 normal emitters; see Siegl et al., 1994.) The weighted regression results differed from the unweighted regression results by 0.2–29% (median, 5%), most notably in that the LD results were lower by weighted regression. The Fort McHenry regression results were obtained on the combined Bore 3 and Bore 4 emissions data. While good estimates of LD emissions are obtainable by regression analysis of the Bore 3 data alone, the Bore 3 regressions contain essentially no information on the HD emission rates since all of the data points are near the 100% LD end of the plot.

Also shown in both tables are fuel economies calculated from the total carbon (CO₂, CO, NMHC, carbonyls) emission rates. The fuel-economy estimates serve as a check on the reasonability of the emission rates; if the fuel-economy estimates appear reasonable, then the emission-rate estimates are unlikely to be far off. The national fuel economy for all types of driving was 21.6 mi gal⁻¹ for cars and 5.6 mi gal⁻¹ for heavy trucks in 1992, and for cars of model years 1986–1992 it was 28.3 mi gal⁻¹ (American Automobile Manufacturers Association, 1994, pp. 65, 83). Better fuel economy would be expected on the highway; for model years 1986–1992 the average on the highway test (average speed 48 mi h⁻¹) is 36.1 ± 0.4 mi gal⁻¹ for automobiles and 26.1 ± 0.4 for LD trucks (Murrell et al., 1993). The Lincoln test car recorded an average of 35 ± 5 mi gal⁻¹ in the Tuscarora Tunnel; the average on the Corsica in the Turnpike tunnels was 48 ± 8 mi gal⁻¹.

Given the similar experimental conditions—speeds, temperatures, and so forth—in the two tunnels, one
might expect the emission-rate estimates in Tables 3 and 4 to be similar. In general, they are. The LD emissions tend to be lower (and fuel economy higher) at Tuscarora than at Fort McHenry—perhaps because of the grades at Fort McHenry (see below). But the HD CO₂ emission rates are lower (and fuel economy better) at Fort McHenry, probably because many of the HD vehicles eastbound in the Fort McHenry Tunnel had dropped off their cargoes at the shipping terminals just west of the tunnel. For example, 3-axle diesel trucks, mostly tandem-axle tractors without their trailers, constituted 11% of the diesel trucks at Fort McHenry, while only 1.3% of the diesel trucks at Tuscarora were 3-axle.

The NMHC values in Tables 3 and 4 are calculated from the Σ ppb C on the assumption of an overall H/C atom ratio of 1.825, which lies between the average ratios in the gasolines analyzed (1.81 at Fort McHenry and 1.80 at Tuscarora) and the ratio 1.85 prescribed for calculating HC emissions from FID exhaust measurements (Code of Federal Regulations, 1989). As much as 60% of the gas-phase NMHC mass (between 30 and 60%, depending on traffic composition, in a given run) consisted of heavy NMHCs, i.e. species reported from the Tenax traps rather than from the canisters.

The NMHC values are probably 10–20% low, for two reasons. (1) The total NMHC in each sample was obtained by summing the quantified identified species; it appears that ~ 5% of the NMHC carbon mass resides in species not quantified. (2) NMHC recoveries from the canisters are not quite quantitative (Zielinska et al., 1995). Fortunately the compounds that appear beyond ethylbenzene in the gas chromatogram were quantified from the Tenax traps rather than from the canisters.

The amount of NMHC in the particulate phase (not measured in these experiments) can be significant, especially from diesel trucks (0.3 gmi⁻¹ from diesel trucks (see Pierson et al., 1983, or Pierson and Brachaczek, 1983)). Since the phase partitioning of the heavier NMHC species is not an intrinsic property but depends on temperature, dilution, amount and type of the particulate matter present, etc., the HD NMHC values in Tables 3 and 4 could be higher or lower than in otherwise comparable situations with, say, different ambient temperature.

Nearly all of the emitted NO₂ is NO (Tables 3 and 4, and Fig. 6). Indeed, the actual NO/NOₓ emission-rate ratios are probably higher than those shown in Fig. 6, because some of the NO was probably oxidized to NO₂ by O₃. NO₂ levels in the exit air of the two tunnels, corrected for incoming NO₂ levels, ranged between 11 and 400 ppb, so that titration of NO by the (not measured, but presumably in the 20–100 ppb range) ambient O₃ in the tunnel, and in the bags awaiting analysis, could account for much of the NO₂ that was generated in the tunnels. Siegl et al. (1994) report that ≥ 99.7% of the NO₂ at the tailpipe of current high and normal emitting vehicles is NO.

Fig. 6. CO/CO₂ and NO/NOₓ emission-rate mole ratios vs traffic composition, Tuscarora Mountain Tunnel, September 1992 experiment.

The trend to higher NO/NOₓ ratio with higher % SI vehicles in Fig. 6 is statistically significant at probability > 99%. There is a decided difference of CO/CO₂ emission-rate ratio according to vehicle type (Tables 3 and 4, and Fig. 6), with the diesels showing the lower CO/CO₂ ratios; this is important to the later discussion of remote sensing.

The LD emission rates in the present experiments are half what they were in 1981 in the Allegheny Mountain Tunnel (elevation 707 m) of the Pennsylvania Turnpike (Gorse, 1984). In fact, LD CO measurements going back to 1976 at Allegheny (Gorse and Norbeck, 1981) together with the present experiments indicate a fivefold decrease in those 16 years. The HD emission rates, however, have not changed significantly since at least 1979 (CO) or 1981 (NOₓ).

