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Technical Report

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

GMC Astro 95, 8V-71 NA

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Abstract

This report presents exhaust emission and fuel economy measurements for one heavy-duty diesel 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, data collected for freeway and non-freeway operation was segregated. A data matrix (relating speed, acceleration and frequency of occurance) was prepared for each city and type of operation. Several different driving cycles were generated for each city and type of operation.

The test program was designed to evaluate the concept of chassis testing for large diesel vehicles. Along with this goal, it was desired to determine emission factors and fuel consumption by category of operation and to determine the variation with vehicle load. Also, to verify the cycle generation technique, the sensitivity of emissions and fuel consumption to changes in driving cycles (for the same class of operation) was to be extablished. Finally, the effect of "linearized" cycles, steady state tests and cold start operation were evaluted.

Large diesel vehicles can be tested for emissions and fuel consumption on a chassis dynamometer. While this work established the concept of such testing, additional resources are needed to develop an adequate dynamometer and CVS. The average emissions and fuel consumption observed during this work are:

Hydrocarbons	2.07	g/km
Carbon Monoxide	28.0	g/km
Oxides of Nitrogen	29.2	g/km
Fuel Consumption	67.7	l/100km

While these emission levels did change with load and type of operation, they were relatively insensitive to linearization of the driving cycles or cold start operation. No practical difference was seen between cycles representing the same category of operation.

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I. Objectives

This test program was designed to answer the following questions:

1. Could a large tandem axle diesel tractor be tested for emissions and fuel consumption on EPA's chassis dynamometer using a large CVS? This work is a continuation of a similar work on a large gasoline-powered heavy-duty vehicle. (See the previous report on the 427 Cubic Inch (California) GMC 6500.)

2. Assuming that such testing can be accomplished, what emission levels occur for the various types of driving and load conditions?

3. What is the sensitivity of emissions and fuel consumption to different driving cycles representing the same category of operation?

4. How do emissions vary between transient and "linearized" driving cycles? Also, can any comparison be made between emissions observed over the driving cycles and emissions as measured on the 13-mode steady state test?

5. What is the effect of cold starting on emissions?

II. Summary of Results

The 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 truck population. This point can not 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. One definite conclusion can be drawn from this work, it is most certainly possible to test a heavy-duty diesel truck on a chassis dynamometer. This is not to say that problems did not occur. But, with a concerted effort, difficulties could be overcome, and "production" testing could be accomplished. Such testing would certainly be more difficult than similar testing for automobiles. (These results from the large vehicle size and the configuration of EPA's test cell.) The wisdom of such a decision is not addressed.

   If heavy-duty testing is to be done on a chassis dynamometer, more work needs to be done to insure that the dynamometer accurately reporduces true road load. Considerable difficulty was experienced during the test program with setting and maintaining a road load curve. It is also possible that a larger CVS will be necessary if lengthy high power modes are to be run. (Some CVS overheating was experienced.) Finally, the general areas of hydrocarbon measurement and tire slip should be more carefully investigated prior to any extensive program.

2. Figure 1 presents the summary of results observed during this experiment. Values presented are the averages of all fully transient cycles for a given category of operation. Hydrocarbon emissions are a function of the driving cycle category only and are not affected by the vehicle load.

3. As a general rule, emissions and fuel consumption are not greatly affected by a change in driving cycle, assuming the same load and category of operation. This is not to say that the driving cycles give the same results; they do not. But, the differences observed are of no real practical significance.

4. No large difference in test results was noticed between full transient and "linearized" driving cycles for emissions or fuel economy. Hydrocarbons are higher by 10%, CO is 18% lower, NOx and fuel consumption are unchanged.

