Technical Report

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Exhaust Emissions and Fuel Consumption of a Heavy-Duty Gasoline Powered Vehicle Over Various Driving Cycles

427 Cubic Inch 1977 California GMC 6500

by

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NOTICE

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
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Abstract

This report presents exhaust emission and fuel economy measurements for one heavy-duty gasoline fueled vehicle operated over various driving cycles. These driving cycles were developed from actual in-use operational data collected in New York and Los Angeles under the CAPE-21 program. In each location, both freeway and non-freeway operational parameters were recorded. A data matrix (relating speed, acceleration and frequency of occurrence) was prepared for each city and class of operation. Several different driving cycles were generated for each matrix.

Evaluation of the concept of chassis testing for heavy-duty vehicles was the major purpose of this project. The test program was designed to measure the sensitivity of exhaust emissions and fuel economy to the various driving cycles and road load conditions. In addition, a brief attempt was made to characterize cold start emissions and the effects of increased vehicle frontal area. Three of the fully transient cycles were "linearized" (steady state cruises and constant accelerations) to see if a simpler type of transient operation could accurately predict fuel economy. Finally, experiments were undertaken to measure the instantaneous exhaust dilution ratio in order to assess the adequacy of the CVS flow rate.

Several significant conclusions can be drawn. It is possible to test vehicles up to approximately 15,000 kg inertia on a chassis dynamometer using transient driving cycles. Emissions over different driving cycles (representing the same category of operation) vary more than would be expected from the test variability. "Linearized" cycles give lower HC and CO emissions than their fully transient counterparts.

The following average emission and fuel consumption values were observed for half load conditions:

	HC (g/km)	CO (g/km)	NOx (g/km)	litre/100 km Fuel
New York Non-Freeway	3.6	137	3.8	73
Los Angeles Non-Freeway	1.5	84	4.1	53
New York Freeway	2.0	107	5.2	48
Los Angeles Freeway	0.9	75	6.3	47

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I. Objectives

The test program had the following six major objectives and questions to answer:

1. The first major objective of this program was to evaluate the capability of EPA's large tandem axle heavy-duty electric dynamometer for emission testing purposes. The test vehicle's size necessitated the use of a large 1.2 m^3/s CVS (Constant Volume Sampler) unit. (Most of the remaining test equipment was identical to that used in light-duty vehicle testing and did not need further evaluation.) An attempt was also made to determine the relationship between standard CVS hydrocarbon measurements and the HFID (Heated Flame Ionization Detector) system used for diesel vehicles.

2. Assuming that exhaust emissions can be accurately measured, it was desired to evaluate the sensitivity of emissions and fuel consumption to the various driving cycles and vehicle loads. The test vehicle was run at three different road load conditions (simulating empty, half and full loads) over the driving cycles. It was desired to determine the variation among the cycles representing one category (e.g., all New York non-freeway cycles) as well as the difference between categories (e.g., New York non-freeway to Los Angeles freeway).

3. The effect of cold start operation on emissions and fuel consumption was also to be investigated.

4. Could "linearized" transient cycles, similar to the old light-duty vehicle 7-mode test, accurately simulate the fuel consumption observed on the full transient test cycle?

5. What is the effect of frontal area (or "windage") on emissions and fuel consumption?

6. What size of CVS is necessary for testing large heavy-duty vehicles?

II. Summary of Results

The emission results obtained in this experiment are representative of one truck only. It would be a grave mistake to make judgments based on one vehicle whose characteristics might be significantly different than the general population. This point cannot be over emphasized. Further testing of different vehicles is necessary before any firm general conclusions can be drawn. In light of this qualification, the following results can be stated:

1. In spite of many teething problems, it is entirely possible to test heavier gasoline fueled vehicles on EPA's large tandem axle dynamometer.

It is certainly a more difficult process than automobile testing due to the vehicle size and general configuration of the test cell. The large CVS functions adequately; however, further work should be done on calibration and maintenance procedures. A more accurate method of determining and setting vehicle road load is also required.

Agreement between the integrated continuous HFID and standard CVS hydrocarbon results was not very good. The HFID averaged 8% higher with variability of ± 40%. No explanation is available. More work must be done with probe location, calibration, and integrator operation to correct this difficulty.

2. Significant variations occur between driving cycles generated from the same category (e.g., New York non-freeway). It is unclear why this occurs, since each cycle passes the same statistical criteria and is drawn from the same data matrix. As might be expected, there are also significant differences from category to category.

3. Cold start operation causes a significant increase in emissions and fuel consumption. Typically, a five minute cold start test will show approximately five times as much hydrocarbon, twice as much CO and NOx, and about twenty percent more fuel consumption than a fully warmed-up five minute test. These effects generally disappear after about ten minutes, or two warm-up cycles.

4. Linearized transient cycles (using straight acceleration and deceleration ramps, and steady state cruises) do not accurately duplicate the emissions measured over full transient cycles. Very roughly, the linearized cycles gave half the HC and CO emissions; while NOx and fuel consumption remained about the same.

5. As expected, increasing the simulated frontal area caused increased fuel consumption and emissions. However, a slight decrease in NOx was observed at the largest frontal area tested; this is possibly due to increased EGR at high power levels.

6. A constant volume sampler with a capacity of 1.2 cubic metres per second appears to be adequate for gasoline engine vehicles. This flow rate was adequate even when testing at 12,800 kilograms of simulated inertia.

III. Description of Experiment

A. Vehicle

The test vehicle was a 1977 model GMC 6500 cab-over chassis. Its GVWR was 13,760 kilograms, it had an empty weight of 3725 kilograms. It was equipped with a 7.0 litre V-8 engine with a 7.5 compression ratio and a four barrel carburetor. This engine belongs to the GM 114 family, and was certified to the California emissions standards. The engine was equipped with a canister, throttle return control (throttle kicker), air pump, exhaust gas recirculation and sodium cooled valves. An Allison four-speed automatic transmission was used (MD 1714) with a 7.17 rear axle ratio. Four 11.00 x 20 tires were on the single rear driving axle.

B. Equipment

A heavy-duty Labeco dual roll chassis dynamometer was used for all testing. (As the test truck had a single drive axle, the front dynamometer rolls were disconnected.) This dynamometer has a roll diameter of 1.02 metre, a mechanical inertia of approximately 5400 kilograms in the single roll configuration and can electrically simulate inertia from 2700-50,000 kilograms. Road load force can be simulated by various dynamometer circuits that control the constant, first and second order speed contributions. The dynamometer has motoring capability and can be used at speeds up to 100 km/h. A constant speed cooling fan was used for all testing.

Operational data from the vehicle and dynamometer was recorded on magnetic tape for later computer analysis. Data collected included manifold vacuum, engine RPM, vehicle speed and roll speed. This data was recorded at one second intervals during all testing.

Emission measurement equipment conformed with the light-duty vehicle certification regulations. The only major exception was the use of a 1.2 cubic metre/second CVS (critical flow venturi unit) to handle the increased exhaust flow of the heavy-duty truck. In addition to this normal emission measurement equipment, a HFID and CO_2 analyzer were used to monitor the dilute exhaust flow continuously. (This last equipment was discontinued approximately half-way through the test sequence to reduce testing manpower requirements.)

C. Driving Cycles

Driving cycles for this experiment were developed from actual in-use data collected and analyzed under the CAPE-21 project. In-use vehicles were instrumented in New York City and Los Angeles. Data was collected for freeway and non-freeway operation; it was later organized into separate data matrices. The combination of two cities and two types of driving gives four operation categories.

For each category of operation, a data matrix was compiled. This matrix contains information concerning speed, rate of change, and frequency of occurance. (Several other parameters relating to engine operation were also included in the data matrix; however, these are of no concern here.) Since the data logger operated every 0.864 seconds, the data matrix also reflected that time basis. Drivng cycles were generated using computer programs developed for the CAPE-21 project.

The driving cycles created for this test program used a 1.0 second interval between points. However, as the data matrix had a 0.864 second time basis a slightly "streched out" driving pattern results. Speed distributions will be identical, but all accelerations and decelerations will be less severe than actual truck operation. This course was dictated by the equipment and data transformation programs then available.