Effect of grade. Table 5 shows that the effect of roadway grade on emissions is large (as great as on fuel economy, or greater). In general, emission rates uphill (grades 0 to + 3.76%, average + 3.3%) were double the emission rates downhill (0 to - 3.76%, average - 1.8%).

The fuel-specific emission rates (grams per gram of fuel consumed, or per gallon of fuel consumed) are generally the same downhill as uphill (Table 6). The one exception is LD NOₓ, where the fuel-specific emission rate uphill is 1.4 times the fuel-specific emission rate downhill. Incorporating also the level-road Tuscarora data, one sees that:

```plaintext
Fig. 6. CO/CO₂ and NO/NOₓ emission-rate mole ratios vs traffic composition, Tuscarora Mountain Tunnel, September 1992 experiment.

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```
Table 5. Effect of grade; emission rates downhill and uphill in the Fort McHenry Tunnel, June 1992 (Bore 3 and 4 data combined)

<table>
<thead>
<tr>
<th></th>
<th>Light dutya</th>
<th>Heavy dutyb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downhill</td>
<td>Uphill</td>
</tr>
<tr>
<td>CO₂ g mi⁻¹</td>
<td>237 ± 9</td>
<td>370 ± 32</td>
</tr>
<tr>
<td>CO g mi⁻¹</td>
<td>4.90 ± 0.26</td>
<td>9.1 ± 1.1</td>
</tr>
<tr>
<td>NMHC g mi⁻¹t</td>
<td>0.52 ± 0.04</td>
<td>0.79 ± 0.22</td>
</tr>
<tr>
<td>Formaldehyde g mi⁻¹</td>
<td>0.006 ± 0.002</td>
<td>0.009 ± 0.004</td>
</tr>
<tr>
<td>NO g mi⁻¹ as NO₂e</td>
<td>0.53 ± 0.06</td>
<td>1.11 ± 0.20</td>
</tr>
<tr>
<td>NO₂ g mi⁻¹ as NO₂e</td>
<td>0.58 ± 0.06</td>
<td>1.27 ± 0.19</td>
</tr>
<tr>
<td>mi gal⁻¹</td>
<td>36.2 ± 1.4</td>
<td>23.0 ± 1.9</td>
</tr>
</tbody>
</table>

* As in Table 3.

Table 6. Fuel-specific emission rates (g gal⁻¹): effect of roadway grade

<table>
<thead>
<tr>
<th></th>
<th>LD</th>
<th>HD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fort McHenry</td>
<td>Tuscarora (level)</td>
</tr>
<tr>
<td>CO₂</td>
<td>8569</td>
<td>8520</td>
</tr>
<tr>
<td>CO</td>
<td>177 ± 9</td>
<td>210 ± 24</td>
</tr>
<tr>
<td>NMHC</td>
<td>19 ± 2</td>
<td>18 ± 5</td>
</tr>
<tr>
<td>HCHO</td>
<td>0.21 ± 0.06</td>
<td>0.21 ± 0.10</td>
</tr>
<tr>
<td>NOₓ</td>
<td>21 ± 2</td>
<td>29 ± 4</td>
</tr>
</tbody>
</table>

- The LD CO fuel-specific emission rates downhill, uphill, and on the level are all the same (190 g gal⁻¹), within the experimental r.m.s. uncertainty (± 18).
- The LD HCHO fuel-specific emission rates downhill, uphill, and on the level are all the same, within the experimental r.m.s. uncertainty (± 0.08).
- The HD NOₓ fuel-specific emission rates downhill, uphill, and on the level are all the same (106 g gal⁻¹), within the experimental r.m.s. uncertainty (± 4).

(Note the similarity between the downhill g mi⁻¹ emission rates (Table 5) and the level-road g mi⁻¹ emission rates (Table 4) from the LD vehicles (with the exception of the NMHC). The LD fuel-economy figures downhill and on the level are also similar, whereas one would probably expect better fuel economy downhill; this suggests that the Fort McHenry g mi⁻¹ emission-rate estimates may be slightly high (fuel economy estimates too low) and/or that the Tuscarora g mi⁻¹ emission-rate estimates may be slightly low (fuel economy too high).

Effects of grade on the composition of the NMHC emissions were generally small. Among the compound classes, the largest effect was in the HD unsaturated and aromatic compounds, where the mass ratio (aliphatic and alicyclic)/(unsaturated)/(aromatic)/TNMHC went from 0.47/0.16/0.37/1 downhill to 0.39/0.06/0.55/1 uphill. The LD ethene/acetylene mass ratio did show a large change, from 2.1 ± 0.4 downhill to 5.8 ± 3.5 uphill.

Individual organic species emission rates. Some 200 NMHC and carbonyl species were identified (partially or wholly) in the emissions and were quantified as to emission rates from LD and HD vehicles. (By “partially identified” we mean, for example, that a given peak may be identifiable as a C₁₀ branched alkane but we do not know which isomer.) The results, far too extensive to list here, are given by Sagebiel et al. (1995). Figure 7 is included here for illustration. Two conclusions are immediately obvious:

1. The HD-vehicle NMHC profile (predominantly diesels) has a good deal of material in the > C₁₀ range, i.e. above retention index ~ 1000 in Fig. 7, as is already known (e.g. Hampton et al., 1983). This means that canisters alone are inadequate in ambient atmospheric NMHC sampling in a setting in which diesel exhaust may be a significant contributor. This point has been made before (e.g. Zielinska et al., 1993, 1995).