   Comparisons between transient and steady state testing can best be made on the basis of fuel consumed:

Figure 1
Summary of Results

Operation Category	Emissions (g/km) HC Ave.	CO E	CO H	CO F	NOx E	NOx H	NOx F	Fuel (1/100 km) E	Fuel (1/100 km) H	Fuel (1/100 km) F
NY-NF	3.35	12.2	30.3	45.1	24.2	34.5	40.7	60.4	79.8	90.1
LA-NF	2.37	6.2	16.5	24.1	19.5	26.0	32.0	52.6	66.4	74.7
NY-FWY	1.51	10.4	36.1	38.0	19.2	29.1	35.0	47.8	68.8	74.0
LA-FWY	1.03	21.7	33.0	62.3	25.8	30.5	33.6	57.0	63.3	76.8
AVERAGE	2.07	12.6	30.0	42.4	22.2	30.2	35.3	54.5	69.6	78.9

Notes: NF - Non-freeway
FWY - Freeway
LA - Los Angeles
NY - New York

E - Empty load 13,780 kg
H - Half load 25,680 kg
F - Full load 37.250 kg

Results are averages of all transient driving cycles. For HC, all 3 load conditions are averaged since there was little difference between them.

Emissions (g/kg Fuel)

Test	HC	CO	NOx
9-mode	3.81	11.94	47.40
13-mode	3.58	29.78	49.74
Transient Cycles	3.52	48.23	51.04

Transient cycle results are averages for all operational categories and vehicle loads.

As can be seen there is a great deal of similarity in the results. The largest variation is with carbon monoxide, which also has the largest test-to-test variation. If we assume approximately the same average specific fuel consumption, then the type of test is immaterial in predicting HC and NOx emissions.

5. Cold starting has very little effect on emission levels. Slightly more fuel is used, about 14% (comparisons are for 4 to 9 minute driving cycles.) Hydrocarbons are approximately 14% lower. This latter difference is believed to be caused by some initial hang-up in the sampling system, and not to any actual change in emission levels.

III. Description of Experiment

A. Vehicle

The test vehicle was a 1975 model year GMC Astro 95 tractor. This truck is of the cab-over-engine design with tandem rear axles. It was equipped with a 13 speed transmission and a 4.11 axle ratio. The empty mass was 7600 kilograms.

The engine was a Detroit Diesel, naturally aspirated 8V-71 model. It had the following specifications:

Type: 90° V-8
Injectors: Model C65
Displacement: 9.30 litre
Compression Ratio: 18.7
Maximum Torque: 1147 N M at 1600 RPM
Maximum Power: 237 kw at 2100 RPM

Fuel used was #2 Diesel. This engine had no external emission control devices.

B. Equipment

A heavy-duty LABECO dual roll chassis dynamometer was used for all testing. This unit has an electric power absorber driven through a gear box at 4.9 times the roll speed. Roll diameter is 1.02 metres. Total mechanical inertia is approximately 8200 kilograms in the dual roll configuration; inertias from 2700 to 50,000 kilograms can be electrically simulated. True load force can be reproduced by various dynamometer circuits that control the constant, first and second order speed contributions. Maximum permissible speed is approximately 100 km/h, motoring capability is available throughout the full range. A constant speed cooling fan was used for all the testing.

A 1.2 cubic metre/second constant volume sampler (CVS), Critical Flow Venturi, was used for exhaust sampling. This unit is essentially a scaled-up copy of the CVS used by EPA for light-duty vehicle certification. Exhaust hydrocarbon measurements were made using a heated flame ionization detector (HFID) with heated sample line. The hydrocarbon sample was obtained from a tap just prior to the CVS venturi throat, and thus after the cyclone separators. (It is unsure if this probe location affected the hydrocarbon results.) The remaining analytical equipment was very similar to that used in light-duty vehicle certification.

Fuel consumption was calculated using the carbon balance technique. As a cross check on the total analytical system, it was decided to employ a separate fuel meter. This was a rather unsophisticated device, best described as a "butcher shop scale", used to weigh fuel before and after each test run. It had a total capacity of 6 kilograms and could be read to about 5 grams. During one of the longer test runs, fuel had to be added from a previously weighed container.

C. Driving Cycles

Driving cycles for this experiment were developed from actual in-use data collected and analyzed under the CAPE-21 project. Vehicles were instrumented in New York city and Los Angeles. Data was collected for freeway and non-freeway operation. 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. Driving cycles were generated using computer programs developed under the CAPE-21 project.

In addition to operational category, (e.g., New York Freeway) driving cycles are divided into four types. These types represent the method used in generation, and not the category of truck operation:

1. Non-Interpolated: These cycles were generated using the 0.864 second time basis which was assumed to be one second. That is, the computer-generated speed versus time sequence should have been plotted into drivers traces with 0.864 seconds between each data point. However, for convenience, it was decided to assume that the in-use data was collected on a 1.0 second basis, and to generated driver's traces accordingly. The result of this technique is to slightly "stretch out" the acceleration and deceleration ramps.