Three cycles, 11 through 13, were hand created linearizations of cycles 7 through 9. These linearized cycles are still transient, but the acclerations and decelerations are all at a constant rate. Fluctuating cruise conditions have been changed to steady state. Finally, cycle 14 is the light-duty certification driving schedule, better known as the LA-4.

The fourteen driving cycles used in this test program are summarized in Figure 1. The relationship between average speed and percent idle is indicated in Figure 2A.

In reproducing the driving cycle on the dynamometer, a strip chart showing desired vehicle speed versus time was prepared. The vehicle driver would manually control the acceleration during the test to follow the desired speed trace. Sample speed versus time charts for each of the four cycle categories are shown in Figure 2B to illustrate the driving patterns associated with each category.

D. Test Matrix

Originally it was planned to test the vehicle at three road conditions (empty, half and full loads) on all driving cycles. For each combination, three emissions tests were to be run. This was accomplished, but the throttle kicker was maladjusted which resulted in erratic engine idle speeds. After this problem was corrected, an abbreviated test matrix was run. This included most driving cycles at half load with one driving cycle for each major category at full and empty load conditions. The final test matrix is indicated in Figure 3. All data collected when the engine was maladjusted have been omitted.

Four cold start tests were run on the vehicle. These tests are also indicated on Figure 3. In addition, a sequence of five tests was run to simulate various frontal areas using drivng cycle 04 (New York freeway). This was accomplished by adjusting the "windage" control on the chassis dynamometer. Finally, a chassis version of the 9-mode engine certification test was run.

E. Test Procedure

All emission testing, except for cold starts, was done with the dynamometer warmed-up. The dynamometer would be operated for approximately 15 minutes at about 50 km/h until the dynamometer gear box reached operating temperature. The emission tests would be started with the engine idling and the transmission in drive. The emission tests were run just like the light-duty vehicle certification procedure, the only difference

Figure 1

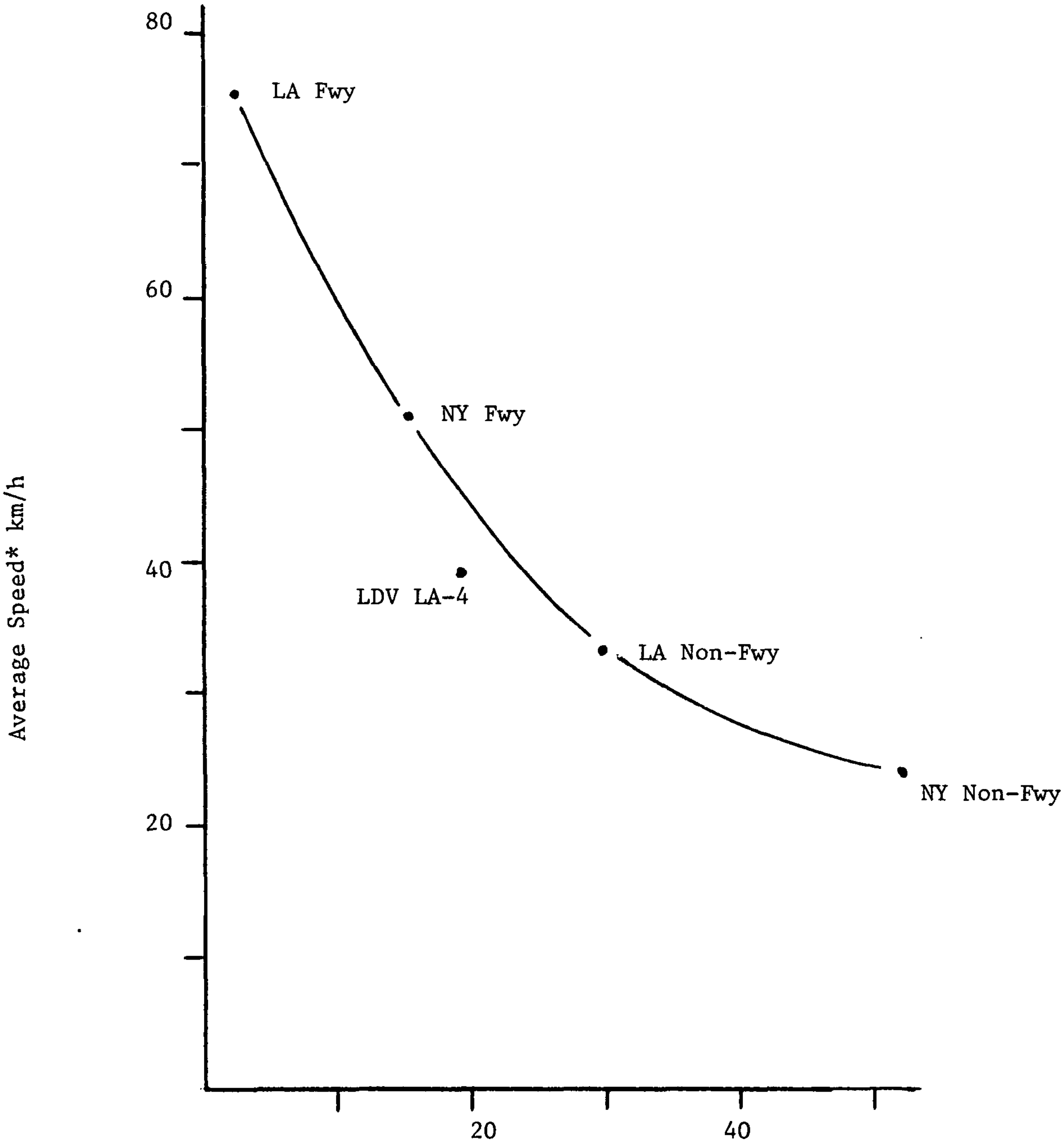
Driving Cycles

No.	Description	Length	Time	Idle	Average Speed*
01	NY Non-Fwy	0.998 km	302 sec	51.1%	24.3 km/h
02	NY Non-Fwy	1.094	331	52.7	25.1
03	NY Non-Fwy	1.014	332	52.7	23.2
04	NY Fwy	3.975	335	14.9	50.2
05	NY Fwy	3.927	331	15.1	50.3
06	NY Fwy	3.895	320	15.7	52.0
07	LA Non-Fwy	2.012	293	30.1	35.4
08	LA Non-Fwy	2.140	332	28.8	32.6
09	LA Non-Fwy	2.108	319	29.6	33.8
10	LA Fwy	25.123	1225	2.3	75.6
11	Linearized 07	1.878	300	37.3	35.9
12	Linearized 08	2.097	300	31.3	36.6
13	Linearized 09	2.076	300	25.3	33.3
14	Light-Duty LA-4	12.038	1371	18.9	39.0

* Does not include idle time.