2. The separation between SI and diesel vehicles in air pollution source apportionment by receptor modeling should be possible by means of NMHC species profiles (Fig. 7).

Ozone reactivities of the emissions. The reactivity of the organic emissions with respect to O₃ formation was calculated using the reactivities given by Carter...
Fig. 7. NMHC individual species emission-rate profiles, in order of chromatographic elution time from 
C\textsubscript{2} to C\textsubscript{21}. The C\textsubscript{2} \textit{n}-alkane is at retention index \(= 200\), and the C\textsubscript{21} \textit{n}-alkane is at retention index \(= 2100\). The light- and heavy-duty-vehicle emission rates for each species were resolved by weighted linear 

The reactivity of the NMHC emissions was in the range of 0.4-6 g O\(_3\) per vehicle-mile, depending on 
vehicle type and upon which reactivity scale is used. HD vehicles contributed twice as much reactivity, on 
a g per veh-mi basis, as did LD vehicles. On the basis 
of grams O\(_3\) per gram NMHC emissions, LD and HD 
vehicles were comparable. On a fuel-specific basis 
(grams O\(_3\) per gallon of fuel consumed), the LD 
vehicles had the higher reactivity by a factor of 2 or 3; 
thus, nationally the SI vehicles are dominant, with 
U.S. gasoline sales 116 billion gallons vs 22 billion 
gallons of diesel fuel consumed in 1992 (National 
Petroleum News, 1994). Much of the reactivity came 
from the aromatic fraction of the emissions. Carbonyl 
compounds were a minor contributor. A substantial 
part of the reactivity in the case of LD vehicles, and half 
or more of the reactivity in the case of HD vehicles, 
came from the heavier NMHC compounds that are 
quantified in the Tenax traps rather than the lighter 
compounds that are quantified in the canisters. The 
reactivities are fully reported by Sagebiel \textit{et al.} (1995). 

As for the NO\(_x\) emissions, the O\(_3\)-formation potential 
in a NO\(_x\)-limited situation would be many times 
greater for one HD vehicle than for one LD vehicle, 
either per mile (Tables 3 and 4) or per gallon of fuel 
consumed (Table 6). Diesel vehicles are estimated to 
have produced \(~ 30\%\) of the NO\(_x\) emitted by on-
road motor vehicles nationwide in 1992 (U.S. Environ-
mental Protection Agency, 1994); judging from 
the nationwide gasoline and diesel fuel consumption 
(above) and the fuel-specific NO\(_x\) emissions in Table 
6, the figure could be \(50\%\).

\begin{align*}
\text{CO}_2 \text{ g mi}^{-1} & \sim 1600 \\
\text{CO} \text{ g mi}^{-1} & \sim 7 \\
\text{NMHC} \text{ g mi}^{-1} & \sim 1.4 \\
\text{NO}_x \text{ g mi}^{-1} & \sim 16
\end{align*}

which turn out to be close—as expected—to the values 
in Table 3 for HD as a whole. In any case it is clear 
that HDSI vehicles, which were only \(2\%\) of the traffic, 

\textit{Heavy-duty spark-ignition (HDSI) vs heavy-duty 
diesel (HDD) emission rates.} We sought to utilize the 
Fort McHenry Tunnel to infer HDSI emission rates, 
as follows: the composition of the LD traffic in Bore 
3 is approximately the same as the composition of the 
LD traffic in Bore 4. Thus, in a given run one can back 
out the Bore 3 emission rate from the Bore 4 emission 
rate—the former representing almost solely LD ve-
hicles and the latter representing a mixture of LD and 
HD vehicles—to obtain for each run an emission rate 
for HD vehicles. If then the HDSI vehicles as a frac-
tion of total HD traffic have some variation from run 
to run, then HDSI emission rates can be resolved 
from HDD emission rates by regression of emission 
rates vs HDSI/HD visual-count ratio in a manner 
analogous to equations (3) and (4). Since the Bore 
3 traffic does have a few HD vehicles in it, backing out 
Bore 3 from Bore 4 in practice required solving two 
simultaneous equations for each run.

The effort was only partly successful because the 
HDSI/HD ratios were too low and the range in the 
HDSI/HD ratio, 0.0576-0.327, was too narrow to 
permit reliable extrapolation to a ratio of 1.0, i.e. to 
the value for HDSI vehicles. The only reliable values 
are the HDD values

\begin{align*}
\text{CO}_2 \text{ g mi}^{-1} & \sim 1600 \\
\text{CO} \text{ g mi}^{-1} & \sim 7 \\
\text{NMHC} \text{ g mi}^{-1} & \sim 1.4 \\
\text{NO}_x \text{ g mi}^{-1} & \sim 16
\end{align*}

as reported by Sagebiel \textit{et al.} (1995).
were not a very important part of the overall vehicle emissions in these experiments. Since the nationwide figure is of the same order as this 2% (American Automobile Manufacturers Association, 1994, pp. 3, 7, 8), the conclusion probably holds generally.