2. Interpolated: These cycles are like those above, except that the results have been interpolated. The 0.864 second based speed versus time listing was converted to a 1.0 second basis by linear interpolation. The result of this process is to very slightly shave some of the "peaks and valleys" out of the cycle. However, these cycles do not have the "streatched-out" profile of the Non-interpolated cycles.

3. Hand generated: An attempt was made to "hand generate", without the aid of a computer, two driving cycles from the Los Angeles Non-freeway input matrix. This was done to achieve the best possible match to the input data speed distribution

4. Speed screened: For these cycles, the computer program was modified to insure that cycles generated would more accurately reflect the speed distribution of the data matrix. The original cycles, both interpolated and non-interpolated, were accepted on the basis of percentage acceleration, deceleration, cruise and idle. Speed distribution was not considered.

Also, there is one variation. Instead of a "fully transient" driving cycle, "linearized" versions can be generated. These driving cycles are quite similar to the original LDV 7-mode with steady state cruises and constant rate accelerations and decelerations. Each linearized cycle is based on a full transient cycle with operating modes selected to best approximate it. Comparisons between the corresponding cycles will indicate the importance of full transient operation.

All driving cycles were "manufactured" into a speed versus time graph used during the test. This process was carried out using a mini-computer and a strip chart recorder.

After the test program was finished, a minor problem was discovered in some of the drivers traces. Apparently, the chart recorder used to generate the traces developed a random calibration shift or temporary instability. This resulted in distortion for parts of some traces, mostly at the higher speeds. The problem was not of major significance, in that it was unnoticed by the drivers. Suspect runs were deleted. Data used in this report is based on test runs with correct, or very close to correct, traces. All emission and fuel consumption data is calculated using actual distance traveled.

The different driving cycles are listed and described in Figure 2. The relationship between average speed and percent idle is illustrated in Figure 3.

D. Test Matrix

Tests were run under three road load conditions; empty, half and full. While most tests were of the hot start variety, with engine idling at the beginning of the test, five cold start sequences were run. Each sequence, hot or cold start, consists of three back-to-back tests. In the case of hot start, this gives three replicates. No replicates were run for cold start tests, but the trend in emissions as the vehicle warms up is indicated by the sequence. The test matrix is shown in Figure 4.

In addition to the chassis cycles listed in the test matrix, several other tests were also run. First, to verify the representativeness of the test engine, a chassis version of the 13-mode certification test was run. It was also decided to run a chassis version of the gasoline 9-mode test, just to see what would be observed. (The 9-mode test has some engine motoring. This is not part of the normal diesel test.) Finally, a tire slip test was run with no emission measurements.