Figure 2A

Driving Cycle Characteristics



* Does not include idle time

Figure 2B

Driving Cycle Characteristics

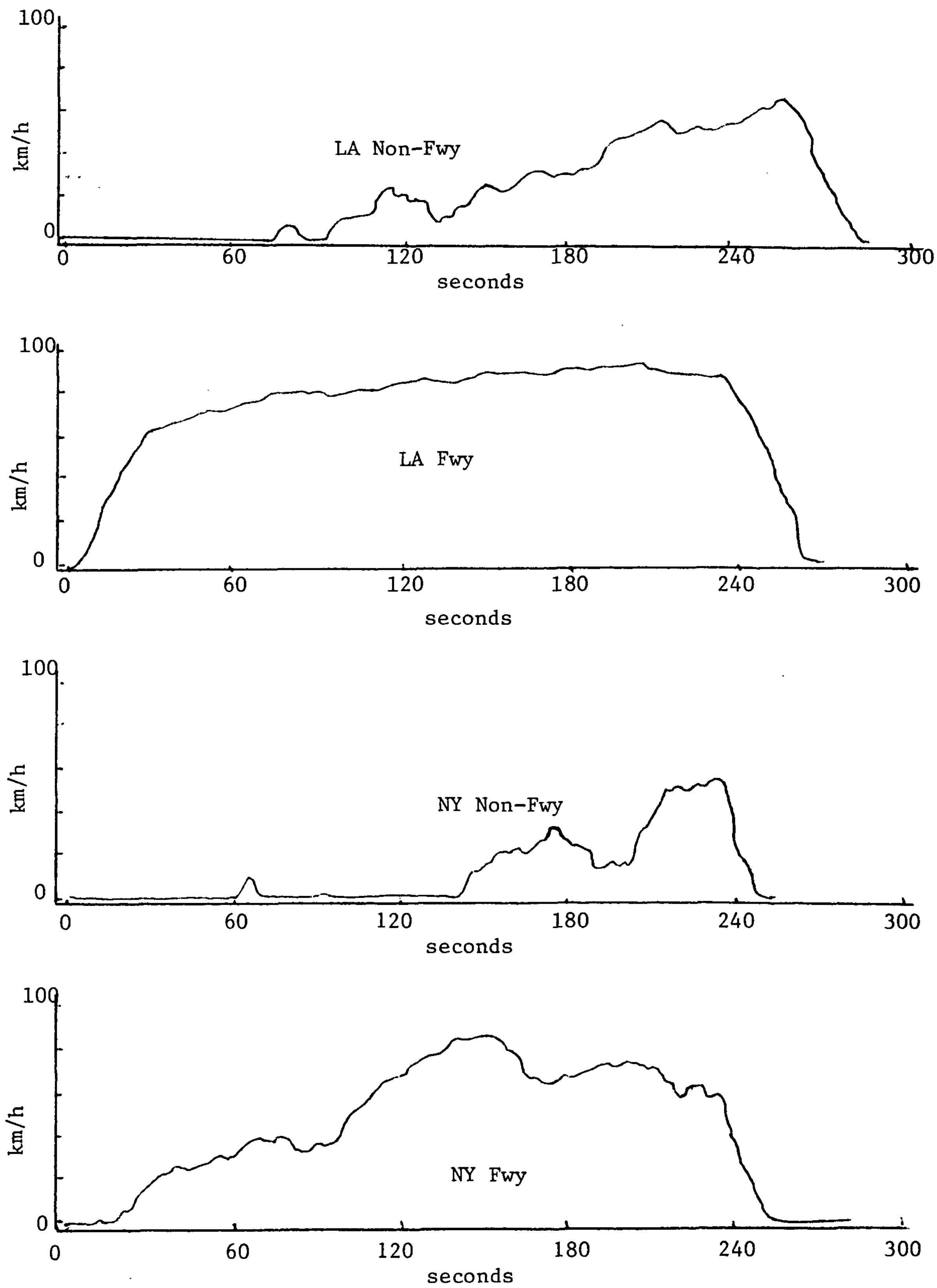


Figure 3

Test Matrix

Driving Cycle Description	No.	Load Simulated: Empty 5840 Kg	Half 7035 Kg	Full 12800 Kg
NY Non-Freeway	01		CX	
	02		X	
	03	X	X	X
NY Freeway	04	CX	CX	X
	05		X	
	06		XX	
LA Non-Freeway	07	X	CX	X
	08		X	
	09		XX	
LA Freeway	10	X*	X*	X*
Linearized	11	X	X	X
	12	X		
	13	X		
Light-Duty LA4	14	X*	X*	

Legend: X = Hot Start Test, 3 runs
C = Cold Start Test Sequence, 3 consecutive runs
* = For cycles 10 and 14, only 1 test run was made

being the shorter driving cycles and larger CVS unit. Calibration checks were done at the beginning of the day or after the cold start test, and at the end of the day.

IV. Road Load

Road load measurements were taken with the vehicle in empty, half and fully loaded conditions. Since this truck was a bare chassis, weights were placed in a box bolted to the frame rails. No attempt was made to give the vehicle a frontal area profile similar to an actual in-use truck. Manifold vacuum and coast down times were recorded from back-to-back runs on a proving ground straight-a-way. These data, along with the calculated drag force, appear in Figure 4. Calculated theoretical road load drag force for a truck with 9.3 square metres of frontal area appear in Figure 5. (This area is typical for a delivery van.)

After obtaining the road load data, the vehicle was placed on the chassis dynamometer where the on-road conditions were duplicated. This was accomplished by adjusting the dynamometer "speed boost" and "windage" controls until both the manifold vacuum and coast down times were duplicated. Emission testing was done with the dynamometer thus adjusted.

At the end of the test program, coast down curves (speed vs. time) were run for each load condition. These curves were differentiated and the dynamometer road load calculated for various speeds. This data appears in Figure 6. Drag forces from the measured, theoretical and dynamometer road loads are compiled in Figure 7, Road Load Comparison. It can be readily observed that the full load dynamometer curve varies significantly from the theoretical. This deviation undoubtedly resulted from the dynamometer setting procedure which essentially relied on only one speed range. A more sophisticated dynamometer setting procedure, using several speed ranges, should resolve the problem.

A discrepancy will be noted between the "empty" dynamometer road load curve and the "empty" 72.4 kilometer calculated drag (from coastdown data). This is due to the fact that the calculated drag was derived from data on a vehicle with a mass of slightly less than 4000 kilograms. When the vehicle was actually tested on the dynamometer, it was decided to add the weight of a cargo box and bring the total simulated vehicle mass to 5800 kilograms. The theoretical and dynamometer drag force curves for the empty test configuration appear to be in very good agreement for the "empty" load condition.

It should be pointed out that "half load" stands for approximately 1/2 of the GVWR, not halfway between "empty" and "full". (This resulted from a misunderstanding when the actual road load determination was being made.) For this particular vehicle, only 1200 kg separate "empty" and "half" loads on the dynamometer.

Figure 4

Measured Road Load Data

Condition	Mass	Manifold Vacuum 64.4 km/h	Manifold Vacuum 80.4 km/h	Coast-down time[1]	Calculated Drag 72.4 km/h
Empty	3995 kg	48.9 kPa	41.2 kPa	14.40s	1233 N
Half	7251 kg	49.7 kPa	42.7 kPa	17.35s	1857 N
Full	13,163 kg	42.0 kPa	35.3 kPa	23.65s	2474 N

[1] Average of several run pairs, 80.4 to 64.4 km/h

Figure 5

Theoretical Road Load

	Drag Force		
Speed	Empty 5,840 kg	Half 7,035 kg	Full 12,800 kg
0 km/h	861 N	1,035 N	1,883 N
20	941	1,115	1,963
40	1,181	1,355	2,202
60	1,580	1,754	2,602
80	2,140	2,314	3,162
100	2,860	3,033	3,881

Note: 9.3 m^2 frontal area assumed.

Source: Study of Emissions from Heavy Duty Vehicles, May 1976, p. 30, EPA-460/3-76-012