Comparison with automotive emission-factor models. Emissions of CO, NMHC, and NO\textsubscript{x} were predicted by MOBILE4.1 and by MOBILE5, for the Fort McHenry Tunnel and for the Tuscarora Tunnel (see Robinson et al., 1995b). The 4 December 1992 (release date) version of MOBILE5 was used. Model inputs, different for each sampling period, included actual traffic vehicle-type composition, actual model-year distributions for each LD vehicle category except motorcycles, the observed speeds of the LD vehicles and of the HD vehicles separately, the observed ambient temperatures and humidities, the RVPs of the collected gasoline samples, and the NO\textsubscript{x} humidity correction. Hot stabilized operation was assumed, on the grounds already discussed. The contribution of diesel automobiles was dealt with as described earlier. The model default tampering rates and trip-length distributions were used. It was assumed that no inspection and maintenance (I/M) or anti-tampering (AT) programs were in effect. The trailer towing correction and air-conditioning correction were not applied, as they are obsolete and their use is not advised. The low-altitude version of the models was run. It should be noted that the resting-loss g mi\textsuperscript{-1} predictions of MOBILE4.1 and MOBILE5 are high by a factor of ~40 relative to the predictions obtained properly for a roadway segment by dividing the g h\textsuperscript{-1} predictions by vehicle speed (see Robinson et al., 1995b); the predictions properly calculated are only ~0.3% of the predicted NMHC total (exhaust + running + resting).

The model outputs were evaluated for their sensitivity to temperature, RVP, tampering rate, I/M and AT program specifications, trip-length distribution, towing and air-conditioning corrections, diesel automobile age distribution, etc., within the ranges that could have held in these experiments. Under the conditions prevailing, all effects were small or modest (~20 to +10%) for CO, NMHC, and NO\textsubscript{x}.

The model emission-rate predictions were compared to the experimental emission rates in two ways: (1) The fleet emission rates of CO, NMHC, and NO\textsubscript{x} for each sampling run were compared to the prediction for that run, as illustrated in Figs 8–10. (2) The model predictions for all runs were subjected to regression analysis, i.e. by equations (3) and (4), to get LD and HD emission-rate predictions that are compared with the regression results on the observed CO, NMHC, and NO\textsubscript{x}, as in Table 7. The latter method lends itself to ascertaining, in case of a discrepancy between observation and prediction, whether the discrepancy has to do with the LD vehicles, the HD vehicles, or both, while the former method has the virtue of being less derivative in nature. The regressions on the model predictions were weighted, and with the same weighting factors as the regressions on the observed data.

We also compared predicted vs observed CO/NO\textsubscript{x} emission-rate ratios, and predicted vs observed NMHC/NO\textsubscript{x} ratios. With ratios, many of the experimental uncertainties—for example, in the tunnel air flow volume—cancel out, providing in some ways a stiffer test of the models than do the absolute rates themselves.

In comparing the models with the observations, it is necessary to consider what constitutes a discrepancy, since the model predictions do not include uncertainty estimates. The model uncertainties probably are substantial; the MOBILE5 predictions are substantially higher, for all species and for both vehicle categories, than the MOBILE4.1 predictions, as is evident in Figs 8—10—on the average, by factors of 1.6 for CO, 1.5 for NMHC, 1.3 for NO\textsubscript{x} (2.5 for LD NO\textsubscript{x}). These variances between essentially two versions of the same model suggest that it is probably too much to expect either MOBILE4.1 or MOBILE5 to predict to within better than a factor of 1.5. The uncertainties quoted in Tables 7 and 8 are the uncertainties (σ) given by, or derived from, the regression analyses or from the run-to-run scatter of predicted/observed ratios.

The model inputs on which the NMHC predictions are based involve FID measurement, which comprises not only nonmethane hydrocarbon but also, at a reduced response per C atom, the carbonyl and other oxygen-containing compounds. Strictly, then, we should have added some fraction of the carbonyl compound measurements to the NMHC measurements to generate "NMHC" numbers for comparing to the model "NMHC" predictions. We chose not to do this, but the effect is small as can be seen in Tables 3 and 4. Inclusion of the carbonyls would lower the predicted/observed NMHC ratios by a few percent.

MOBILE4.1 and MOBILE5 are based on model driving cycles—the Urban Dynamometer Driving Schedule (UDDS or "FTP"), the Highway Fuel Economy Test, etc. None of the cycles represents cruise conditions, the condition that best describes driving behavior at Fort McHenry and especially at Tuscarora. This might be expected to favor a tendency to overprediction since emissions are generally associated with driving transients.

The results are summarized in Tables 7 and 8, and in Figs 8–10:

(1) The models generally agree with experiment. One-third of the predictions in Table 7 agree with observation within one standard deviation of their difference. Two-thirds of the predictions are within ±50% of the observed values.

(2) There is, however, a tendency to overprediction. The predicted number was the higher more often than it was the lower (about twice as often, Table 7), and a pattern of overprediction is evident in Fig. 10 for CO and NMHC at Tuscarora. However, the
difference between model and observation is generally no greater than the divergence between the models themselves.

(3) The tendency to overpredict is greater for MOBILE5 than for MOBILE4.1.

(4) The tendency to overpredict is greater at Tuscarora than at Fort McHenry. The predictions of higher LD emissions at Tuscarora than at Fort McHenry do not materialize (Table 7).

(5) HD NO\textsubscript{x} is quite well predicted.

(6) The only instances of underprediction are at Fort McHenry by MOBILE4.1 in LD CO, LD NMHC, and LD NO\textsubscript{x} (Table 7, Figs 8 and 9).

