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Emission from In-Use Heavy-Duty Gasoline Trucks

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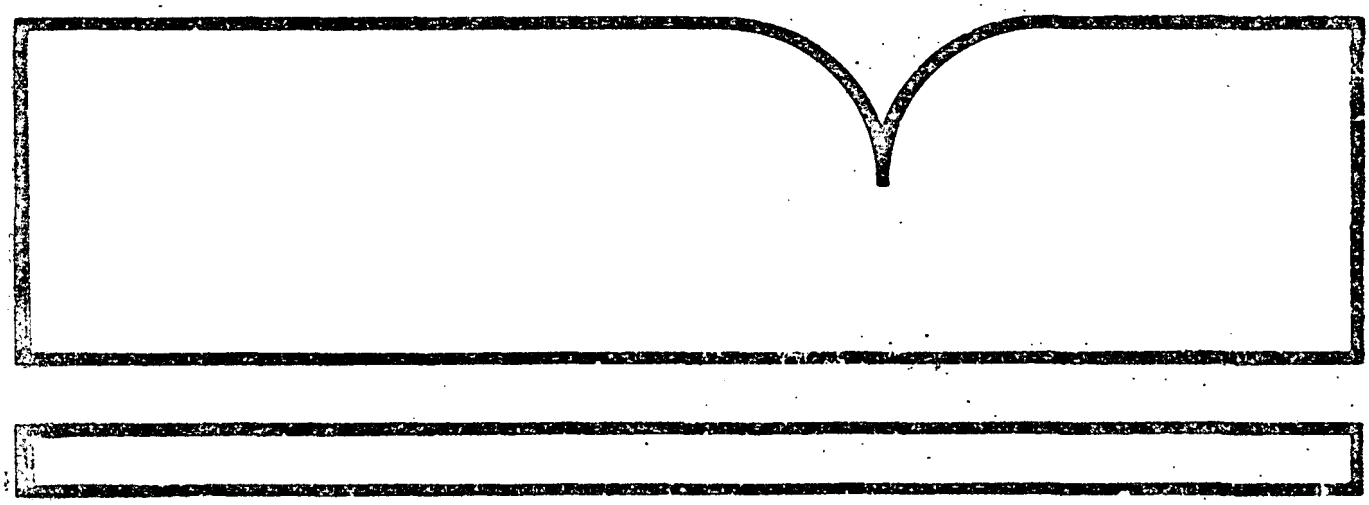

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EMISSION FROM IN-USE HEAVY-DUTY GASOLINE TRUCKS

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ABSTRACT

Apportionment of air pollution to sources requires knowledge of source emission strengths and/or chemical and physical characteristics. The literature is deficient in data useful for this purpose for heavy-duty motor vehicles, which can be important sources of air pollution in certain microenvironments. Emission factors are developed in this study for heavy-duty gasoline trucks using chassis dynamometer simulations of urban driving conditions. The sensitivity of the emissions to such considerations as the characteristics of the speed-time driving schedule, vehicle payload, and chassis configuration are examined. Emissions characterization includes total and individual hydrocarbons, aldehydes, carbon monoxide, oxides of nitrogen, total particulate matter, particulate organics, lead, bromine, chlorine, and the fraction of total particulate less than 2 μm. Preliminary comparisons of emissions obtained using transient engine and transient chassis test procedures are also reported.

AIR POLLUTION CONTROL AUTHORITIES are often tasked with assessment of the relative contribution of various sources, both mobile and stationary, to the degradation of local, regional, and national ambient air quality. This knowledge is necessary to develop and implement control strategies that will achieve the legislatively mandated ambient air quality standards.

Several procedures have been developed in recent years to aid in the apportionment of observed air pollutant concentrations to various sources. Dispersion models have been used with knowledge of the location of sources and receptors, source emission strengths, and the meteorological conditions that transport and disperse the emitted pollutants. Source-receptor models have also been used to estimate the proportional contribution of sources by associating the detailed composition of the various source emissions with the composition of the air at the receptor (1-4).* In their simplest form, a single substance known to be essentially completely emitted by one kind of source is measured in the ambient air. From the source emissions characteristics, the mass ratios of this "tracer" compound to the compounds of interest are determined, and then, by simply multiplying the measured ambient concentrations of the tracer by the ratios, the source contribution to the observed concentrations of the compounds of interest is calculated. This technique has been called the chemical element balance method. Lead has often been used as a tracer or surrogate for mobile source emissions (5,6). Somewhat more complicated approaches use internal ratios of chemical components for various sources in a matrix solution. Since the analysis often involves more than just elemental composition, this method is referred to as chemical mass balance. Other receptor models used for source apportionment include target transformation factor analysis, ridge regression, and multiple linear regression analysis (7-10).

These methods all require knowledge of source emission rates and/or composition. Motor vehicles are difficult sources to deal with because the vehicle characteristics, e.g., size, shape, engine, control devices, fuel, age, and usage pattern are widely variant, and their emissions characteristics are sensitive to these considerations.

*Numbers in parenthesis designate references at end of paper.

Furthermore, the emissions vary with ambient conditions, e.g., temperature, humidity, and barometric pressure. The practice that has developed to accommodate many of these considerations involves determination of baseline emission factors using standardized test conditions with the major categories of motor vehicles, followed by mathematical manipulation to adjust for the characteristics of the vehicle population and operating conditions in the area where air quality is being examined. The computer model used for this purpose, MOBILE 2, permits vehicle-miles-traveled (VMT) weighting of eight primary vehicle categories (11). The standardized test conditions most often used to generate exhaust emission rates with motor vehicles and/or engines are representative of summer urban driving conditions (12). As such, these emission rates must be manipulated in order to be useful for conditions not aligned with the standardized conditions. MOBILE 2 permits estimation of fleet average emission factors by the vehicle mix (trucks, cars, diesel engines, gasoline engines, vehicle age, etc.), with corrections for speed, ambient temperature, and other operating modes different from those examined with the standardized test conditions. Presently the model can be used for total hydrocarbon (THC), carbon monoxide (CO), and oxides of nitrogen (NOx). Modules for particulate emissions and the unregulated emissions do not currently exist.

Sources of the basic emission factor data are many, but the primary source is the Environmental Protection Agency (EPA) administered exhaust emissions surveillance program (13). In this program consumer-owned motor vehicles are examined with test procedures similar to those used for new motor vehicle and/or motor vehicle engine emissions certification. For light-duty motor vehicles these are chassis dynamometer procedures and the emissions are reported in grams per mile (g/mi) units. With heavy-duty motor vehicles the procedures involve engine dynamometer tests and the emissions are reported in work equivalent gram per brake-horsepower-hour (g/bhphr) units. Since vehicle usage patterns are normally defined in terms of miles traveled, it is necessary to convert the heavy-duty g/bhphr values to g/mi values for use in estimating the air quality impact of the emissions from these vehicles.

The efforts reported in this paper were directed at an alternative to conversion of g/bhphr data to g/mi values for heavy-duty motor vehicles. The uncertainty associated with defining the necessary bhphr/mi conversion factors is eliminated by using chassis dynamometer procedures similar to those used with light-duty motor vehicles to develop g/mi emission factors. Regulated THC, CO, and NO_x emission rates were determined; and the unregulated individual hydrocarbon, aldehyde, total particulate, organic particulate, particulate less than 2 μm, lead, bromine, and chlorine emission rates were also examined to support possible source-receptor model applications of the data. Due to facility limitations this program examined only trucks in classes 2B (GVW 8500-10000 lb) to 6 (GVW 19501-26000 lb). Larger trucks and buses are being examined in a similar program sponsored by EPA at Southwest Research Institute, San Antonio, Texas (Contract No. 68-02-3722).

It has been estimated that in 1980 heavy-duty vehicles were responsible for about 10 percent of the THC emissions, 15 percent of the CO emissions, and 34 percent of the NOx emissions from highway motor vehicles (14). It has also been estimated that heavy-duty vehicles were responsible for about 44 percent of the engine-related particulate emissions from highway motor vehicles in 1977 (15). These percentages were based on national average emission factors and VMT. For specific microenvironments, these values could be much higher or lower depending upon the relative miles traveled by heavy-duty and light-duty motor vehicles.

The emission factors reported in this paper are for gasoline heavy-duty trucks operated over urban transient driving routes. Various chassis configurations, transient driving cycles, and payload conditions were examined to study the sensitivity of the emissions to these considerations.

The program is continuing, and a later report will publish data for additional trucks, including diesels.