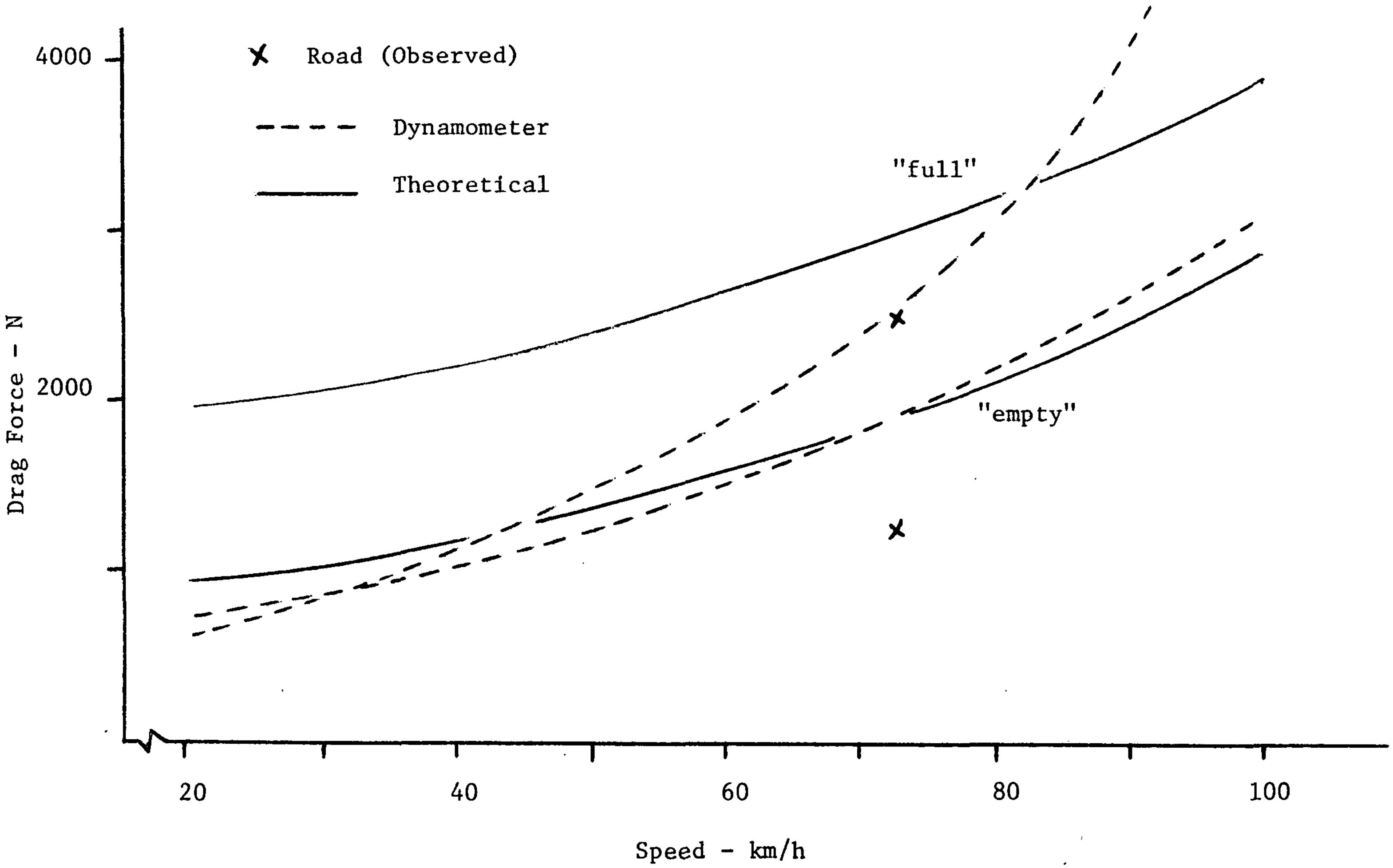
Figure 6

Dynamometer Road Load

	Test Condition/Inertia		
Speed	Empty 5,840 kg	Half 7,035 kg	Full 12,800 kg
24 km/h	787 N	627 N	720 N
34	956	925	996
43	1,161	1,125	1,308
53	1,330	1,325	1,624
63	1,624	1,605	2,095
72	1,868	1,908	2,590
82	2,157	2,250	3,118
92	2,660	2,842	4,368

Figure 7

Road Load Comparisons



V. Results

A. Chassis 9-Mode Test

A chassis 9-mode test was run on the vehicle to determine if the engine had similar emissions characteristics to its certification data engine. This was a somewhat complicated procedure as the vehicle had an automatic transmission that did not permit steady speed operation around the 2000 RPM test point. However, in spite of this difficulty, an attempt was made to run the 9-mode test. Emissions were collected using the CVS during three minute test modes. Engine RPM and manifold vacuum were recorded to permit calculation of the engine power output. (See Technical Support Report for Regulatory Action, HDV 76-04, "Engine Horsepower Modeling for Gasoline Engines," December 1976.) Results from this "modified" chassis 9-mode test are given, mode by mode, in Figure 8. Also included, are the certification emission data engine results and the 1977 California standards.

Except for carbon monoxide, the results are fairly close to the emission data engine. This discrepancy is explained by the difficulty in controlling the vehicle with the automatic transmission as well as the possibility of minor throttle fluctuations during the test. This test was run with the driver monitoring a manifold vacuum gauge and attempting to control the engine to the test point. It is also suspected that the carburetor was not functioning properly, even after the adjustment earlier in the test sequence.

B. Driving Cycle Emissions and Fuel Consumption

For all transient cycles run at half load, average emission and fuel consumption values can be found in Figure 9. Results are presented in terms of distance traveled (g/km, l/100 km) as well as in terms of engine power output (g/kWh). Power output was calculated from the second by second RPM and manifold vacuum recordings using the gasoline engine horsepower model. (See Technical Support Report for Regulatory Action, HDV 76-04, "Engine Horsepower Modeling for Gasoline Engines", December 1976.) Emissions and fuel consumption for the individual cycles are listed in Figures 10 through 17. Figure 18 gives average emissions in terms of fuel consumed.

All fuel consumption figures are based on an exhaust carbon balance and not actual fuel measurement. This is the identical procedure used for light-duty vehicle gas mileage numbers.

For a given cycle category and vehicle load, the various driving cycles did not give the same emissions or fuel consumption. This observation is readily apparent from a quick inspection of the results, Figures 10 through 17. For several cases an analysis of variance was performed to determine the relative variability from test to test (same cycle) and between the cycles. Our intuitive feeling was confirmed; the cycles do give statistically different results. However, this is not to say that there is any real practical difference. Raw results are included in the appendix, the reader can draw his or her own conclusions.

Figure 8

Chassis 9-Mode Results

Mode		Power	HC	CO	NOx
1	Idle	0.0 kW	20.4 g/h	458 g/h	3.2 g/h
2	16 in Hg	23.6	5.8	746	136.6
3	10	60.4	7.4	1,667	377.4
4	16	23.2	4.6	562	126.8
5	19	8.0	20.4	318	52.2
6	16	24.1	4.6	624	153.2
7	3	105.2	96.4	13,297	366.2
8	16	25.9	3.4	853	117.0
9	CT	0.0	6.6	163	12.4
Weighted Average		30.7	20.25	2,178	143.0

	Test Results	Certification Data Engine	1977 California Standards
HC	0.66 g/kWh	0.55 g/kWh	1.34 g/kWh
CO	70.94	23.60	33.53
NOx	4.66	6.68	10.06

Figure 9

Average Driving Cycle Emissions and Fuel Consumption

Cycle Category	g/km HC	g/km CO	g/km NOx	1/100 km Fuel	g/kWh HC	g/kWh CO	g/kWh NOx	g/kWh Fuel
NY-NF	3.64	137	3.78	72.8	5.19	196	5.38	775
NY-FWY	2.02	107	5.29	47.8	2.48	130	6.48	431
LA-NF	1.54	84	4.09	53.4	2.22	121	5.91	570
LA-FWY	0.90	75	6.32	46.6	0.99	82	6.95	378
Average	2.03	101	4.87	55.2	2.72	132	6.18	538
LDV-LA4	1.51	99	5.44	55.5	1.79	118	6.49	488

Note: This figure contains the averages for all hot start transient driving cycles run at half load. The LDV-LA4 results are included for comparison.

Figure 10

Driving Cycle Emissions

HC - g/km

Cycle Category	No.	Empty	Load Half	Full
NY-NF	01		3.01	
	02		4.45	
	03	2.84	3.45	4.86
NY-FWY	04	2.61	2.57	4.11
	05		1.74	
	06		1.74	
LA-NF	07	2.42	1.35	3.47
	08		1.75	
	09		1.52	
LA-FWY	10	1.15	0.90	2.03
Linear 07	11	0.76	1.08	1.49
08	12	0.49		
09	13	0.80		
LDV-LA4	14	1.08	1.51	

Figure 11

Driving Cycle Emissions

CO - g/km

Cycle Category	No.	Empty	Load Half	Full
NY-NF	01		114.5	
	02		158.2	
	03	122.2	137.1	221.4
NY-FWY	04	145.4	131.1	235.3
	05		97.2	
	06		92.4	
LA-NF	07	89.4	79.3	141.7
	08		94.9	
	09		77.8	
LA-FWY	10	118.8	74.9	214.6
Linear 07	11	43.5	60.6	87.8
08	12	33.0		
09	13	49.3		
LDV-LA4	14	76.7	98.8	