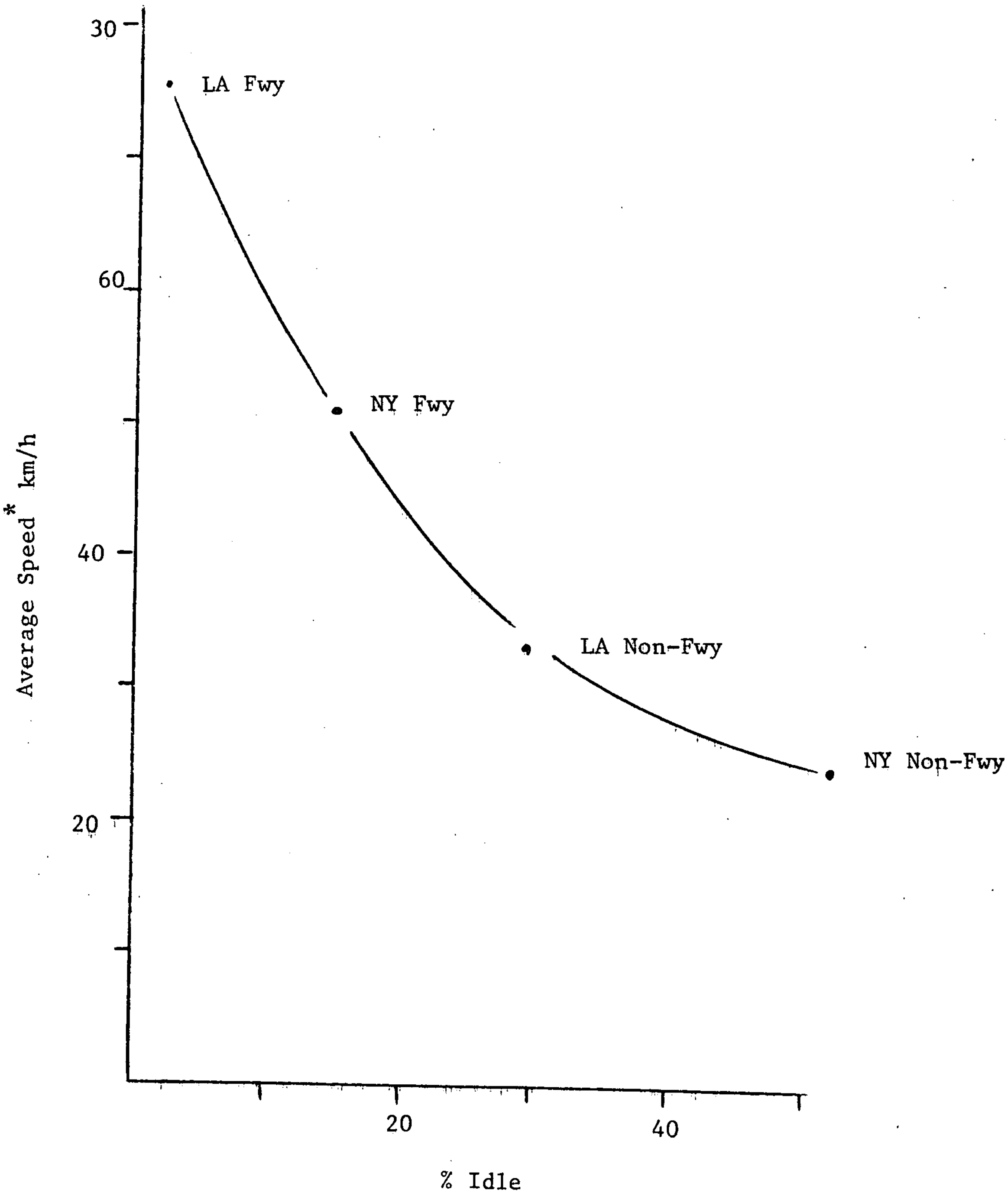
Figure 2
Driving Cycles

No.	Description	Length	Time	Idle	Average Speed	Type
07	LA Non-Fwy	2.01 km	293 s	30.1%	35.4 km/h *	Non-interpolated
08	LA Non-Fwy	2.14	332	28.8	32.6	" "
09	LA Non-Fwy	2.11	319	29.6	33.8	" "
11	LA Non-Fwy	1.88	300	37.3	35.9	Linearized 07
12	LA Non-Fwy	2.08	300	25.3	33.3	" 08
13	LA Non-Fwy	2.10	300	31.3	36.6	" 09
20	LA Non-Fwy	3.63	544	31.0	34.9	Interpolated
23	NY Non-Fwy	1.86	544	49.4	24.3	"
28	LA Fwy	10.76	530	2.1	74.6	"
31	NY Fwy	3.36	279	15.4	51.3	Speed Screened
32	NY Non-Fwy	0.85	254	52.0	25.2	" "
34	NY Non-Fwy	0.92	259	50.1	26.0	" "
39	NY Non-Fwy	0.97	302	50.3	23.2	Hand Generated
40	NY Non-Fwy	0.97	299	50.2	23.5	" "
41	NY Non-Fwy	0.87	260	50.8	24.4	Interpolated 01
42	NY Non-Fwy	0.93	285	52.6	24.9	" 02
44	NY Fwy	3.43	289	14.9	50.2	" 04
45	NY Fwy	3.40	285	14.7	50.3	" 05
46	NY Fwy	3.36	214	15.3	52.2	" 06
47	LA Non-Fwy	4.05	543	33.4	40.3	Linearized 20
48	NY Non-Fwy	1.91	543	50.5	25.6	Linearized 23
50	LA NY St. Lou.	9.75	1669	38.9	34.4	Linearized Composite 20, 23, 51
51	St. Lou Non-Fwy	3.79	581	33.8	36.6	Linearized
52	LA Fwy	5.42	267	2.6	75.0	Interpolated
53	LA Fwy	5.38	267	2.6	74.5	"
54	LA Non-Fwy	1.85	285	28.8	32.9	" 08

* Does not include idle time.
Note: Cycles 01 through 06 were generated for an earlier test program.