EXPERIMENTAL PROCEDURES

Many of the historical emissions data for heavy-duty motor vehicles were based on steady-state engine dynamometer test procedures involving a series of 13 operational modes at constant engine speed and load (16). Emissions under the steady-state modes of operation have been mathematically combined to obtain emission rates in grams per brake horsepower hour, grams per kilowatt hour, and grams per kilogram of fuel consumed (17,18). These results are, however, difficult to relate to the mass emitted per unit distance traveled by the vehicles. Further, motor vehicle operation in urban areas generally involves transient conditions of engine speed and load. In 1979, EPA described heavy-duty transient engine test procedures (19) and transient chassis test procedures (20). The first application of the transient chassis test procedures for heavy-duty truck emission rate determinations was reported by Dietzmann et al. in 1980 (21,22).

The transient chassis test procedures

used in this study were also based primarily on the Recommended Practice (RP) of France et al. (20). Laboratory simulation of motor vehicle roadway conditions requires accurate knowledge of engine load as a function of vehicle speed, and a representative transient driving schedule. The RP provides a general equation of the form:

$$RLP = 0.67\ (H-0.75)W + 0.00125\ [LVW - (N \times DW)] \quad (1)$$

where
- RLP = road-load power at 50 mph (horsepower)
- H = vehicle overall height (feet)
- W = vehicle overall width (feet)
- LVW = loaded vehicle weight (pounds)
- N = number of dynamometer rolls supporting a tire
- DW = vehicle weight supported by dynamometer

for determination of the road-load horsepower at 50 mph for dynamometer simulations. The aerodynamic drag component of the RLP is represented by 0.67 (H-0.75)W, the frictional component by 0.00125 LVW, and the dynamometer frictional compensation by -0.00125(N x DW). At the time the RP was written, the power absorbed by the dynamometer at other vehicle speeds was dictated by the mechanical characteristics of a water brake system. This design permitted the operator to select the absorbed horsepower at one speed only, generally 50 mph. Current-technology microprocessor-controlled DC electric dynamometers, as used in this project, provide much greater flexibility for simulation of vehicle road-load. If the road-load can be accurately defined at all vehicle speeds, the dynamometer controller can be programmed to simulate that load.

Roadway coast-down procedures, as defined by the Society of Automotive Engineers, were used to determine road-load as a function of speed for the program test vehicles (23). Several previously reported studies have also used coast-down procedures to examine the road-load characteristics of heavy-duty motor vehicles (24-28). Force-velocity functions were developed at zero wind and zero road grade with the stake-bed and van truck configurations studied under varied payload conditions. Having defined the road-load force functions, losses associated with operating the vehicles on a chassis dynamometer, e.g., frictional losses of the tires on the rolls and the vehicle drive train, were determined for appropriate compensation with the dynamometer control system. These losses were measured directly with each vehicle tested by determining the horsepower required to rotate the vehicle drive train (transmission in neutral) and wheels using the dynamometer DC motor and torque transducer. These measurements were made after the tires were warmed to the temperature of the urban transient driving schedules examined in this project. Final validation of the road-load simulation involved comparison of the speed-time traces obtained coasting the vehicles down on the highway to those obtained coasting the vehicles down on the dynamometer.

Table 1 presents descriptions of the program test vehicles with the road-load horsepower values given at 50 mph. The horsepower values determined by coastdown were generally within 10 percent of those predicted by the RP (excluding dynamometer compensation). An exception was the 1980 Ryder "Gas Saver" chassis, which had rounded vertical and horizontal edges on the van and a substantially reduced aerodynamic drag component of road-load relative to the squared-edge vans. This vehicle had essentially the same frontal area as the 1979 Ford van (83.3 ft.^{2} versus 82.4 ft.^{2}), but about 18 percent less 50 mph road-load. The road-load horsepower increased with vehicle payload as a result of increased tire rolling resistance and frictional losses. Two of the vehicles tested used manufacturer-provided engines to permit comparison of the fuel-specific emission rates obtained using transient chassis procedures to those obtained using transient engine procedures. The engine tests were performed by the manufacturer. Each of the trucks was tested at two inertia simulations, one representing an empty vehicle and a second at about half of rated payload. All vehicles were tested as received, i.e. no engine maintenance was performed.

The RP identifies a transient driving schedule for heavy-duty chassis emissions tests that was based on a computer manipulation of Coordinating Research Council CAPE-21 data (29,30). CAPE-21 was a survey of in-use truck driving patterns obtained by instrumenting approximately 100 trucks and buses operated in and around New York City and Los Angeles. Several questions have been raised by the Motor Vehicle Manufacturers Association (MVMA) as to the representativeness of this cycle (31). The basic contention of the MVMA study was that the mathematical model, the "Markov Model," used to process the data base to representative average over-the-road engine and chassis operational characteristics could not adequately represent actual engine and vehicle operation; that the cycle contained excessive fluctuation of acceleration rate with random up and down shifts in speed; and that attempts to drive the cycle would result in abnormal manipulations of the accelerator and brake pedals with possible abnormal emissions.

Two approaches were used to define

Table 1 - Description of Test Vehicles/Engines

Manufacturer	Chassis	Engine	Odometer, mi	GVW lb	Dynamometer Inertia, lb	Dynamometer Load, HP @ 50 mph
International Harvester	1973 Stake-Bed	V8-345	105,000	20,000	9,819 15,047	47.5 55.4
General Motors	1975 Stake-Bed	V8-350	35,000	25,000	11,150 16,378	43.6 50.4
General Motors	1980 Van (Ryder Gas Saver)	V8-366 (1979)	73,000*	23,000	10,514 15,798	48.8 55.4
Ford	1979** Van	V8-6.1L (1983)	51,000*	19,200	9,920 14,560	60.2 66.4
Ford	1979** Stake-Bed	V8-6.1L (1983)	51,000*	19,200	9,920 14,560	42.9 49.1
Ford	1976 Van	V8-351W	91,000	9,900	6,380 8,215	47.5 50.1

* The engines installed in these chassis have accumulated mileages less than 10,000 mi

** These are actually the same vehicle. The differences lie only in the dynamometer road load simulations which were established to permit examination of the sensitivity of emissions to chassis configuration, i.e. stake bed versus van

transient chassis cycles for the purpose of studying the importance of cycle characteristics to observed emissions in this project. One involved empirical determination of the acceleration-deceleration characteristics typical of heavy-duty trucks being operated in an urban driving situation. Subsequently, the driving schedule of the RP was "smoothed" by removing the unrealistic speed changes. The details of this process are presented in Appendix A. The second approach involved developing driving schedules by operating an instrumented test vehicle in local urban traffic. Fig. 1 illustrates the speed versus time plots of each cycle examined in the project, and Table 2 presents cycle specifications. Fig. 2 displays the first 150 seconds of the RP cycle as defined and as smoothed by filtering at 0.5 Hz, which was determined to be the highest frequency associated with meaningful speed changes for the trucks examined (see Appendix A). The smoothed cycle is well within the acceptable speed tolerances on the original cycle as defined in the RP for satisfactory emissions tests.

The RP cycle has distinct periods associated with Los Angeles and New York nonfreeway driving and with Los Angeles freeway driving. The locally derived cycles also include periods of nonfreeway and freeway driving, in about the same proportions as the RP cycle. The locally derived cycles were developed by operating a truck empty and with about half of rated payload over a designated local road route. The average speed for these local cycles was about 25 mph, as compared to about 19 mph for the RP cycle. The local route was also driven in reverse order to permit examination of the sensitivity of emissions to the location in the cycle of the high-speed freeway driving period.

Specifications for the fuels used in this program are given in Table 3. Tests with the International 345 (1973) and Ford 6.1L (1983) were completed with fuel No. 1; the remainder were completed with fuel No. 2. With regard to particulate lead emissions, it is important to note that fuel No. 1 contains 1.05 g/gal lead; fuel No. 2 contains 1.48 g/gal.