Figure 12

Driving Cycle Emissions

NOx - g/km

Cycle Category	No.	Load: Empty	Load: Half	Load: Full
NY-NF	01		3.74	
	02		4.62	
	03	2.47	2.97	4.68
NY-FWY	04	4.65	5.11	6.14
	05		5.32	
	06		5.45	
LA-NF	07	3.21	3.82	5.40
	08		4.32	
	09		4.14	
LA-FWY	10	4.01	6.32	6.00
Linear 07	11	3.99	3.51	5.92
08	12	3.26		
09	13	3.68		
LDV-LA4	14	5.33	5.44	

Figure 13

Driving Cycle Fuel Consumption

litres/100 km

			Load	
Cycle Category	No.	Empty	Half	Full
NY-NF	01		70.8	
	02		75.0	
	03	72.8	72.6	90.8
NY-FWY	04	50.7	49.1	65.6
	05		47.2	
	06		47.1	
LA-NF	07	52.0	52.6	62.5
	08		55.4	
	09		52.3	
LA-FWY	10	48.2	46.6	61.7
Linear 07	11	50.8	51.1	61.2
08	12	46.1		
09	13	48.8		
LDV-LA4	14	52.2	55.5	

Figure 14

Driving Cycle Emissions

HC - g/kWh

Cycle Category	No.	Load: Empty	Half	Full
NY-NF	01		4.49	
	02		5.71	
	03	4.35	5.38	5.06
NY-FWY	04	3.05	3.04	3.27
	05		2.29	
	06		2.10	
LA-NF	07	3.59	1.93	3.47
	08		2.45	
	09		2.29	
LA-FWY	10	1.35	0.99	1.58
Linear 07	11	1.25	1.51	1.48
08	12	0.93		
09	13	1.37		
LDV-LA4	14	1.37	1.79	

Figure 15

Driving Cycle Emissions

CO - g/kWh

			Load	
Cycle Category	No.	Empty	Half	Full
NY-NF	01		170.8	
	02		202.7	
	03	187.3	213.7	230.2
NY-FWY	04	170.1	154.8	187.2
	05		124.5	
	06		111.6	
LA-NF	07	132.6	113.1	141.8
	08		132.6	
	09		116.6	
LA-FWY	10	139.2	82.3	167.2
Linear 07	11	71.9	85.0	87.1
08	12	62.8		
09	13	84.8		
LDV-LA4	14	97.7	117.6	

Figure 16

Driving Cycle Emissions

NOx - g/kWh

Cycle Category	No.	Empty	Load Half	Full
NY-NF	01		5.58	
	02		5.92	
	03	3.78	4.64	4.88
NY-FWY	04	5.44	6.04	4.89
	05		6.81	
	06		6.59	
LA-NF	07	4.75	5.46	5.41
	08		6.04	
	09		6.23	
LA-FWY	10	4.75	6.95	4.68
Linear 07	11	6.60	4.93	5.88
08	12	6.22		
09	13	6.34		
LDV-LA4	14	6.79	6.49	

Figure 17

Driving Cycle Fuel Consumption

g/kWh

Cycle Category	No.	Load: Empty	Half	Full
NY-NF	01		779.5	
	02		709.4	
	03	824.2	835.9	697.9
NY-FWY	04	438.2	428.2	385.5
	05		445.9	
	06		420.0	
LA-NF	07	569.6	555.5	462.1
	08		572.4	
	09		581.4	
LA-FWY	10	417.0	378.4	354.8
Linear 07	11	619.2	529.4	448.0
08	12	650.0		
09	13	619.7		
LDV-LA4	14	491.0	487.8	

Figure 18

Average Emission Indexes

g/kg Fuel

Pollutant	Category	Load: Empty	Load: Half	Load: Full
HC	NY-NF	5.28	6.70	7.25
	NY-FWY	6.96	5.33	8.48
	LA-NF	6.30	3.92	7.51
	LA-FWY	3.24	2.62	4.46
	LDV-LA4	2.79	3,67	3.30
CO	NY-NF	227.0	253.0	330.0
	NY-FWY	388.0	280.0	486.0
	LA-NF	233.0	209.0	307.0
	LA-FWY	333.0	217.0	472.0
	LDV-LA4	199.0	241.0	194.0
NOx	NY-NF	4.58	6.94	6.99
	NY-FWY	12.41	13.94	12.68
	LA-NF	8.34	10.46	11.71
	LA-FWY	11.39	18,37	13.22
	LDV-LA4	13.83	13.30	13.12

C. Linearized Cycles

Linear cycle 11 is the simplified counterpart of Los Angeles Non-Freeway cycle 07. Results from both can be compared for all three load conditions in Figures 10-13. It is evident that the linearized cycle gives substantially less hydrocarbon and carbon monoxide. Fuel consumption is also lower, but to a much lesser degree. NOx emissions were about the same on average.

Comparisons for the other linear cycles (12 & 13) cannot be made because paired test runs were not made. (These cycles were run at "empty" load while their transient counterparts were tested at half load.)

D. Cold Start Emissions

As indicated on the test matrix, four cold start test runs were made. These tests occurred early in the morning after the truck had been sitting overnight on the dynamometer. They were run in a similar manner to the hot start tests, except that the dynamometer was obviously not warmed-up. Three consecutive tests were run back-to-back with the truck approaching hot start operation by the third test. In Figure 19 the ratios of the cold start test results to the hot start averages are indicated. Generally, by the third test run the vehicle has reached stable operation. It can also be tentatively concluded that the more severe the cycle, the more work done by the vehicle, the quicker it warms up. This is evidenced by comparing half load cycles 01 (NY non-freeway) and 04 (NY freeway). The more severe freeway operation shows a much quicker warm-up.

The hydrocarbon values for the cycle 07, half load test, appear to be suspicious. A preliminary, and very cursory examination of the raw test data does not indicate why these values should be so high.

As mentioned previously, these cold start tests were run with the dynamometer not warmed-up. This dynamometer has a rather large gear box between the rolls and the power absorber. For normal testing, the dynamometer is warmed up by operating the vehicle for 15-20 minutes at 40 km/h. This allows the gear box lubricant temperature to stabilize. It is estimated that up to 20% greater drag force is experienced with a cold dynamometer. It is possible to warm up the dynamometer by motoring it. However, since the test vehicle had an automatic transmission, motoring would require loosening the tie-downs and jacking the vehicle up. (Vehicle operating instructions cautioned against towing without removing the driveshaft or raising the rear wheels. This precluded a simple motoring of the dynamometer.)

E. Dilution Ratios

One of the reasons for performing this experiment was to determine the size of CVS required to test the larger heavy-duty trucks. If the CVS flow is inadequate, condensation can form in the sample bags and, in

Figure 19

Cold Start Ratios

Cycle	Load	Run	HC	CO	NOx	Fuel Consumed
04	Empty	1	4.71	1.14	1.85	1.17
		2	0.99	0.75	1.22	0.99
		3	1.00	0.83	1.07	0.98
01	Half	1	11.09	3.41	2.28	1.49
		2	2.54	1.46	1.49	1.14
		3	1.57	1.34	1.26	1.11
04	Half	1	4.93	1.31	1.84	1.20
		2	1.06	0.93	1.30	1.10
		3	0.78	0.96	1.19	1.08
07	Half	1	17.49*	2.22	1.91	1.18
		2	2.76	0.97	1.29	1.01
		3	2.75	0.99	1.04	0.99

Data are ratios of the cold start results to the hot start averages.

* Suspicious HC data, no explanation available.

extreme cases, sample can be lost when the volume from the vehicle exceeds the CVS capacity. By examining the dilute exhaust constituents, the average dilution ratio can be calculated for a test cycle. The average power during the test cycle can be calculated using EPA's gasoline engine model (see Technical Support Report for Regulatory Action, HDV 76-04, "Engine Horsepower Modeling for Gasoline Engines", December 1976) from the RPM and manifold vacuum. This was done for all the hot start tests in the test matrix, results appear in Figures 20 and 21. As expected, the average dilution ratio is a very smooth function of the average power level. This relationship can be used for sizing the CVS unit if the average power level is known.