(7) The instances of clear and substantial overprediction are at Tuscarora in CO, NMHC, and (by MOBILE5) LD NO\textsubscript{x}; and at Fort McHenry in LD NO\textsubscript{x} by MOBILE5 (Table 7 and Figs 8–10).

(8) Referred to NO\textsubscript{x}, however, the LD CO and LD NMHC are not overpredicted (Table 8); the observed LD CO/NO\textsubscript{x} ratios and LD NMHC/NO\textsubscript{x} ratios are within the predicted ranges or slightly underpredicted (suggesting slightly richer operation than predicted).

(9) The HD CO/NO\textsubscript{x} ratios are marginally overpredicted. The HD NMHC/NO\textsubscript{x} ratio is within the predicted range at Fort McHenry but is overpredicted at Tuscarora.

(10) For all vehicles taken together without reference to vehicle type, CO/NO\textsubscript{x} and NMHC/NO\textsubscript{x} ratios are very close to, but slightly higher than (richer than), the predicted ratios at Fort McHenry and
lower than (leaner than) the predicted ratios at Tuscarora.

The model predictions for LD vehicles are substantially higher at Tuscarora than at Fort McHenry (Table 7). This evidently is a speed effect. When MOBILE5 was re-run for Tuscarora but with the 49 mi h⁻¹ Fort McHenry average instead of the Tuscarora speeds, the predictions for LD vehicles by weighted regression became essentially identical to the Fort McHenry predictions. The slight difference in the LD distribution among cars, motorcycles, and vans/pickup trucks/utility vehicles between Fort McHenry and Tuscarora made a relatively small difference in the model predictions.

This does raise an issue, though: the observed LD emission rates at Fort McHenry were higher, not lower, than those at Tuscarora, contrary to the model predictions (Table 7). Grade cannot explain it; even the downhill LD emission rates at Fort McHenry (Table 5) are as high as the Tuscarora emission rates (Table 4). We surmise that the change in the LD emissions between 49 and (say) 58 mi h⁻¹ as given by the models is exaggerated and possibly even in the wrong direction. Other experiments have suggested less dependence of CO and HC g mi⁻¹ emissions on speed in the real world than the models predict; see Pierson et al. (1990).

The situation at Fort McHenry and Tuscarora contrasts with that in the 1987 SCAQS tunnel experiment.
in Van Nuys, California (Ingalls, 1989), wherein the CO and HC were badly underpredicted as were the CO/NOx and HC/NOx ratios. Some of the underprediction has been ameliorated by model evolution since 1987; but even in the more recent EMFAC7EP California emission model the Van Nuys CO and HC emission rates, and CO/NOx and HC/NOx ratios, at 41 mi h⁻¹ are underpredicted by average factors of 2–3 (Pierson et al., 1993). Most other real-world results to date (Pierson et al., 1990) are consistent with Van Nuys. Why this difference between Van Nuys and Fort McHenry/Tuscarora? There are at least three possibilities:

1. Model differences. The model is not the same for Van Nuys (EMFAC) as for Fort McHenry/Tuscarora (MOBILE).

2. The generally better condition of the vehicles traversing Fort McHenry and Tuscarora. The low LD CO/CO₂ and HC/CO₂ ratios, high ethene/acetylene ratios, and low formaldehyde emission rates at Fort McHenry and Tuscarora all attest to emission control systems in good working order. The higher-than-predicted CO/NOx and HC/NOx ratios at Van Nuys are said (Ingalls, 1989) to be indicative of poor maintenance.

3. The driving conditions. The driving at Fort McHenry, and especially at Tuscarora, was close to steady-speed driving, lacking in the power enrichment or other transients which give rise to emissions. The cycles used in generating the model predictions do have accelerations and decelerations in them, but not

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**Fig. 10.** MOBILE4.1 and MOBILE5 model predictions vs experimental observations of emission rates, Tuscarora Mountain Tunnel, September 1992 experiment. The sampling runs are ranged in order of % heavy-duty vehicles, to bring out any trends.
### Table 7. Predicted and observed emission rates (g mi\(^{-1}\)); from regression analyses

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>NMHC</th>
<th>NO(_x)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fort</td>
<td>Tuscarora</td>
<td>Fort</td>
</tr>
<tr>
<td><strong>Light-duty vehicles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>3.66 ± 0.26</td>
<td>7.12 ± 0.46</td>
<td>0.29 ± 0.02</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>6.93 ± 0.31</td>
<td>12.6 ± 1.0</td>
<td>0.54 ± 0.03</td>
</tr>
<tr>
<td>Observed</td>
<td>6.35 ± 0.54</td>
<td>4.89 ± 0.49</td>
<td>0.62 ± 0.10</td>
</tr>
<tr>
<td><strong>Heavy-duty vehicles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>11.1 ± 1.4</td>
<td>8.9 ± 1.5</td>
<td>1.26 ± 0.09</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>13.9 ± 1.6</td>
<td>10.4 ± 3.2</td>
<td>1.54 ± 0.13</td>
</tr>
<tr>
<td>Observed</td>
<td>9.8 ± 2.8</td>
<td>6.0 ± 1.6</td>
<td>1.54 ± 0.45</td>
</tr>
<tr>
<td><strong>All vehicles (arithmetic average)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>4.6</td>
<td>8.0</td>
<td>0.45</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>7.8</td>
<td>12.2</td>
<td>0.71</td>
</tr>
<tr>
<td>Observed</td>
<td>7.4</td>
<td>5.8</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*a (1/11) \(\sum_{a=1}^{11} E_a\) for Tuscarora, (1/22) \(\sum_{a=1}^{22} E_a\) (both bores combined) for Fort McHenry.