A Burke Porter model 1059 chassis dynamometer was used for inertia and road-load simulation. The system uses 9.5 in. diameter rolls, flywheels, and a DC electric motor with a Reliance digital microprocessor controller for inertia simulation in 1-lb increments from 1,000 to 18,200 lb, and for simulation of the aerodynamic and frictional components of

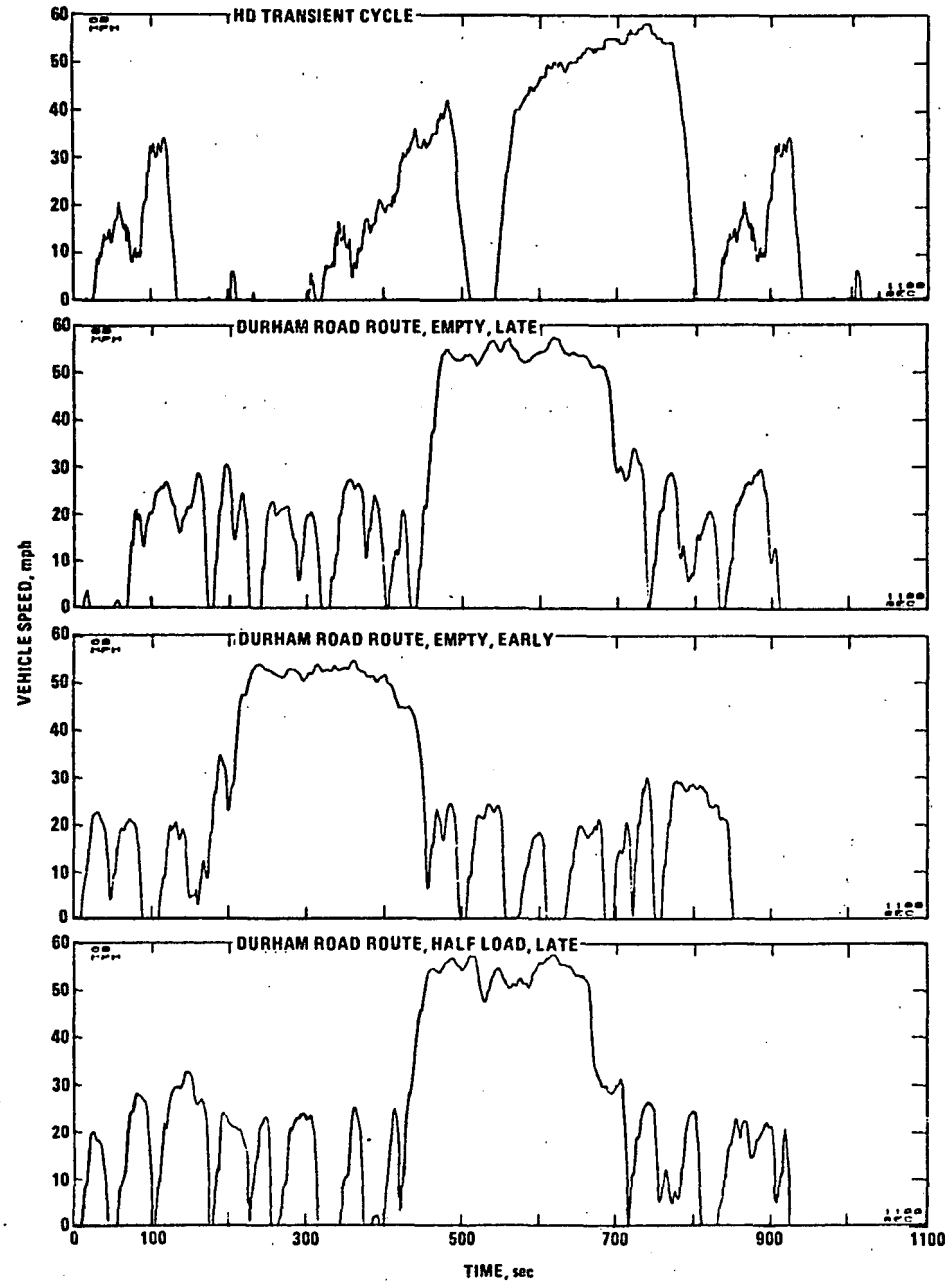

Fig. 1 - Heavy-duty transient cycles

road-load. A Horiba Constant Volume Sampling (CVS) system with selectable flow rate from 200 to 5000 cubic feet per minute (CFM) was used to dilute and sample exhaust for subsequent analysis. This system was operated at 1200 CFM to maintain the diluted exhaust temperatures below 125°F as required for particulate sampling (32). The CVS included an 8 in. diameter dilution tunnel with approximately 25 ft. from the point of initial dilution air mixing to the particulate filtration probe system.

Exhaust characterization included THC, CO, NOx, individual hydrocarbon and aldehyde compounds, total particulate, organic particulate, particulate less than 2μm, lead, bromine, and chlorine. THC, CO, and NOx emission rates were determined using

Table 2 - Transient Test Cycle Specifications

Name	Time, s	Distance, mi	Average Speed, mph
HD Transient Cycle	1,060	5.55	18.86
New York Nonfreeway	254	0.53	7.56
Los Angeles Nonfreeway	285	1.15	14.55
Los Angeles Freeway	267	3.33	44.94
New York Nonfreeway	254	0.53	7.56
HD Transient Cycle - Smoothed	1,060	5.55	18.86
Durham Road Route, empty-late	910	6.39	25.29
Durham Road Route, empty-early	853	5.91	24.96
Durham Road Route, half-late	927	6.37	24.72

Table 3 - Test Fuel Specification

Fuel Type	No.1 Leaded Regular Gasoline	No.2 Leaded Regular Gasoline
Lead (g/gal)	1.05	1.48
Sulfur (wt.%)	0.034	0.034
RVP (PSI)	10.7	8.3
API gravity, 60°F	60.2	60.5
Distillation		
% 65°C	29	26.8
% 118°C	63	65
% 190°C	94	93
End point, °C	211	214
% Recovery	97	97
% Residue	1.0	1.2
Octane, (R+M)/2	89.6	88.6
Gas Chromatography		
% Saturates	64.5	64.9
% Olefins	12.0	15.0
% Aromatics	23.5	20.1

standard flame ionization, nondispersive infrared, and chemiluminescence analytical procedures, respectively. Previously described capillary column gas chromatographic procedures were used to determine individual hydrocarbon compound emission rates (33). This analysis quantified 83 individual hydrocarbon species. The emission rates of 19 individual aldehyde/ketone compounds were determined using 2,4-dinitrophenylhydrazone derivative high-pressure liquid chromatographic procedures (34). Total particulate mass and methylene chloride extractable particulate-phase organic mass were determined using previously described filtration-gravimetric and solvent extraction procedures (33), and the particulate mass less than 2.μm was determined using the cyclone size-selective sampling procedures of John et al. (35). Previously described x-ray fluorescence analytical procedures were used for the determination of lead, bromine, and chlorine emission rates (36).

The emission factors reported in this paper were based on the mean values of a minimum of three repetitions of each test

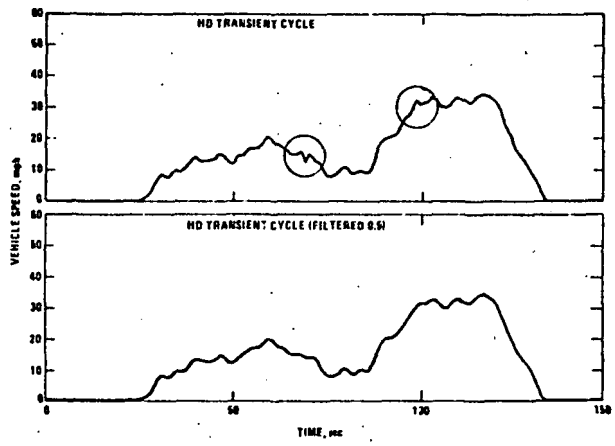

Fig. 2 - Comparison of original and smoothed versions of HDTC (0-150 sec)

condition. Cold start and hot start tests were completed for each cycle, with the composite results based on 1/7 cold start and 6/7 hot start relative weightings. Data quality control included reference to National Bureau of Standards, when possible, for all of analytical procedures.

RESULTS AND DISCUSSION

The objectives of this program included development of emission factors for heavy-duty gasoline trucks using transient chassis dynamometer test procedures with study of the sensitivity of emissions to such considerations as payload, chassis configuration, and driving cycle characteristics used to simulate urban driving conditions. The van and flat-bed/stake-bed trucks studied were tested empty and at about half of rated payload. All of the trucks were tested with the Heavy-Duty Transient Cycle (HDTC) of the RP, and with the appropriate Durham Road Route (DRR) cycles for the payload being examined. The DRR cycles were with "late" freeway driving periods unless otherwise indicated. Tables 4 and 5 present THC, CO, and NOx emission rates and fuel economy for each vehicle and test condition. Hydrocarbon emissions observed with the DRR driving cycle averaged about 55 percent of those with the HDTC; CO emissions averaged about 74 percent. The NOx emission rates were approximately equivalent for the two cycles, with the DRR values averaging about 101 percent of HDTC values. The DRR fuel economies averaged about 124 percent of the HDTC values. It is suggested that the higher THC and CO emission rates and the reduced fuel economy associated with the HDTC driving schedule result from attempting to follow the numerous rapid up and down speed shifts characteristic of this cycle. With carbureted gasoline engines, these driving patterns result in excessive accelerator-pump actuation with associated fuel rich combustion and elevated THC and CO emissions.

To further examine the possibility that the elevated THC and CO emissions were associated with the cycle speed dither, a series of tests were completed permitting comparison of emissions with the original HDTC cycle and the smoothed version of this cycle previously discussed. These tests involved only hot start runs. The results are presented in Table 6. With the smoothed cycle, both the THC and CO emission rates were about 84 percent of the values observed with the original HDTC. An additional series of cycle sensitivity tests were completed to examine the importance of the period of time in the cycle when the high speed freeway driving occurs to the observed emission rates. The emissions results presented in Table 7 suggest that this consideration is insignificant.