Figure 3

Driving Cycle Characteristics



* Does not include idle time

Figure 4
Test Matrix

Cycle	Type	No.	Empty	Half	Full
NY-NF	Original	23	X		
	Lin 23	48		X	
	Original	41	X	XC	X
		42	X	X	X
	Hand Gen.	39	X		X
		40	X	X	X
	Speed Screen	32	X	XC	X
LA-NF	Original	07			X
	Lin. 07	11	X	X	X
	Original	08	X	X	X
	Lin. 08	12	X	X	X
	Original	09	X	X	X
	Lin. 09	13	X	X	X
	Original	20			XC
	Lin. 20	47	XC	X	X
	Original	54	XC	X	X
NY-FWY	Original	44	X	X	X
		45	X	X	X
		46	X	X	X
	Speed Screen	31		X	X
LA-FWY	Original	28		X	X
		52	X	XC	X
		53	X	X	X
St. L-NF	Special	51	X	X	
Composite	Special	50		X	

X = Hot Start (3 replicate tests)

C = Cold Start (3 test sequence)

IV. Road Load

Road load measurements for this vehicle and standard semi trailer were taken for empty, half, and fully loaded conditions. (The standard trailer was 12.2 metres long, 3.65 metres high and 2.44 metres wide.) This work was done at the Transportation Research Center of Ohio, East Liberty, Ohio. The large, 7.5 mile oval track was used for all conditions. The following vehicle masses were tested:

Empty	13,780 kg
Half	25,680 kg
Full	37,250 kg

Multiple coastdown runs were made using a strip chart recorder and fifth wheel to generate velocity versus time profiles. Back-to-back runs were made (on opposite sides of the oval) to minimize the variations caused by wind and the slight track grade, 0.228%. Weather conditions were 35°C, humid and low wind.

In this discussion, the following symbols will be used:

Symbol	Quantity	Units
a	Coefficient constant	m/s^2
A	Area, frontal	m^2
c	Squared term coefficient	1/m
C_D	Drag coefficient	
F	Total road load force	N
F_A	Aerodynamic resistance	N
F_R	Rolling resistance	N
g	Gravitational acceleration	9.8 m/s^2
M	Mass	kg
U	Tire rolling resistance coefficient	
V	Velocity	m/s
t	Time	s
W	Work	j
p	Density of air	1.15 kg/m^3

The speed versus time coastdown traces were manually reviewed and the data points entered into a computer. For each data interval, an acceleration was calculated, these accelerations were then mathematically fit to a curve of the following formula:

$$\frac{dV}{dt} = a + cV^2 \qquad (1)$$

The coefficients a and c are generated using a standard data regression technique.

This equation form was chosen because, in the past, it has represented light-duty vehicle data very well. The constant term, a, is assigned to tire rolling resistance. Aerodynamic losses are represented by the squared term coefficient, c. These are the only losses considered; skin friction is ignored.

Data were reviewed for each run pair. If the coefficients differed from the average by too much, or if the results were in any way suspicious, that pair was deleted. Once the "good" runs were isolated, the data analysis continued.

Total force on the vehicle can be calculated from Newtons law once the mass is known:

$$F = M\frac{dV}{dt} \qquad (2)$$

Only the translational vehicle mass is reflected in this equation; energy stored in rotating components (tires, axles, etc.) is not considered. This simplification does not unduly compromise the overall accuracy. First, 8 of the 18 wheels and the entire drivetrain rotate during dynamometer testing. Second, the remaining 10 wheels are not a large factor, especially when compared to a loaded truck.