In addition to calculating the average dilution ratio, continuous CO_2 measurements were taken for several emission runs. By knowing the peak CO_2 level observed in the dilute exhaust stream during a cycle, the lowest instantaneous dilution ratio can be estimated. (This is only a rough check since the raw CO_2 level out of the exhaust pipe can vary slightly with the mode of engine operation.) These estimated peak dilution ratios are plotted as a function of the average dilution ratio in Figure 21. The line drawn indicates the worst case condition for the particular average dilution ratio. As expected, as the average dilution ratio goes down (and correspondingly, the average power level rises), the peak dilution ratio also goes down. However, it is interesting to note that the margin between the average and peak dilution ratio decreases. (Peak dilution ratios were calculated by assuming a constant 13.4% CO_2 in the raw exhaust.)

F. Emission and Fuel Consumption with Windage

A sequence of six tests was run to determine the variation of emissions and fuel consumption with increased frontal area. These tests were run with cycle 04, New York Freeway, under half load conditions with 7,035 kilograms of simulated inertia. The dynamometer was adjusted normally, with the exception of the "windage" control. (This control is supposed to control the effect of aerodynamic drag, i.e., drag force will increase with the square of the vehicle speed.) The windage setting was varied from zero up to a value approximately twice normal for this truck. Results from this sequence of six tests are presented in Figures 22 and 23. Generally, emissions and fuel consumption increased with increased frontal area. However, NOx decreased slightly at the highest windage setting. As with earlier reversals of NOx emissions, it is suspected that this is due to an increased EGR flow at the higher power levels.

G. Hydrocarbons Measured by HFID

During some of the test runs, an attempt was made to measure hydrocarbons by continuously analyzing the dilute exhaust stream with a heated flame ionization detector. The analyzer output was integrated to give an average value. This system is very similar to that used for light-duty diesel vehicles. The purpose behind this experiment was to see if the bag sample and the dilute continuous sample would yield the

Figure 20

Average Dilution Ratios

Run	Cycle	Load	Average Dilution	Average Power
1	03	Empty	46.7	7.2 kw
3	04	Empty	18.8	36.5
4	07	Empty	30.7	16.7
5	10	Empty	11.7	63.0
6	11	Empty	34.9	13.7
7	12	Empty	34.2	13.2
8	13	Empty	33.2	14.5
9	14	Empty	24.1	24.8
11	01	Half	44.7	8.0
12	02	Half	45.0	9.2
13	03	Half*	47.0	7.0
15	04	Half	19.3	36.2
16	05	Half	20.1	33.4
17	06	Half	19.7	36.2
19	07	Half	30.6	17.3
20	08	Half	30.7	16.6
21 & 22	09	Half	32.0	15.8
23	10	Half	12.1	67.3
24	11	Half	34.4	16.1
25	14	Half	23.2	26.5
26	03	Full	38.6	10.5
27	04	Full	14.5	53.7
28	07	Full	25.9	24.7
29	10	Full	9.1	94.8
30	11	Full	28.4	22.7

*Note: For this test program, half load means half of the GVWR, not GVWR plus half of the payload capacity.

Figure 21

Dilution Ratios

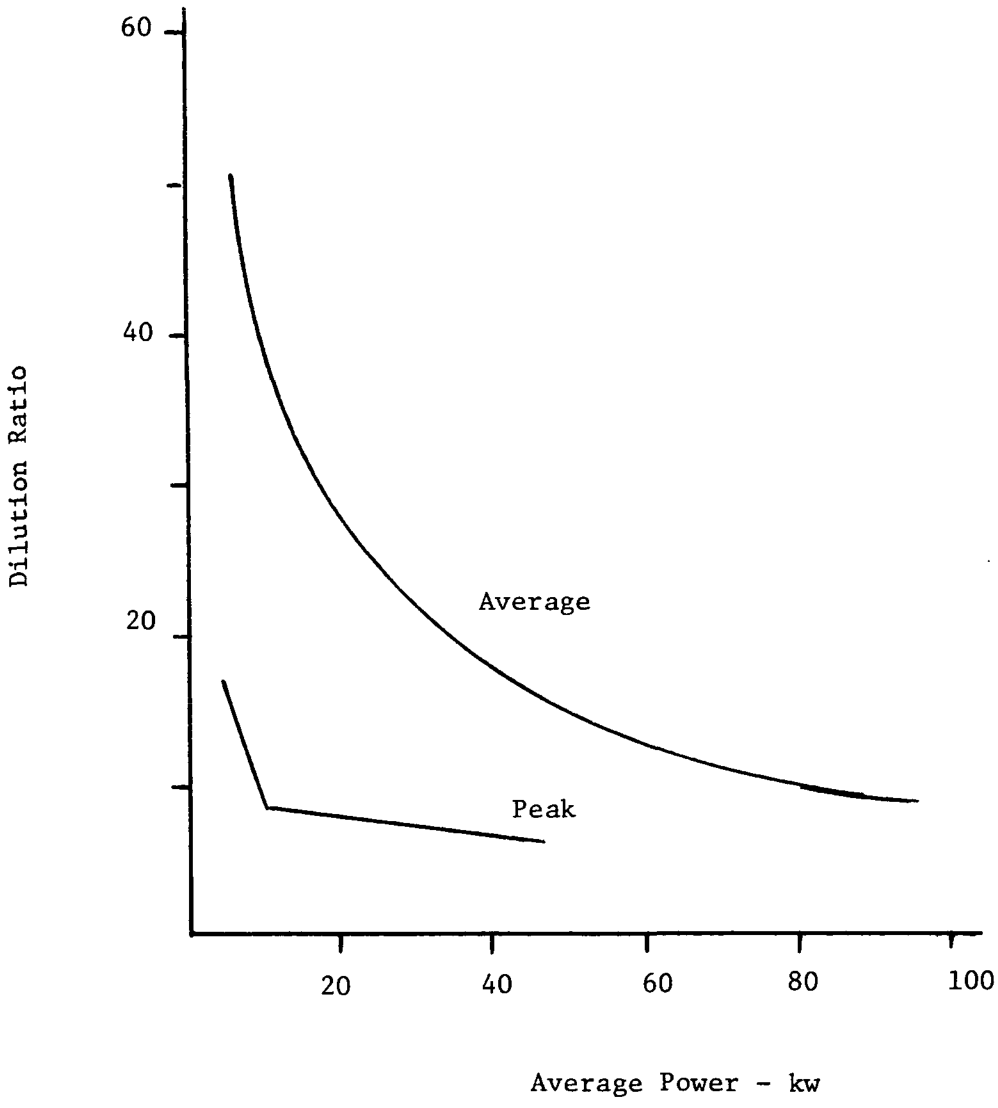


Figure 22

Windage Test Results

Windage Setting	Coast Down[1]	Drag Force[2]	HC	g/km CO	NOx	litre/100 km Fuel Consumption
0.00			1.32	69.3	3.82	38.3
0.06	23.80 s	1354 N	2.16	103.1	4.41	43.7
0.12	19.00	1696	2.50	122.7	4.99	48.0
0.17[3]	17.35	1857	2.57	131.1	5.11	49.1
0.24	13.75	2343	2.54	159.8	5.80	55.9
0.36	9.65	3339	3.54	236.0	5.21	63.7

[1] 80.4 to 64.4 km/h

[2] At 72.4 km/h

[3] Normal Condition

All tests, Cycle 04 NY Freeway, Half Load, 7035 kg inertia same results. Since it is assumed that exhaust hydrocarbons from gasoline engines do not condense using the normal CVS technique, both methods should give about the same analysis. Unfortunately they did not. The heated flame ionization detector gave values from 40% below to 40% above the bag sample. The reason is unknown. On top of the large variability observed, there was an offset of 8% in favor of the HFID. That is, the heated flame ionization detector, on average, recorded an 8% higher hydrocarbon value. However, this is a relatively new system, and had just been assembled for this experiment. The analyzer had not been optimized nor had various probe locations been evaluated.

VI. Recommendations

This experiment was concerned with emissions and fuel consumption measurements on one 1977 model year California heavy-duty truck. Care should be taken not to extrapolate the results from this one vehicle farther than good engineering practice will allow. Before any firm, definite and far reaching conclusions can be drawn, many other types and sizes of vehicles should be tested.