The HDTC is based on three distinct driving schedules: the New York Nonfreeway (NYNF), the Los Angeles Nonfreeway (LANF), and the Los Angeles Freeway (LAF) (see Figure 1 and Table 2). These driving schedules include average speeds of 7.6 mph, 14.6 mph, and 44.9 mph for the NYNF, LANF, and LAF routes, respectively, and present an opportunity for examination of the sensitivity of emissions to average speed. The relative emission rates for the three schedules are listed in Table 8 for each truck and payload condition. The final three phases of the hot start tests were used to develop the reported values. The results are normalized to the highest emission factor for each vehicle-payload combination, i.e., 1.00 would be associated with the highest value, 0.56 would indicate emissions at 56 percent of the highest value.

The THC, CO, and NOx results are illustrated in the statistical box-and-whisker plots of Fig. 3, 4, and 5, respectively. Box-and-whisker plots show how a variable is distributed and are useful for comparing variables. The dashed line running across the box represents the median value of the data set. The upper and lower ends of the box mark the quartiles. Half of the observations in a variable lie above the median, and half below it. The quartiles are the medians of each half. The straight lines running out of each end of the box are the whiskers. The length of the box is called the Q-spread. The ends of the whiskers define values within 1.5 Q-spreads. A plus marked value lies between 1.5 and 3.0 Q-spreads; and a square marked value lies outside 3.0 Q-spreads. Each box is notched with a special interval permitting comparison of two boxes. The notch is placed symmetrically around the median at $\pm$ (1.58 x Q-spread)/ $\sqrt{n}$. Two groups whose notched intervals do not overlap are significantly

Table 4- THC and CO Emission Rates*

Truck	Cycle	Test Inertia, lb	THC, g/mi	CO, g/mi
1973				
IH	HDTC	9,819	12.1 ± 1.4	213.6 ± 16.9
Stake		15,047	13.9 ± 1.2	233.1 ± 25.1
	DRR	9,819	6.7 ± 0.3	171.0 ± 13.0
		15,047	7.4 ± 0.3	173.4 ± 7.9
1975	HDTC	11,150	29.6 ± 3.6	211.1 ± 22.5
GMC		16,378	31.4 ± 1.9	237.4 ± 25.3
Stake				
	DRR	11,150	19.4 ± 3.3	185.3 ± 35.0
		16,378	16.9 ± 1.2	203.2 ± 9.2
1980	HDTC	10,514	14.1 ± 1.2	91.4 ± 3.8
GMC		15,798	26.3 ± 2.9	113.7 ± 5.9
Van				
	DRR	10,514	9.8 ± 0.6	51.6 ± 4.3
		15,798	15.8 ± 1.6	74.2 ± 8.9
1979	HDTC	9,920	15.6 ± 1.0	115.5 ± 9.5
Ford		14,560	22.7 ± 2.9	147.6 ± 22.4
Van				
	DRR	9,920	6.7 ± 0.7	78.3 ± 4.9
		14,560	9.1 ± 0.9	104.8 ± 13.0
1979	HDTC	9,920	15.3 ± 2.2	98.8 ± 10.1
Ford		14,560	20.4 ± 3.3	142.4 ± 9.0
Stake				
	DRR	9,920	6.8 ± 0.5	65.4 ± 9.6
		14,560	9.8 ± 0.9	95.7 ± 15.3
1976	HDTC	6,380	6.9 ± 0.4	73.9 ± 8.6
Ford		8,215	10.0 ± 1.1	101.1 ± 11.8
Van				
	DRR	6,380	4.7 ± 0.2	57.5 ± 0.3
		8,215	6.3 ± 0.8	84.1 ± 15.8

* Values based on weighting 1/7 cold start, 6/7 hot start

different at approximately the 5% level. Mean values and associated standard deviations are also given for each speed.

The THC and CO emission rates were clearly speed sensitive, with the higher values associated with lower average vehicle speeds. NOx emissions speed sensitivity was not clearly indicated. The data in Table 8 suggest that the lower inertia van configurations had higher NOx at higher average speeds, but this trend was not apparent with higher inertia and smaller vehicle frontal areas (aerodynamic drag).

Heavy-duty motor vehicles are generally marketed to carry a payload from point A to point B. To study the sensitivity of the emissions to payload, program test vehicles were examined empty and at about half of rated payload. The data in Tables 4 and 5 suggest that THC, CO, and NOx emissions are less when vehicles are operated empty; the empty emission rates were about 80 percent of the half-load rates (THC, 78%, CO, 79%, NOx, 82%).

The data reported for the 1979 Ford permit examination of the sensitivity of urban emissions to chassis configuration. By manipulating the road-load function with the dynamometer controller, this truck was tested as a van and as a stake-bed. As indicated in Table 1, the empty 50-mph road-load horsepower values were 60.2 and 42.9 for the van and stake-bed configurations, respectively, and the half-payload values were 66.4 and 49.1, respectively. The NOx and CO

Table 5 - NOx Emission Rates and Fuel Economy*

Truck	Cycle	Test Inertia, lb	NOx, g/mi	Fuel Economy, mi/gal
1973				
IH	HDTC	9,819	7.2 ± 0.9	4.7 ± 0.9
Stake		15,047	9.4 ± 0.5	4.4 ± 0.3
	DRR	9,819	7.6 ± 0.9	6.5 ± 0.4
		15,047	9.5 ± 0.4	6.0 ± 0.3
1975	HDTC	11,150	8.3 ± 0.7	5.2 ± 0.3
GMC		16,378	10.2 ± 1.3	5.1 ± 0.2
Stake				
	DRR	11,150	6.5 ± 0.3	5.8 ± 0.6
		16,378	11.3 ± 1.3	5.7 ± 0.3
1980	HDTC	10,514	7.0 ± 0.6	5.1 ± 0.1
GMC		15,798	8.3 ± 0.8	4.8 ± 0.2
Van				
	DRR	10,514	7.8 ± 0.3	6.5 ± 0.2
		15,798	8.3 ± 0.5	6.1 ± 0.1
1979	HDTC	9,920	8.3 ± 0.4	5.4 ± 0.3
Ford		14,560	9.5 ± 1.8	4.7 ± 0.2
Van				
	DRR	9,920	7.8 ± 0.5	6.2 ± 0.3
		14,560	9.5 ± 1.0	5.5 ± 0.1
1979	HDTC	9,920	7.3 ± 0.9	5.3 ± 0.6
Ford		14,560	9.4 ± 0.4	4.6 ± 0.1
Stake				
	DRR	9,920	6.1 ± 1.2	6.6 ± 0.4
		14,560	8.0 ± 1.3	5.9 ± 0.4
1976	HDTC	6,380	7.9 ± 0.5	7.8 ± 0.5
Ford		8,215	8.7 ± 0.8	6.9 ± 0.2
Van				
	DRR	6,380	9.6 ± 0.3	9.6 ± 0.2
		8,215	10.3 ± 1.1	8.4 ± 0.3

* Values based on weighting 1/7 cold start, 6/7 hot start

emission rates were somewhat sensitive to the chassis configuration, with the stake-bed values averaging 87 and 89 percent, respectively, of the van values; THC emissions were relatively insensitive to the chassis configuration, with the average stake-bed and van values nearly equivalent. Average fuel economy was about 3 percent higher with the stake-bed simulation.