### Table 8. CO/NO\(_x\) and NMHC/NO\(_x\) ratios (g g\(^{-1}\))

<table>
<thead>
<tr>
<th></th>
<th>LD</th>
<th>HD</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO/NO(_x)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fort McHenry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>6.1 ± 0.5</td>
<td>0.76 ± 0.09</td>
<td>1.58</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>5.3 ± 0.3</td>
<td>0.82 ± 0.10</td>
<td>2.01</td>
</tr>
<tr>
<td>Observed</td>
<td>7.8 ± 1.1</td>
<td>0.68 ± 0.20</td>
<td>2.24</td>
</tr>
<tr>
<td>Tuscarora</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>12.5 ± 2.5</td>
<td>0.47 ± 0.08</td>
<td>1.36</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>8.1 ± 1.0</td>
<td>0.47 ± 0.14</td>
<td>1.64</td>
</tr>
<tr>
<td>Observed</td>
<td>12.7 ± 8.5</td>
<td>0.31 ± 0.08</td>
<td>0.96</td>
</tr>
<tr>
<td>NMHC/NO(_x)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fort McHenry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>0.48 ± 0.04</td>
<td>0.086 ± 0.006</td>
<td>0.15</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>0.41 ± 0.03</td>
<td>0.091 ± 0.008</td>
<td>0.18</td>
</tr>
<tr>
<td>Observed</td>
<td>0.76 ± 0.14</td>
<td>0.107 ± 0.032</td>
<td>0.23</td>
</tr>
<tr>
<td>Tuscarora</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOBILE4.1</td>
<td>0.65 ± 0.13</td>
<td>0.058 ± 0.003</td>
<td>0.10</td>
</tr>
<tr>
<td>MOBILE5</td>
<td>0.46 ± 0.05</td>
<td>0.059 ± 0.004</td>
<td>0.12</td>
</tr>
</tbody>
</table>
| Observed         | 0.76 ± 0.53 | 0.035 ± 0.010 | 0.08     

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enough to cause power enrichment in most cars. Since power enrichment did not appear to occur at Fort McHenry or Tuscarora, the proper model comparison was made. By contrast, two of the runs at Van Nuys had substantial stop-and-go driving, and the speed variability from vehicle to vehicle on the other 19 runs was large (\(\bar{\sigma} = 17\) mi h\(^{-1}\)). Groblicki (1993) states that traffic-flow disturbances at Van Nuys propagate into the tunnel, and that Fort McHenry driving by comparison is smooth.

It is probably fair to speculate from the foregoing that the models can predict fairly well (i.e. within ± 50% of the observed values most of the time) in situations where most of the model assumptions are reasonably well met, including lack of power enrichment, and that the problems come in when one has to deal with urban traffic with its more erratic driving and possibly poorer maintenance. Probably the salient message in the model comparisons is that in the Fort McHenry and Tuscarora situations we have been able to get the models agreeing with the observations most of the time, which at least provides a place to start from in trying to understand the discrepancies in more complex situations.

The means by which the models were adapted to the tunnel situation (or to any fixed road segment) is described by Robinson et al. (1995a). The full comparison between predicted and observed emissions in the present experiments appears in Robinson et al. (1995b).

**Evaporative emissions vs exhaust emissions.** There is recent concern that nontailpipe emissions may constitute a large part of the HC emissions from a moving LD vehicle. This was evaluated in the present study by means of receptor modeling. The LD NMHC emissions profile from the tunnel was compared with tailpipe and nontailpipe profiles. The tailpipe profiles were from the literature (Sigsby et al., 1987; Fujita...
The CO/CO₂ ratios correspond to exhaust levels where LD signifies the ratio for light-duty vehicles. U.S. roadway traffic are in the 1% range (e.g. Bishop et al., 1994; Gorse, 1993), a troublesome aspect of this is that the literature exhaust profiles are not real-world exhaust profiles. For the nontailpipe profile, a series of trial nontailpipe profiles was utilized, constructed by various combinations of fuel analyses and headspace analyses.

The results are consistent with the Fort McHenry September 1991 pilot experiment (Pierson, 1992) which had indicated that the running losses were minor. In the present studies we find $15 \pm 3\%$ nontailpipe NMHC at Fort McHenry and $16 \pm 4\%$ at Tuscarora. Since the RVP values of the fuels (average 6.8 at Fort McHenry, 8.2 at Tuscarora) bracket the nationwide average for summer 1992 gasolines (7.7; Dickson, 1993), this result appears applicable nationally, at least in summer 1992.

The nontailpipe NMHC emission rates at Fort McHenry and Tuscarora were 0.09 and 0.05 g mi$^{-1}$, respectively. As low as these percentages and g mi$^{-1}$ numbers are, they are still higher than the MOBILE4.1 and MOBILES predictions. A full discussion is given by Gertler et al. (1995).