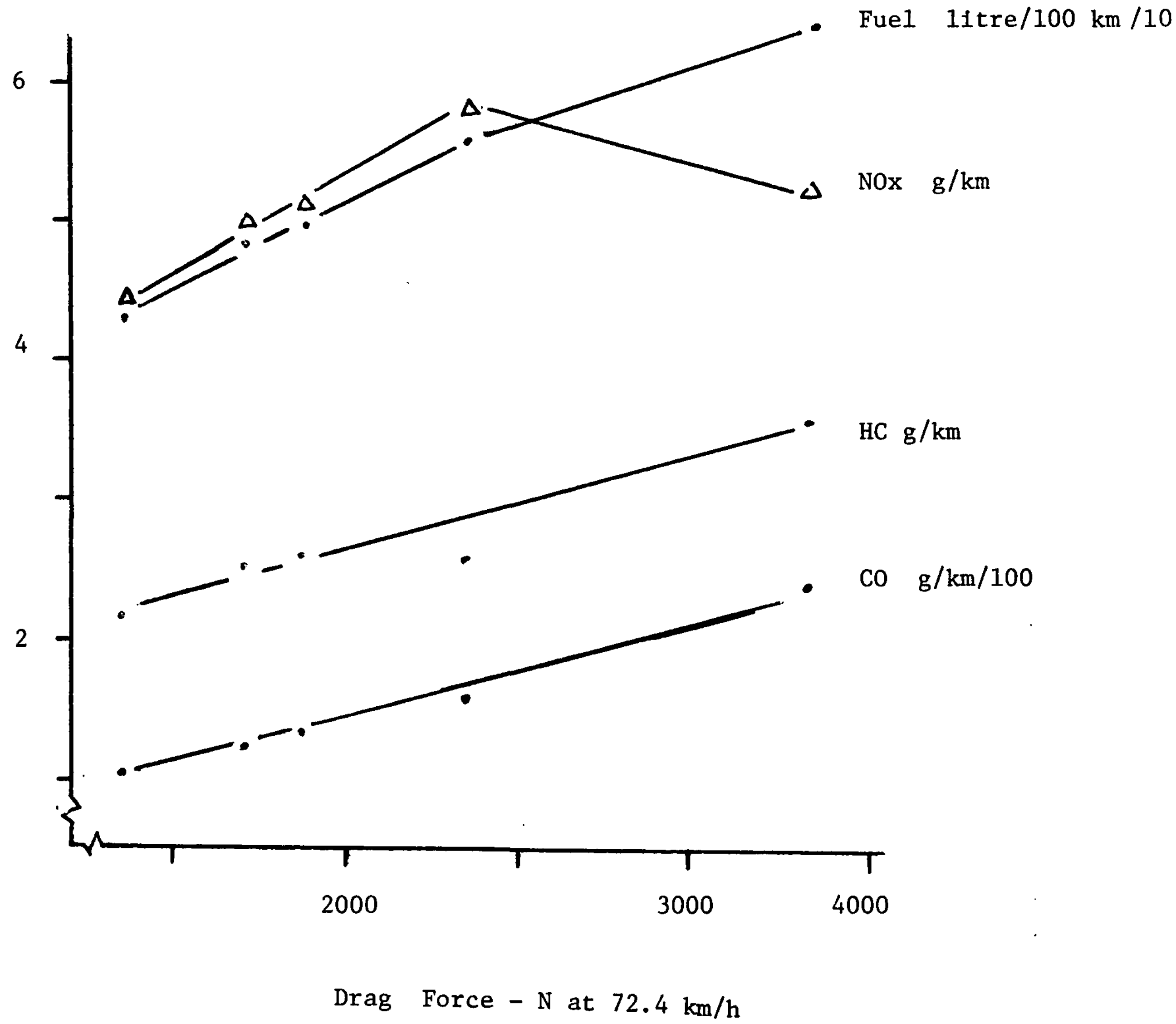
One particularly interesting point, which should be examined in more detail, is the variation of emissions with the various driving cycles from the individual categories. The reasons for these variations should be investigated to determine what, if any, changes might be made in the cycle generation procedure. Hopefully, cycles generated from the same input matrix and screened to the same statistical level will yield the same emission values. Also, the variation of emissions between the various categories of operation might be more thoroughly defined with a larger test fleet. This test fleet should consist of vehicles from the major manufacturers representing all types and sizes of heavy-duty engines.

In view of the variation between some of the dynamometer road load curves and their theoretical counterparts, a more thorough investigation of road load is justified. In addition to examining the vehicle road load, a new dynamometer setting procedure might eliminate some of the variation. No firm recommendations can be made in this vein, only the suggestion that the entire matter warrants further investigation.

The final topic, HFID hydrocarbon measurement, is particulary troublesome. No ready explanation is available for the offset in emission values observed or in the large variability. This will be a crucial element for diesel vehicle testing. In the next phase of gasoline truck testing, significant efforts should be expended to locate the cause of these discrepancies and to correct them.

Figure 23

Windage Test - Emissions and Fuel Consumption



APPENDIX A

Raw Emission Data

No.	Cycle	Load	Run		g/km HC	g/km CO	g/km NOx	litre/100 km Fuel	kWh Work	g/kWh HC	g/kWh CO	g/kWh NOx	g/kWh Fuel
1	03	Empty	1		2.87	123.0	2.62	74.2	0.66	4.40	188.5	4.01	839.7
			2		3.06	135.5	2.42	73.4	0.66	4.69	207.7	3.70	830.6
			3		2.58	108.2	2.37	70.9	0.66	3.95	165.8	3.63	802.3
			Av		2.84	122.2	2.47	72.8		4.35	187.3	3.78	824.2
2	04	Empty	1	Cold	12.30	166.3	8.60	59.4	3.88	12.60	170.4	8.81	449.2
			2		2.59	109.3	5.67	50.4	3.30	3.12	131.6	6.83	448.1
			3		2.62	120.6	4.96	49.7	3.30	3.15	145.2	5.97	442.0
3	04	Empty	1		2.39	129.4	4.61	49.6	3.37	2.82	152.6	5.44	431.9
			2		2.58	146.4	4.62	51.0	3.40	3.02	171.1	5.40	440.1
			3		2.86	160.4	4.72	51.6	3.42	3.32	186.5	5.48	442.7
			Av		2.61	145.4	4.65	50.7	3.40	3.05	170.1	5.44	438.2
4	07	Empty	1		2.51	91.9	3.48	53.1	1.37	3.68	135.0	5.11	575.7
			2		2.35	84.7	3.03	51.3	1.35	3.50	126.2	4.52	564.4
			3		2.41	91.7	3.11	51.7	1.35	3.59	136.6	4.63	568.8
			Av		2.42	89.4	3.21	52.0	1.36	3.59	132.6	4.75	569.6
5	10	Empty			1.15	118.8	4.01	48.2	21.44	1.35	139.2	4.75	417.0
6	11	Empty	1		0.80	46.2	4.05	51.6	1.15	1.30	75.4	6.62	622.0
			2		0.71	42.5	3.96	50.3	1.14	1.17	70.0	6.53	611.7
			3		0.76	41.9	3.96	50.4	1.12	1.28	70.3	6.64	623.8
			Av		0.76	43.5	3.99	50.8	1.14	1.25	71.9	6.60	619.2
7	12	Empty	1		0.53	33.5	3.40	46.5	1.10	1.02	63.7	6.47	652.8
			2		0.47	33.9	3.18	45.8	1.11	0.89	63.9	5.99	637.0
			3		0.46	31.5	3.21	45.9	1.09	0.88	60.9	6.21	654.1
			Av		0.49	33.0	3.26	46.1	1.10	0.93	62.8	6.22	650.0