Considering all of the data collectively, for the vehicles and test conditions examined, THC emission rates ranged from a low value of 4.7 g/mi for an empty class 2B (GVW 8500-10,000 lb) van with the DRR driving schedule to a high value of 31.4 g/mi for a half-loaded class 6 (GVW 19,501-26,000 lb) stake-bed with the HDTC driving schedule. As will be discussed later, the particulate-phase organic emissions from the "high" vehicle were also elevated, suggesting a possible lubricant consumption problem. The CO emission rates ranged from a low value of 51.6 g/mi, again with an empty DRR driving schedule simulation, to a high value of 237.4 g/mi with a half-load HDTC driving schedule simulation. The range of observed NOx emission rates was smaller from a low value of 6.1 g/mi to a high value of 11.3 g/mi, with empty DRR and half-load DRR simulations, respectively. The two gasoline trucks examined by Dietzmann et al. using RP transient chassis test procedures had THC and CO emission rates intermediate to these

Table 6 - Comparison of Emissions - HDTC and HDTC (Smoothed) Transient Driving Schedules*

Cycle	THC, g/mi	CO, g/mi	NOx, g/mi	Economy, mi/gal
HDTC	13.4 ± 0.7	104.4 ± 9.1	8.4 ± 0.4	5.5 ± 0.3
HDTC (Smoothed)	11.2 ± 2.5	88.0 ± 9.0	7.2 ± 0.2	5.9 ± 0.1

* Values based on hot start tests

Table 7 - Sensitivity of Emissions to Early and Late Cycle Freeway Driving Periods

Truck	Cycle	THC, g/mi	CO, g/mi	NOx, g/mi	Fuel Economy, mi/gal
1979 Ford Van (1983 engine)	DRR, E	6.8 ± 0.7	76.3 ± 4.1	6.9 ± 1.3	6.6 ± 0.2
	DRR, L	6.7 ± 0.7	78.3 ± 4.9	7.8 ± 0.5	6.2 ± 0.3
1975 GMC Stake	DRR, E	19.2 ± 1.3	174.9 ± 11.6	7.4 ± 0.4	6.2 ± 0.6
	DRR, L	19.4 ± 3.3	185.3 ± 35	6.5 ± 0.3	5.8 ± 0.6

ranges, but slightly higher NOx emission rates at 13-14 g/mi with the trucks tested at 16,000 lb inertia (22). Direct comparison with current EPA mobile source emissions model (MOBILE 2) values is difficult because the model uses VMT-weighted class (2B through 6 for gasoline engines) emission factors with expected increases associated with mileage accumulation (deterioration factors). However, the values being considered for MOBILE 3 heavy-duty gasoline trucks for the model years and mileages associated with the vehicles examined in this project range from about 3 to 11 g/mi THC, 97 to 193 g/mi CO, and 5 to 8 g/mi NOx (37).

The gaseous organic emissions were characterized for individual hydrocarbon and aldehyde composition. A total of 83 hydrocarbon compounds and 19 aldehyde compounds were determined. Hydrocarbon percentage compositions for several of the more abundant compounds and for the major organic subfractions (paraffinic, olefinic, aromatic, and acetylenic) are presented in Appendix B. A summary of the organic subfraction data is given in Table 9. The hydrocarbon compositions varied somewhat from vehicle to vehicle, but were not highly sensitive to the transient driving schedules or vehicle payloads examined. Methane emissions ranged from about 3 to 10 percent of THC, benzene from about 2 to 4 percent of THC, and total olefinic from 15 to 30 percent of THC. The higher-mileage engines had larger olefinic and acetylenic subfractions. The aldehyde emissions are presented in Table 10. As with the hydrocarbon emissions, the percentage compositions of the aldehydes were not highly sensitive to the vehicle loads or transient driving schedules examined. Therefore, the percentage values reported are based on all of the tests with each vehicle. The lower percentage values observed with the 1975 GMC probably resulted from the elevated contribution of lubricant (i.e. oil burning vehicle) to the THC emissions from this truck. The total aldehyde emission rates, based on summation of the 19 compounds

Table 8 - Emissions Sensitivity to Transient Driving Pattern Average Speed

Truck	Load	Test Phase*	Average Speed, mph	Normalized THC	Normalized CO	Normalized NOx
1973 IH Stake	empty	LANF	14.6	0.66	0.72	0.87
		LAF	44.9	0.42	0.59	1.00
		NYNF	7.6	1.00	1.00	0.96
	half	LANF	14.6	0.68	0.72	0.88
		LAF	44.9	0.40	0.58	0.97
		NYNF	7.6	1.00	1.00	1.00
1975 GMC Stake	empty	LANF	14.6	0.79	0.71	1.00
		LAF	44.9	0.24	0.51	0.99
		NYNF	7.6	1.00	1.00	0.90
	half	LANF	14.6	0.84	0.62	0.97
		LAF	44.9	0.24	0.49	1.00
		NYNF	7.6	1.00	1.00	0.95
1979 Ford Stake	empty	LANF	14.6	0.77	1.00	0.87
		LAF	44.9	0.18	0.51	0.76
		NYNF	7.6	1.00	0.99	1.00
	half	LANF	14.6	0.91	0.86	0.91
		LAF	44.9	0.19	0.56	0.67
		NYNF	7.6	1.00	1.00	1.00
1979 Ford Van	empty	LANF	14.6	0.80	0.89	0.76
		LAF	44.9	0.20	0.55	1.00
		NYNF	7.6	1.00	1.00	0.70
	half	LANF	14.6	0.93	1.00	0.90
		LAF	33.9	0.31	0.75	1.00
		NYNF	7.6	1.00	0.95	0.89
1980 GMC Van	empty	LANF	14.6	0.81	0.76	0.84
		LAF	44.9	0.21	0.29	1.00
		NYNF	7.6	1.00	1.00	0.92
	half	LANF	14.6	0.90	0.75	0.88
		LAF	44.9	0.26	0.38	0.82
		NYNF	7.6	1.00	1.00	1.00
1976 Ford Van	empty	LANF	14.6	0.73	0.55	0.61
		LAF	44.9	0.53	0.34	1.00
		NYNF	7.6	1.00	1.00	0.58
	half	LANF	14.6	0.70	0.56	0.79
		LAF	44.9	0.42	0.41	1.00
		NYNF	7.6	1.00	1.00	0.70

* Heavy-Duty Transient Cycle (see Table 2).

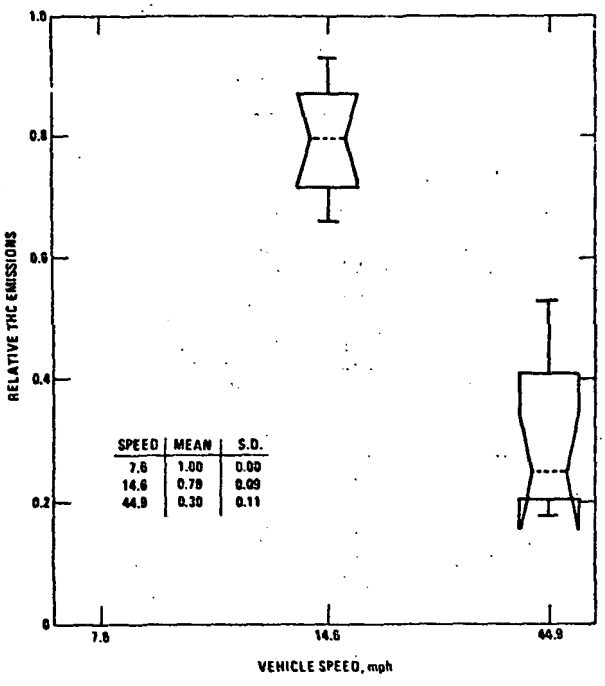

Fig. 3 - Relative hydrocarbon emissions as a function of cycle average speed

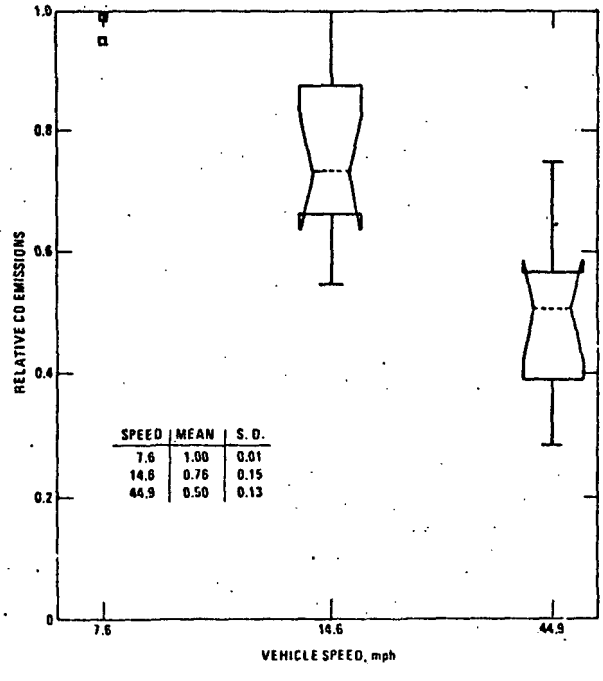

Fig. 4 - Relative carbon monoxide emissions as a function of cycle average speed

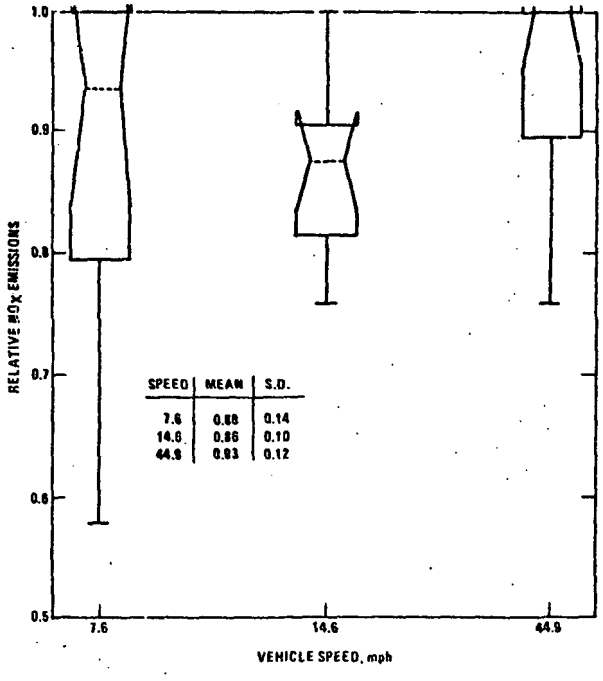

Fig. 5 - Relative oxides of nitrogen emissions as a function of cycle average speed

analyzed, were equivalent to about 6 percent of the THC emission rates. Generally, formaldehyde accounted for about 50 percent of the total aldehyde emissions observed.