**Remote sensing.** The CO/CO₂ remote sensing worked extremely well. A comparison was made at Tuscarora between the tunnel bag measurements and the average of the concurrent remote sensing CO/CO₂ ratios on the LD vehicles, during the five sampling runs wherein most (91–94%) of the traffic consisted of LDSI (light-duty spark-ignition) vehicles so that the bag measurements could be directly compared with the remote sensing measurements. The remote sensing beam crosses the road only at automobile tailpipe height and thus usually does not measure diesel exhaust, which, as is evident in Fig. 6, has a much lower CO/CO₂ ratio than does SI-vehicle exhaust.) The result is

$$\left(\frac{\text{CO/CO}_2}\text{RS}{\text{CO/CO}_2}\text{bag}\right) = 1.00 \pm 0.16$$

where RS signifies remote sensing.

Alternatively, one can calculate the CO/CO₂ emission-rate mole ratio for LD vehicles alone (0.033 ± 0.004) from the LD emission rates at Tuscarora as given in Table 4, and compare that with the remote sensing average CO/CO₂ mole ratio for all runs (0.027 ± 0.010, excluding the entrance-sensor measurement of HD diesels in Run 11), and find

$$\left(\frac{\text{CO/CO}_2}\text{RS}{\text{CO/CO}_2}\text{bag,LD}\right) = 0.83 \pm 0.32$$

where LD signifies the ratio for light-duty vehicles alone.

This was a severe test of CO/CO₂ remote sensing. The CO/CO₂ ratios correspond to exhaust levels of only ~ 0.35% CO, whereas averages more typical of U.S. roadway traffic are in the 1% range (e.g. Bishop et al., 1993; Lawson et al., 1990; Peterson and Stedman, 1992; Stephens, 1994; Stephens and Cadle, 1991). The LD-vehicle ethene/acetylene emission-rate mass ratios $-2.9 \pm 0.6$ at Fort McHenry and $3.7 \pm 0.5$ at Tuscarora—are indicative of cars with catalytic converters properly working. The ratio should be $\geq 4$, vs ~ 1 for a car without a properly working—or any—catalytic converter; see e.g. Black et al. (1980), Hoekman (1992), Siegl et al. (1994), Sigsby et al. (1987), and Stump et al. (1992). So are the low formaldehyde emission rates (Tables 3 and 4—compare with e.g. Siegl et al. (1994)).

At Fort McHenry the CO/CO₂ comparison between remote sensing and bag or FTIR measurements was less satisfactory. As for the drive-by comparisons with the instrumented GM and EPA test cars at Fort McHenry, agreement with remote sensing was excellent uphill but not downhill. The fuel-specific CO emission rates extracted from the remote sensing CO/CO₂ ratios at Fort McHenry, assuming a fuel density of 0.7406 g cm$^{-3}$ as quoted by Stump et al. (1992) for the national average test fuel density and assuming a fuel empirical formula C$_n$H$_{1+0.2S}$, were the same uphill and downhill, viz. 236 ± 20 g gal$^{-1}$. This is consistent with the figure given by Guenther et al. (1994) for 4 yr old vehicles throughout the United States and Canada, and is fairly consistent also with the figures from the bag measurements (Table 6).

Results of the HC/CO₂ remote sensing comparisons were poor. The exceedingly low NMHC emission rates (Tables 3 and 4) are undoubtedly responsible for some of the difficulty. Also, the remote sensor response per C atom is not uniform over all species; and the remote sensing measurement includes methane while the NMHC measurement, by definition, does not.

The possibility of vehicles that are intermittent high emitters (e.g. Cadle and Stephens, 1994) was evaluated by using license-plate readings to trace vehicles between two remote sensors measuring CO/CO₂ ratios, 1235 m apart (Fort McHenry) or ~1625 m apart (Tuscarora). The conclusion is that vehicles that were low CO emitters tended to be consistently low but that, among the minority that were high emitters, consistently high CO emitters were less common than intermittent emitters. High emitters are known to be unstable in their CO and HC emissions, presumably as a result of the lack of control of the air/fuel ratio (Siegl et al., 1994); this is seen in the form of drift in emissions, but probably should show up as erratic behavior, depending on the failure cause.

At the end of the Tuscarora experiment, some exploratory remote sensing data on HD diesels were obtained: $\langle \text{CO/CO}_2 \rangle = 0.009 \pm 0.001$ (mole ratio), $\langle \text{HC/CO}_2 \rangle = 0.002 \pm 0.001$ (carbon-atom ratio), $n = 60$. For comparison, the Tuscarora HD emission rates determined from the bag/canister/Tenax data by weighted regression (Table 4) gave carbon-atom ratios CO/CO₂ $= 0.0059 \pm 0.0016$ and NMHC/CO₂ $= 0.0014 \pm 0.0004$. 
The remote sensing work in these experiments gave rise to several technological improvements described by Bishop et al. (1994) and Guenther (1992). The remote sensing experiments at Fort McHenry and Tuscarora are discussed in detail by Bishop et al. (1995).