No.	Cycle	Load	Run		g/km HC	CO	NOx	litre/100 km Fuel	kWh Work	g/kWh HC	CO	NOx	Fuel
8	13	Empty	1		0.93	67.4	3.51	49.5	1.20	1.62	116.6	6.07	632.0
			2		0.79	42.4	3.63	48.5	1.22	1.34	72.3	6.20	611.2
			3		0.68	38.1	3.91	48.4	1.20	1.16	65.6	6.74	616.0
			Av		0.80	49.3	3.68	48.8	1.21	1.37	84.8	6.34	619.7
9	14	Empty			1.08	76.7	5.33	52.2	9.44	1.37	97.7	6.79	491.0
10	01	Half	1	Cold	33.39	390.0	8.51	105.7	0.85	39.01	455.6	9.94	911.6
			2		7.65	167.5	5.59	81.0	0.76	10.12	221.4	7.39	790.4
			3		4.74	153.7	4.70	78.8	0.76	6.19	200.5	6.12	759.2
11	01	Half	1		3.03	113.4	3.75	70.5	0.67	4.51	169.0	5.60	776.2
			2		2.90	109.1	3.73	70.2	0.67	4.33	162.7	5.56	772.9
			3		3.10	121.0	3.74	71.7	0.67	4.62	180.5	5.57	789.4
			Av		3.01	114.5	3.74	70.8		4.49	170.8	5.58	779.5
12	02	Half	1		4.90	161.2	4.78	75.5	0.83	6.44	212.1	6.30	733.0
			2		4.53	163.9	4.52	76.7	0.85	5.81	210.1	5.78	725.2
			3		3.92	149.3	4.55	72.9	0.88	4.88	186.0	5.67	669.9
			Av		4.45	158.2	4.62	75.0	0.85	5.71	202.7	5.92	709.4
13	03	Half	1		3.65	143.4	2.98	73.0	0.65	5.69	223.5	4.66	840.0
			2		3.40	139.3	2.84	72.6	0.66	5.22	213.7	4.36	822.2
			3		3.30	128.7	3.10	72.3	0.64	5.23	203.8	4.91	845.5
			Av		3.45	137.1	2.97	72.6	0.65	5.38	213.7	4.64	835.9
14	04	Half	1	Cold	12.68	172.2	9.42	59.0	3.87	13.01	176.6	9.67	446.9
			2		2.72	122.2	6.64	54.0	3.55	3.05	136.8	7.44	446.3
			3		2.01	125.4	6.09	53.2	3.56	2.24	140.1	6.80	438.8
15	04	Half	1		2.87	141.8	5.11	50.2	3.35	3.41	168.3	6.07	439.7
			2		1.97	117.1	5.11	48.2	3.40	2.31	136.9	5.97	416.1
			3		2.87	134.3	5.12	49.0	3.35	3.41	159.3	6.07	428.9
			Av		2.57	131.1	5.11	49.1	3.37	3.04	154.8	6.04	428.2

No.	Cycle	Load	Run		g/km HC	g/km CO	g/km NOx	litre/100 km Fuel	kWh Work	g/kWh HC	g/kWh CO	g/kWh NOx	g/kWh Fuel
16	05	Half	1		1.95	106.6	5.40	47.8	3.06	2.50	136.6	6.92	452.2
			2		1.49	84.1	5.38	46.6	3.11	1.89	106.3	6.80	434.7
			3		1.78	101.0	5.19	47.2	3.04	2.30	130.6	6.71	450.8
			Av		1.74	97.2	5.32	47.2	3.07	2.29	124.5	6.81	445.9
17	06	Half	1		1.97	102.6	5.52	47.6	3.25	2.36	122.9	6.62	421.0
			2		1.69	90.1	5.43	46.6	3.20	2.06	109.8	6.61	419.2
			3		1.55	84.4	5.41	47.0	3.22	1.88	102.1	6.55	419.7
			Av		1.74	92.4	5.45	47.1	3.22	2.10	111.6	6.59	520.0
18	07	Half	1	Cold	23.61	175.9	7.29	62.3	1.59	29.96	223.2	9.25	583.7
			2		3.73	76.9	4.93	53.2	1.35	5.54	114.2	7.33	583.2
			3		3.71	78.2	3.98	51.9	1.33	5.61	118.2	6.01	579.2
19	07	Half	1		1.59	91.2	3.74	52.9	1.44	2.22	127.8	5.24	547.1
			2		1.33	75.2	3.98	52.6	1.42	1.89	106.7	5.65	550.9
			3		1.13	71.3	3.75	52.4	1.37	1.67	104.8	5.51	568.5
			Av		1.35	79.3	3.82	52.6	1.41	1.93	113.1	5.46	555.5
20	08	Half	1		1.75	95.0	4.37	55.5	1.55	2.41	130.8	6.01	563.9
			2		1.73	87.7	4.36	54.9	1.53	2.42	122.8	6.11	567.4
			3		1.77	101.4	4.21	55.8	1.50	2.51	144.2	5.99	585.8
			Av		1.75	94.9	4.32	55.4	1.53	2.45	132.6	6.04	572.4
21	09	Half	1		1.52	71.5	3.96	50.1	1.30	2.47	115.8	6.42	599.2
			2		1.70	74.9	3.92	50.7	1.31	2.73	120.4	6.31	601.6
			3		1.42	68.9	4.04	50.7	1.29	2.32	112.6	6.60	611.3
			Av		1.55	71.8	3.98	50.5	1.30	2.51	116.3	6.44	604.1
22	09	Half	1		1.53	82.1	4.40	53.9	1.49	2.17	116.5	6.24	564.5
			2		1.39	82.6	4.09	53.8	1.50	1.96	116.1	5.75	558.1
			3		1.51	86.3	4.41	54.6	1.54	2.08	118.5	6.06	553.2
			Av		1.48	83.7	4.30	54.1	1.51	2.07	117.0	6.02	558.6
Average Runs 21 & 22					1.52	77.8	4.14	52.3	1.40	2.29	116.6	6.23	581.4

No.	Cycle	Load	Run	g/km HC	g/km CO	g/km NOx	litre/100 km Fuel	kWh Work	g/kWh HC	g/kWh CO	g/kWh NOx	g/kWh Fuel
23	10	Half		0.90	74.9	6.32	46.6	22.90	0.99	82.3	6.95	378.4
24	11	Half	1	1.21	69.6	3.41	50.5	1.35	1.69	96.7	4.74	517.7
			2	1.05	59.0	3.53	51.2	1.34	1.47	82.7	4.95	529.7
			3	0.97	53.2	3.59	51.5	1.32	1.39	75.6	5.11	540.9
			Av	1.08	60.6	3.51	51.1	1.34	1.51	85.0	4.93	529.4
25	14	Half		1.51	98.8	5.44	55.5	10.11	1.79	117.6	6.49	487.8
26	03	Full	1	4.53	245.1	3.92	91.8	0.99	4.65	251.9	4.04	696.6
			2	4.52	207.7	4.88	91.4	0.97	4.73	217.4	5.10	706.4
			3	5.53	211.4	5.24	89.3	0.97	5.80	221.4	5.50	690.7
			Av	4.86	221.4	4.68	90.8	0.97	5.06	230.2	4.88	697.9
27	04	Full	1	3.81	227.0	6.91	66.3	4.96	3.05	181.9	5.54	392.2
			2	4.52	237.1	5.96	65.0	5.02	3.58	187.9	4.72	380.4
			3	4.01	242.0	5.56	65.6	5.01	3.18	191.9	4.41	384.0
			Av	4.11	235.3	6.14	65.6	5.00	3.27	187.2	4.89	385.5
28	07	Full	1	3.96	161.6	4.75	63.9	2.02	3.95	161.1	4.74	470.4
			2	3.53	135.3	5.68	62.3	2.02	3.51	134.8	5.65	458.1
			3	2.92	128.1	5.76	61.3	1.99	2.95	129.6	5.83	457.9
			Av	3.47	141.7	5.40	62.5	2.01	3.47	141.8	5.41	462.1
29	10	Full		2.03	214.6	6.00	61.7	32.26	1.58	167.2	4.68	354.8
30	11	Full	1	1.53	90.1	6.22	63.2	1.92	1.49	88.1	6.08	456.2
			2	1.49	88.0	6.04	60.5	1.86	1.50	89.0	6.11	451.4
			3	1.45	85.3	5.51	59.9	1.90	1.43	84.2	5.44	436.3
			Av	1.49	87.8	5.92	61.2	1.89	1.48	87.1	5.88	448.0

APPENDIX B

Driving Cycle Identification

Cycle No.	Identification No.
01	123 667 645 7
02	179 960 930 5
03	104 736 920 3
04	741 286 985
05	209 279 083 3
06	137 610 363
07	152 778 878 5
08	210 620 459 3
09	211 939 981 9
10	235 541 19