Particulate emission rates and compositional data are presented in Tables 11 and 12. Total particulate emission rate, the percentage of the total particulate mass extractable with methylene chloride solvent, and the percentage of the total particulate mass less than 2 μm aerodynamic diameter were determined. Elemental analyses for Pb, Br, and Cl were also completed and are reported for the fine (less than 2 μm) particulate. The data for the 1979 Ford with the low-mileage 1983 engine were highly erratic, with abnormally large proportions of coarse particulate matter, suggesting less than adequate mileage accumulation (break-in) for particulate emissions measurement. Excluding the 1979 Ford data, the total particulate emission rates ranged from about 0.14 g/mi to 0.54 g/mi. The DRR emission

Table 9 - Hydrocarbon Emissions Composition*

Truck	Weight Percentage of THC (ranges from Appendix B)			
	Paraffinic	Olefinic	Aromatic	Acetylenic
1973,IH	38.7 - 42.2	25.8 - 29.7	22.0 - 23.9	8.5 - 9.0
1975, GMC	48.7 - 52.9	15.0 - 19.1	24.0 - 30.0	4.5 - 5.5
1976, Ford	39.6 - 44.1	25.3 - 26.8	22.7 - 24.2	8.0 - 9.4
1979, Ford ('83 eng.)	46.1 - 49.6	14.9 - 16.9	30.6 - 33.7	3.7 - 4.7
1980,GMC ('79 eng.)	47.9 - 52.1	17.4 - 18.6	25.5 - 29.5	4.0 - 5.0

* Values based on weighting 1/7 cold start, 6/7 hot start

Table 10 - Aldehyde Emissions

Truck	Weight Percentage of THC	
	Formaldehyde	Total Aldehyde
1973, IH	3.69 ± 0.51	6.67 ± 0.95
1975, GMC	1.17 ± 0.15	2.82 ± 0.35
1979, Ford ('83 eng.)	2.79 ± 0.24	5.82 ± 0.79

* Values based on weighting 1/7 cold start, 6/7 hot start.

rates averaged about 74 percent of the values observed with the HDTC, and the empty-payload rates averaged about 86 percent of the half-payload values. Methylene chloride extractable organic mass ranged from about 15 to 30 percent of the total particulate mass, except for the 1975 GMC truck, which had values from 35 to 45 percent. Although further characterization of the particulate organics was not undertaken in this project, it has been reported that particulate organic emissions from leaded gasoline engines are active in the Ames bioassay, suggesting the presence of mutagenic compounds, and that polynuclear aromatic (PNA) compounds such as benzo(a)pyrene and nitropyrene are present (38).

There were no apparent sensitivities of particulate size distribution or Pb, Br, and Cl emission fractions to the driving cycles or vehicle payloads studied, and therefore, the remainder of the particulate data will be reported by truck only, representing averages of all cycles and payloads tested. Size-selective examination of the particulate emissions indicated a range of from 12 to 90 percent with aerodynamic diameters less than 2 μm . The low value was associated with a low mileage engine and resulted from a relatively high emission rate of coarse break-in or wear products; the high value was associated with an engine emitting excessive organic aerosol which is generally characterized by fine liquid droplets (39). A fine particulate (less than 2 μm) emission rate of between 35 and 60 percent of the total particulate rate would appear normal for the vehicles examined. It should be noted that the total particulate rate was defined using a laboratory dilution tunnel and that very large particles (greater than about 300 μm) are lost to the walls of the tunnel due to gravitational settling and therefore could not be "counted" (40). Table 12 presents Pb, Br, and Cl data for the fine particulate emissions. Excluding the 1975 GMC data, Pb constitutes about 30 to 45 percent of the total less than 2 μm particulate emissions. Lead is emitted from motor vehicle engines primarily as the halide PbClBr, and secondarily as binary complex compounds of PbClBr and NH_4Cl (41). The mass ratios of Pb to Br to Cl observed in this study were consistent at about 59 to 33 to 8. The theoretical ratios for PbClBr would be 64 to 25 to 11. The observed Br/Pb mass fraction of 0.56 is substantially higher than the 0.2 value typical of atmospheric aerosols (42-45). However, a reduction of this fraction on atmospheric aging has been indicated by Pierson and Brachaczek, who observed lower ratios outside of roadway tunnels than inside (e.g., 0.51 inside the Detroit and Canada Tunnel and 0.30 outside 16 m above street level; 0.42 inside the Allegheny Tunnel and 0.15 a few

hundred meters outside of the exit) (46).

Two of the program trucks were fitted with engines provided by the manufacturers to permit comparison of fuel-specific emission rates obtained with engine and chassis transient test procedures (the engine tests performed by the manufacturer). The results with a 6.1-L Ford engine are reported in Table 13. The General Motors results will be available at a later date. The greatest differences were observed in THC emissions, where the HDTC chassis rates were about a factor of 3 higher than the engine rates. The CO and NOx rates compared more favorably. It should be noted that Ford used the MVMA version of the engine transient schedule which is smoothed relative to the EPA version. As previously discussed, the high chassis THC rates are related to the driver's attempt to follow the rapid up and down speed shifts characteristic of the HDTC driving schedule.

SUMMARY AND CONCLUSIONS

Efforts by air pollution control authorities to apportion observed ambient air pollutants to sources require knowledge of source emission strengths and/or compositional characteristics. For specific microenvironments, motor vehicles can be very important sources. Motor vehicle emissions are complex and widely variant depending upon chassis (car, truck, bus), engine, fuel, usage pattern, and ambient conditions, among other considerations. Available emissions data for heavy-duty trucks useful for estimation of their air quality impact are very limited. This is due in part to the certification practice for this vehicle category which develops work-specific g/bhphr emission rates rather than the g/mi rates normally required by air quality models.

The effort reported in this paper developed g/mi emission rates and detailed emissions characteristics for a small fleet of leaded gasoline heavy-duty trucks. The sensitivity of the emissions to such considerations as transient driving schedule, vehicle payload, and chassis configuration was studied using laboratory dynamometer simulations.

The following observations and conclusions were made:

1. THC emissions ranged from 4.7 g/mi to 31.4 g/mi, CO emissions ranged from 51.6 g/mi to 237.4 g/mi, and NOx emissions ranged from 6.1 g/mi to 11.3 g/mi.

2. THC and CO emissions were sensitive to the characteristics of the transient driving schedule. The emission rates were higher with the HDTC (taken from the EPA RP) with its characteristic rapid up and down speed shifts than with the locally derived cycles with less speed dither. THC and CO emissions also varied with cycle average speed, increasing as the average speed decreased. NOx emissions were not as sensitive to the cycle characteristics examined.

3. THC, CO, and NOx emissions were elevated by increased vehicle payload. Empty rates were about 80 percent of half-payload rates.

Table 13 - Comparison of Emissions Using HDV Transient Chassis and Engine Procedures with 1983 MY 6.1L-4V Ford Engine

Chassis	Cycle	Payload (inertia)	g/kg fuel THC	CO	NOx
Stake-Bed	HDTC	Empty (9920)	28.3 ± 4.1	182.8 ± 18.7	13.5 ± 1.6
		Half (14560)	32.8 ± 5.3	228.6 ± 14.5	15.1 ± 0.6
	DRR	Empty (9920)	15.8 ± 1.1	151.6 ± 22.3	14.1 ± 2.8
		Half (14560)	20.1 ± 1.9	196.1 ± 31.4	16.4 ± 2.8
Van	HDTC	Empty (9920)	29.4 ± 1.9	217.7 ± 17.9	15.6 ± 3.0
		Half (14560)	37.2 ± 4.8	242.1 ± 36.7	15.6 ± 3.0
	DRR	Empty (9920)	14.4 ± 1.5	169.4 ± 10.6	16.9 ± 1.1
		Half (14560)	17.5 ± 1.7	201.1 ± 24.8	18.2 ± 1.9
Transient Engine Results* (47)			11.7 ± 0.7	254.4 ± 2.8	13.1 ± 0.5

* These results are based on the smoothed MVMA version of the Federal Heavy-Duty Engine Transient Cycle

4. CO and NOx emission rates were somewhat sensitive to the vehicle chassis configuration, with stake-bed rates about 90 percent of van rates.