SUMMARY

Real-world emission rates of CO₂, CO, NMHC species, total NMHC, NO, NOₓ, and carbonyl compounds from motor vehicles in highway driving have been determined. (Details in Bishop et al. (1994, 1995), Gertler et al. (1995), Robinson et al. (1995b), Sagebiel et al. (1995), and Zielinska et al. (1995).) We were able to determine the light-duty-vehicle (LD) emission rates and the heavy-duty-vehicle (HD) emission rates by regression analysis, but we were unable to resolve the HD component further into spark-ignition and diesel components. The LD NMHC emissions have been resolved into exhaust and nonexhaust components. Some 200 organic species were identified and their emission rates from LD and HD vehicles were determined, as well as the reactivity of the organic emissions with respect to O₃ formation. The emission rates have been compared with the predictions of current federal emissions models (MOBILE4.1, MOBILE5). Infrared remote sensing has been evaluated in the tunnels by comparing its CO/CO₂ ratios and HC/CO₂ ratios against the other measurements in the tunnels. Some of the main results from this work are:

- Emissions are usually predicted to within ±50% by the models, although there is a tendency to overprediction, especially by MOBILE5 and especially at Tuscarora. HD NOₓ generally agrees, however. And MOBILE4.1 does underpredict LD CO, LD NMHC, and LD NOₓ at Fort McHenry.
- CO/NOₓ and NMHC/NOₓ ratios are close to, but slightly higher than, the predicted ratios. LD CO/NOₓ ratios and LD NMHC/NOₓ ratios are within the predicted ranges or slightly underpredicted. HD CO/NOₓ ratios are marginally overpredicted. HD NMHC/NOₓ ratios are within the predicted range at Fort McHenry but are overpredicted at Tuscarora.
- This situation contrasts with the 1987 SCAQS tunnel experiment in Van Nuys, California, where CO and HC were badly underpredicted and where CO/NOₓ and HC/NOₓ ratios were also badly underpredicted. The difference probably has to do with factors enumerated in the Results and Discussion section.
- Since the fleets were unusually clean and since transients—notably power enrichment—were lacking at Fort McHenry and Tuscarora, the models might be expected to underpredict in more complex situations such as urban driving.
- The effect of roadway grade upon emissions per mile is too large—a factor of 2 in the present case—to be ignored in emission factor models.
- On a fuel-specific basis, emissions are almost independent of grade.
- LD emissions do not show the predicted steep increase with speed in the 49–59 mi h⁻¹ range.
- There is a distinct difference in NMHC composition between LD and HD emissions, the latter having far more material in the region above C₁₀. This suggests that (1) canisters alone will be inadequate for atmospheric gas-phase HC quantitation, at least in some settings, and that (2) LD and HD vehicle emissions should be resolvable from each other in source-apportionment receptor modeling by use of the NMHC species.
- The reactivity of the organic emissions with respect to O₃ formation was in the range of 0.4–6 grams O₃ per vehicle-mile depending on vehicle type and reactivity scale. Per vehicle-mile, the HD vehicle NMHC emissions possessed a higher reactivity than did the LD vehicle NMHC emissions.
- Per gram of NMHC emitted, the O₃ reactivities of LD and HD NMHC emissions were comparable. Per gallon of fuel consumed, the LD NMHC emissions had the higher reactivity.
- A substantial part of the O₃ reactivity of automotive emissions resides in the aromatic compounds.
- A substantial part of the O₃ reactivity of automotive emissions resides in compounds quantified by Tenax sampling rather than lighter compounds quantified from the canisters.
- Per vehicle-mile, NOₓ emissions and the O₃ reactivity associated therewith were dominated by the HD vehicles.
- HD spark-ignition vehicles are probably not a large contributor to automotive emissions overall.
- Nontailpipe NMHC emissions accounted for ~15% of the LD NMHC at each site. They were generally less than the MOBILE model predictions.
- Remote sensing of LD exhaust CO/CO₂ worked well but LD HC/CO₂ at these low HC emission rates did not do well.
- Remote sensing was successfully applied to initial measurement of CO/CO₂ ratios and HC/CO₂ ratios in HD diesel exhaust.

RECOMMENDATIONS

Eight recommendations emerge:

1. Real-world data should be used in evaluating and refining automotive emission models.
2. Grams per gallon is probably a more stable modeling basis than grams per mile.
Emissions models need to begin incorporating the effect of roadway grade.

Uncertainty estimates need to be incorporated into the models. Power enrichment and other high-load transients need to be incorporated. Other model deficiencies include the present corrections for towing, load, and air conditioning, and the inflexibility in choice of trip length vs speeds. The model speed corrections at high speeds appear to warrant further evaluation.

The HC capabilities of remote sensing must improve if the technology is to be used for quantifying HC emissions from the cleanest vehicles.

A means to determine real-world exhaust-only profiles needs to be devised, so that the relative roles of tailpipe and non-tailpipe emissions can be more clearly discerned.

Important questions about real-world emissions remain that, if they are to be addressed by a tunnel experiment, require a tunnel carrying urban traffic, the kind of traffic that appears to be responsible for most of our automotive-related O₃ pollution.

Repeated studies in an urban tunnel would provide information on the effects of changes in fuels (e.g. do oxygenated fuels reduce on-road CO emissions?—increase on-road NOₓ emissions?), in control technologies, in I/M and AT programs, etc., in a real-world setting.

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Code of Federal Regulations (1989) 40 CFR Ch. 1 (7-1-89 Edn), Part 86, Sec. 86.144-90, (c) (i) (ii).


U.S. Environmental Protection Agency (1993) Unpublished MOBILE5 user's guide, released 26 March 1993 by U.S. Environmental Protection Agency National Vehicle and...
APPENDIX—All rates in g/veh-mi

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*Estimates based on limited data due to loss of some samples.