5. Detailed hydrocarbon composition varied from vehicle to vehicle, but was not highly sensitive to the transient driving schedules or vehicle payloads examined. Methane constituted 3 to 10 percent of the THC, benzene constituted 2 to 4 percent, and olefinic hydrocarbons constituted 15 to 30 percent. Higher olefinic emissions were associated with higher levels of mileage accumulation.

6. Aldehyde emission rates were equivalent to about 6 percent of the THC emission rates. Formaldehyde constituted about 50 percent of the total aldehyde emissions.

7. Total particulate emission rates varied from about 0.14 g/mi to about 0.54 g/mi. The emission rates were higher with the HDTC than with the DRR cycles, and were higher with larger vehicle payloads.

8. The total particulate emissions were generally characterized by about 15 to 30 percent methylene chloride extractable organic mass. Approximately 35 to 60 percent of the particulate mass was less than 2 μm aerodynamic diameter. This fine particulate matter was about 30 to 45 percent Pb. The observed Br/Pb ratio was 0.56.

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APPENDIX A: PROCEDURES FOR SMOOTHING OF TRANSIENT MOTOR VEHICLE DRIVING CYCLES

The transient driving schedule identified for heavy-duty motor vehicle emissions testing in the EPA Recommended Practice (RP) was developed using CAPE-21 in-use truck driving pattern data. These data were processed to the recommended chassis cycle using Markov model mathematical procedures. The Motor Vehicle Manufacturers Association has suggested that this model is inappropriate for the purpose of generating a test cycle representative of heavy-duty motor vehicle driving patterns, and that the resultant cycle has excessive fluctuation of acceleration rates with random up and down speed shifts. Attempts to follow this cycle with its excessive speed dither could significantly influence emissions, particularly with motor vehicles using carbureted gasoline engines.

A procedure has been developed to smooth the cycle, eliminating unrealistic speed dither, and permitting examination of the importance of this cycle characteristic to emissions. Any signal-time display can be examined in the frequency domain by using available Fourier Transform techniques. Actual speed versus time data were obtained

by operating program test vehicles in local urban traffic. The frequency domain for purposeful speed changes and operator speed control system interactions was then examined by establishing the Fourier Transform of the speed-time data. The amplitudes of the frequency components of the recommended cycle not present in the actual roadway driving data were edited to zero in the Fourier Transform listing; subsequently, the inverse transform was generated to define the smoothed cycle.

The Fourier Transform converts time series data into frequency data by calculating the discrete transform:

$$Xd(K) = \sum_{n=o}^{N-1} X(n)e^{-J2\pi n\, K/N} \qquad (A\text{-}1)$$

for K = 0,1.....,N/2.

The original speed data array then contains

D(1), a real number representing the DC (direct current) value of the speed signal; and

D(2), a real number representing the value of the discrete Fourier Transform at the NYQUIST frequency (1/2 the sampling frequency).

The remainder of the array "D" contains the real and imaginary components of the Fourier coefficients. A selected starting point in the array can be set to zero, eliminating or "filtering" the higher-frequency data from the array. The filtered data are then converted back to time series speed data by taking the inverse transform. The mileage associated with the speed-time data array can be readily adjusted to the original mileage. However, experience has indicated this adjustment to be less than 0.1 mi.

Figure A-1 illustrates the product of this process for a section (574 s - 768 s) of the Los Angeles freeway mode of the RP cycle smoothed by filtering at 0.15 Hz. The character of the original speed-time trace is very "blocky", with several rapid up and down speed shifts, all of which were eliminated in the smoothing process. Selection of the frequency appropriate for filtration of the RP cycle involved examination of actual roadway speed-time data in the frequency domain. Figure A-2 illustrates the frequency data for the roadway driving and the RP cycle. The roadway data reach a near constant, low-amplitude "noise" level at about 0.5 Hz, whereas the original cycle continues at high-amplitude over the plotted frequency range. Thus, 0.5 Hz was selected as the frequency for smoothing the RP cycle. As a test of the appropriateness of this

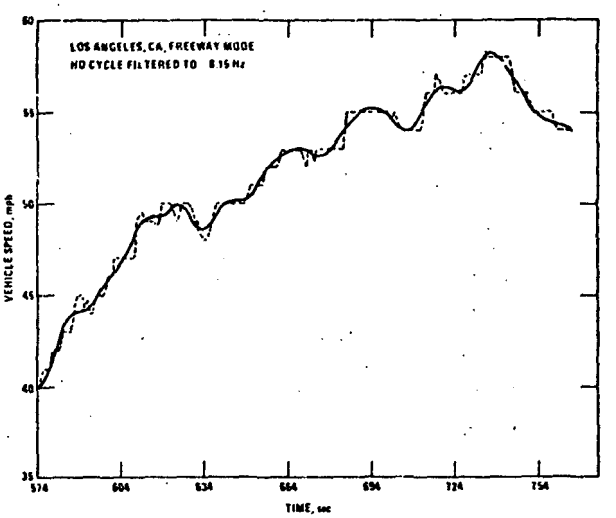

Fig. A1 - Transient cycle smoothing by frequency filtering

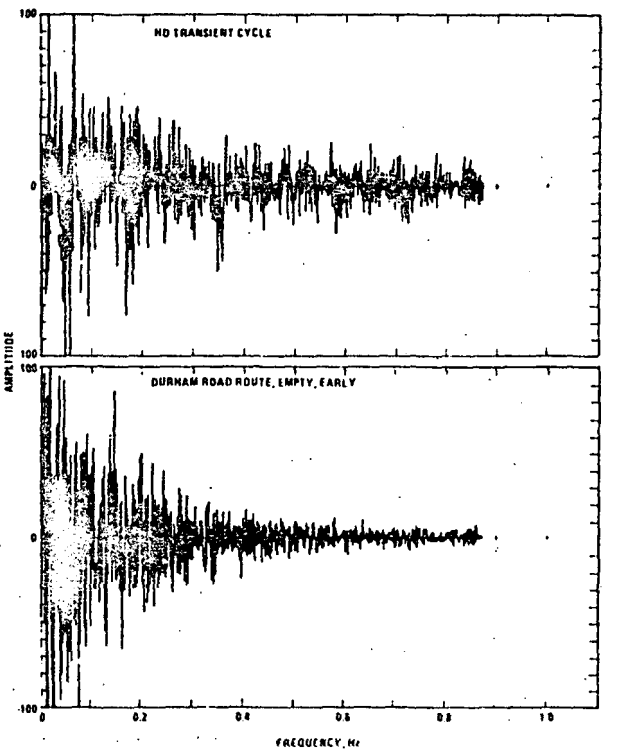

Fig. A2 - Frequencies associated with speed changes in the HDTC and DRR driving schedules

frequency, plots of acceleration rate versus time were examined for both the filtered and unfiltered versions of the RP and local roadway driving cycles. Figure A-3 illustrates sections of these plots scaled to permit ready visualization of changes. With the local roadway data, very little change was observed by filtering at 0.5 Hz; however, significant differences were observed with the RP data (note the different time scales for the two cycles). Filtering at 0.4 Hz caused excessive change to the local road route data. Similar observations were made when comparing the speed-time data.

The described smoothing process permits a cycle to be modified so that it can be followed by a vehicle category of interest. Average speed and trip length are unmodified, and the resultant speed-time trace is within the permitted speed tolerances of the RP on the original cycle.

APPENDIX B: DETAIL HYDROCARBON EMISSIONS COMPOSITION

Tables B1 through B5 detail the hydrocarbon emissions percentage compositions for each truck and test condition examined. A total of 83 compounds were analyzed and appropriate summations were used to determine the percentages in each major organic classification. All values are based on 1/7 cold start, 6/7 hot start relative weightings.

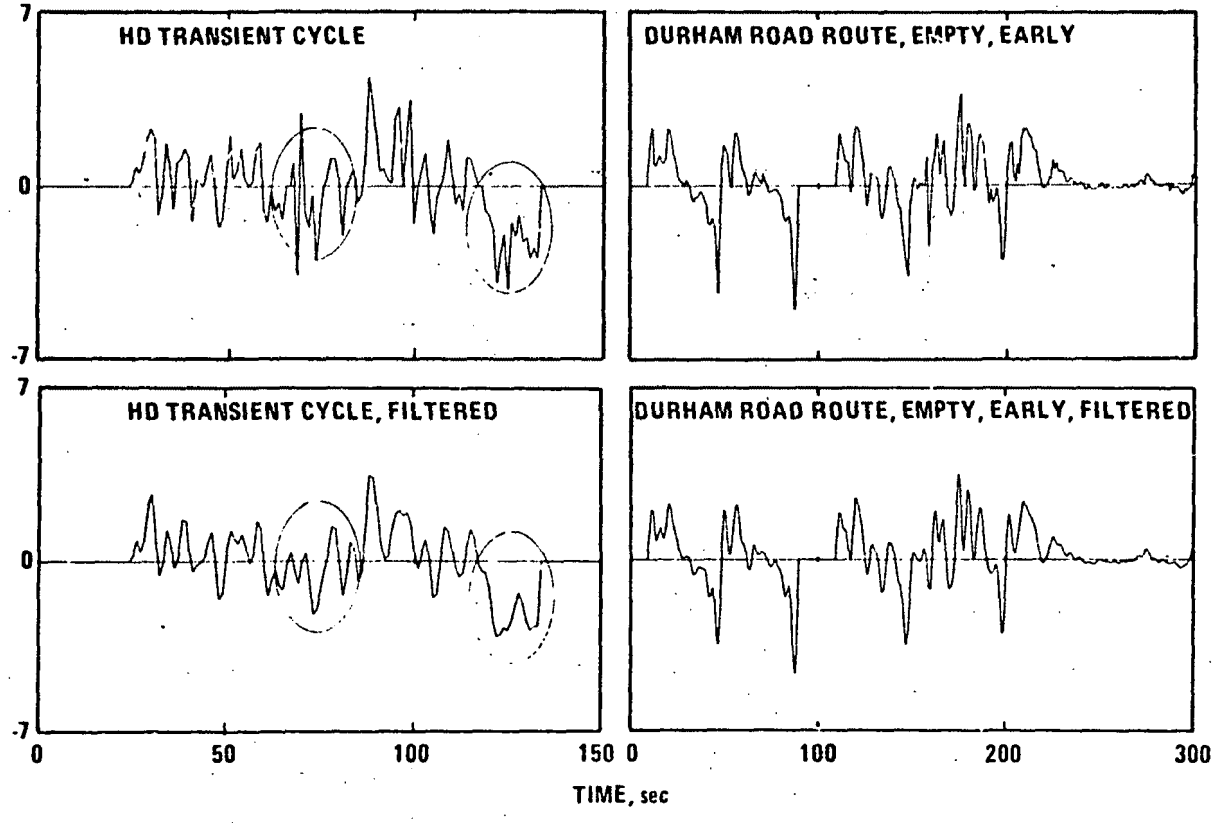

Fig. A3 - Acceleration rates for HDTC and DRR driving schedules, original and filtered at 0.5Hz

Table B1 - 1973 IH Hydrocarbon Emissions Compositions

	Weight Percentage of THC			
	DRR-Empty	DRR-Half	HDTC-Empty	HDTC-Half
Methane	9.7 ± 0.34	9.4 ± 0.55	8.3	8.6 ± 0.35
Ethylene	16.4 ± 0.38	16.0 ± 0.26	12.8	14.3 ± 0.45
Propylene	4.4 ± 1.54	4.8 ± 1.00	4.4	3.6 ± 0.36
N-Butane	5.1 ± 0.18	4.7 ± 0.52	4.1	4.8 ± 0.16
Isopentane	3.3 ± 0.21	3.0 ± 0.54	2.9	3.3 ± 0.13
N-Pentane	1.9 ± 0.14	1.5 ± 0.21	1.7	1.8 ± 0.06
Isooctane	0.7 ± 0.04	0.8 ± 0.06	0.8	0.9 ± 0.07
Benzene	3.9 ± 0.20	4.0 ± 0.11	3.1	3.5 ± 0.10
Toluene	4.9 ± 0.03	5.0 ± 0.11	4.2	4.7 ± 0.16
Paraffinic	39.2 ± 0.71	38.7 ± 1.34	42.2	40.6 ± 0.59
Olefinic	29.7 ± 1.10	29.5 ± 1.64	25.8	26.5 ± 0.82
Aromatic	22.0 ± 0.72	22.9 ± 0.32	23.5	23.9 ± 0.71
Acetylenic	9.0 ± 0.64	9.0 ± 0.03	8.5	9.0 ± 0.30

Table B2 - 1975 GMC Hydrocarbon Emissions Compositions

	Weight Percent of THC			
	DRR-Empty	DRR-Half	HDTC-Empty	HDTC-Half
Methane	3.7	4.1 ± 0.73	3.6 ± 0.21	4.1
Ethylene	4.9	6.4 ± 0.42	5.9 ± 0.42	6.5
Propylene	2.3	2.2 ± 0.33	2.4 ± 0.55	2.3
N-Butane	4.7	1.6 ± 0.36	3.0 ± 0.63	2.3
Isopentane	4.5	2.6 ± 0.94	3.7 ± 0.18	2.9
N-Pentane	2.8	1.6 ± 0.79	2.2 ± 0.12	1.9
Isooctane	2.1	1.1 ± 0.37	1.4 ± 0.19	0.7
Benzene	2.6	2.3 ± 0.89	2.7 ± 0.13	2.4
Toluene	5.6	3.6 ± 1.33	4.6 ± 0.33	3.9
Paraffinic	49.5	52.9 ± 6.41	48.7 ± 0.73	51.0
Olefinic	15.0	18.7 ± 1.84	17.2 ± 0.76	19.1
Aromatic	30.0	24.0 ± 7.20	28.8 ± 0.87	24.5
Acetylenic	5.5	4.5 ± 1.04	5.3 ± 0.37	5.4

Table B3 - 1980 GMC Hydrocarbon Emissions Compositions

	Weight Percentage of THC			
	DRR-Empty	DRR-Half	HDTC-Empty	HDTC-Half
Methane	2.4 ± 0.26		3.3	
Ethylene	4.0 ± 0.21		5.8	
Propylene	1.9 ± 0.17		1.6	
N-Butane	2.3 ± 0.09		2.9	
Isopentane	2.6 ± 2.14		5.0	
N-Pentane	1.5 ± 1.21		2.9	
Isooctane	1.2 ± 0.12		1.0	
Benzene	2.3 ± 0.16		2.2	
Toluene	3.9 ± 1.74		5.7	
Paraffinic	47.9 ± 6.40		52.1	
Olefinic	18.6 ± 3.46		17.4	
Aromatic	29.5 ± 3.47		25.5	
Acetylenic	4.0 ± 0.35		5.0	

Table B4. 1979 Ford Hydrocarbon Emissions Compositions

	Weight Percentage of THC			
	DRR-Empty	DR2-Half	HDTC-Empty	HDTC-Half
Methane	2.7 ± 0.24	2.8	3.1 ± 0.10	3.4
Ethylene	4.5 ± 1.12	4.8	5.8 ± 0.17	5.7
Propylene	2.1 ± 0.51	2.1	2.3 ± 0.42	2.5
N-Butane	4.3 ± 0.67	2.9	3.4 ± 0.16	2.8
Isopentane	3.6 ± 0.86	2.7	2.7 ± 0.12	2.6
N-Pentane	2.4 ± 0.36	2.0	1.9 ± 0.08	1.8
Isooctane	0.9 ± 0.11	0.8	0.7 ± 0.05	0.7
Benzene	2.2 ± 0.22	2.3	2.5 ± 0.07	2.5
Toluene	4.9 ± 0.12	5.0	4.8 ± 0.26	4.7
Paraffinic	49.6 ± 3.63	47.7	46.1 ± 0.77	47.8
Olefinic	15.4 ± 1.39	14.9	16.4 ± 0.66	16.9
Aromatic	31.3 ± 3.11	33.7	33.0 ± 1.02	30.6
Acetylenic	3.7 ± 0.28	3.7	4.5 ± 0.26	4.7

Table B5. 1976 Ford Hydrocarbon Emissions Compositions

	Weight Percentage of THC			
	DRR-Empty	DRR-Half	HDTC-Empty	HDTC-Half
Methane		6.1 ± 0.35	6.3	4.9
Ethylene		12.3 ± 0.18	11.2	10.5
Propylene		5.3 ± 0.17	5.2	4.8
N-Butane		2.9 ± 0.40	2.7	3.0
Isopentane		2.9 ± 0.43	2.7	3.2
N-Pentane		2.2 ± 0.04	1.7	2.0
Isooctane		0.9 ± 0.22	0.6	0.6
Benzene		4.2 ± 0.07	3.7	3.8
Toluene		5.1 ± 0.38	4.4	4.4
Paraffinic		39.6 ± 0.31	41.3	44.1
Olefinic		26.8 ± 0.73	26.3	25.3
Aromatic		24.2 ± 1.31	24.2	22.7
Acetylenic		9.4 ± 0.31	8.2	8.0

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