This total force is the sum of the rolling and aerodynamic resistances:

$$F = F_R + F_A \qquad (3)$$

Combining the first three equations, separating the linear and squared terms into rolling and aerodynamic factors, yields:

$$F_R = aM \qquad (4)$$

$$F_A = cV^2M \qquad (5)$$

It is established convention to define a tire rolling resistance coefficient, u, as a ratio of drag force to normal force:

$$u = \frac{F_R}{Mg} \qquad (6)$$

Combining with equation 4:

$$u = \frac{\dot{a}}{g} \qquad (7)$$

Aerodynamic resistance is similarly presented in terms of a drag coefficient. This coefficient is related to the frontal area, air density and relative velocity:

$$C_D = \frac{2\ F_A}{pAV^2} \qquad (8)$$

The equation for aerodynamic drag, 5, can be substituted, yielding:

$$C_D = \frac{2\ cM}{pA} \qquad (9)$$

For the three load conditions these quantities were calculated and overall values established. (The overall values are not the arithmetic averages, but are based on engineering judgment.)

Load	Mass	u	C_D
Empty	13,780 kg	0.0088	1.01
Half	25,680 kg	0.0076	1.21
Full	37,250 kg	0.0077	1.13
Overall Values		0.0077	1.12

The overall values assume that the coefficients are constant; this is a reasonable assumption and the results agree fairly well with those in the literature.

For this experiment one would expect the drag coefficient to remain constant. (It appears that the analysis for empty load gave a low aerodynamic factor and compensated with a higher rolling resistance. This is a classical example of the problems with least squares regressions of more than one variable.) One would expect a square plate to have a drag coefficient of 1.0 - 1.2; a factor of 1.12 for this truck seems reasonable. (Skin resistance was ignored in this analysis; it obviously was represented in the coastdown data and in the overall equation.) Total drag force is predicted by the following equation:

$$F = 0.0077\ M\ (9.8) + 1.12\ V^2 (5.1)$$

(Numbers in parentheses represent various constants, frontal area, density of air, gravitation, etc.)

Unfortunately, analysis of the actual road coastdown data was not available in time to permit accurate dynamometer adjustment. The dynamometer was adjusted using a very few coastdown times. Later, the dynamometer speed versus time curves were analyzed in much the same way as the on-road curves. Although the resulting equations have the same form, the coefficients are vastly different:

Load	u	C_D
Empty	0.0028	1.30
Half	0.0015	1.73
Full	0.0016	2.33

Figure 5 demonstrates the difference between road and dyno drag for empty and full loads. It can be readily noted that there are large discrepancies.

In order to estimate the significance of these road load discrepancies, it would be desirable to calculate the total power required for a driving cycle. This would be done for the on-road curve and the dynamometer curve. Unfortunately, such an analysis would be a very difficult task, requiring a large number of calculations to go through an actual driving cycle second by second. However, this effort is significantly reduced if a linearized cycle is used. It is a relatively easy task to make integrations for the 12 simple modes of linearized cycle #11, Los Angeles Non-Freeway. This was done; the following equation for work resulting:

$$W = 0.00418\ uM + 0.574\ C_D + 0.000049\ M$$

Applying this relationship to the actual and dynamometer road load curves gives the following deviations from true "on-road" work over the cycle:

Empty	-9.6%
Half	-11.6%
Full	-7.0%

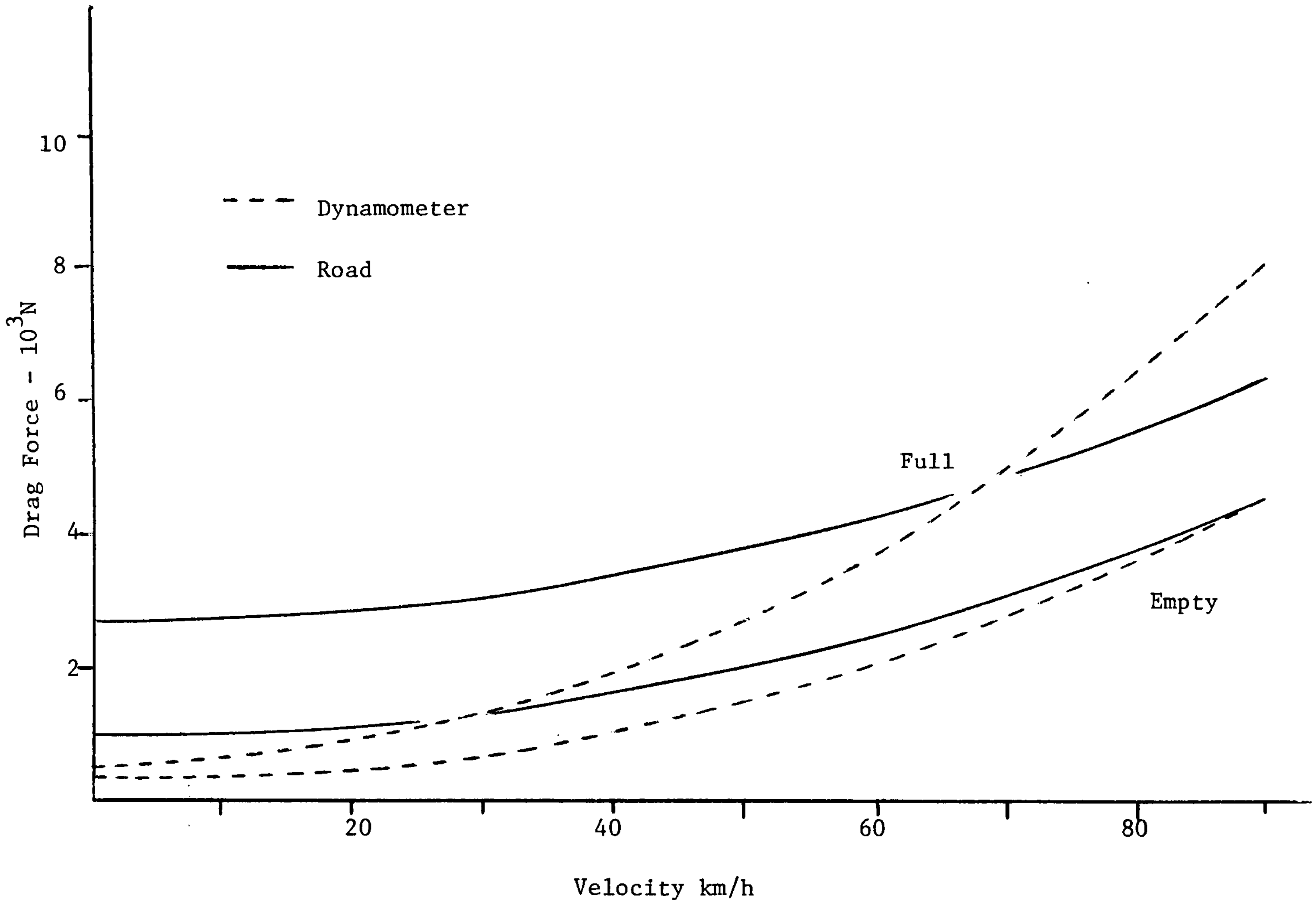
V. Results

A. Chassis Verison 9- and 13-mode Tests

In order to assess the representativeness of the test engine, a chassis version 13-mode test was run. An appropriate transmission gear was selected and the dynamometer was operated in speed control to hold the engine RPM constant. The driver controlled the level of torque with the accelerator pedal while monitoring a strip chart recorder. This recorder was adjusted to give the percentage of maximum torque at the given engine speed. (This method assumes that the dynamometer gear box losses, along with other drive train losses, change linearly with torque. This may or may not be true. But as will be seen, diesel engine emissions do not change appreciably with small changes in torque.)

Figure 5

Road Load Curves



Exhaust samples were collected and analyzed in the same manner as the transient driving cycle tests. A three minute mode time gave an adequate bag sample for analysis and also eliminated overheating of the CVS at high power levels. Results for the 13-mode test are detailed in Figure 6. Also included on that Figure are results obtained from an engine dynamometer test on a similar (reference) engine. (This engine was used in the development of the 1979 test procedure.) They compare quite closely.

A chassis version 9-mode test was also run on this vehicle. While a 9-mode is used only for gasoline engine certification, it was decided to see how closely results would compare. Also, since the 9-mode engine test has a closed throttle motoring mode, it would give a fair idea of diesel motoring emissions. Results are listed in Figure 7. As indicated in the Table below, except for carbon monoxide, emissions on the 9- and 13-mode tests, as well as for the reference engine, are quite similar:

g/kwh

	Test Engine (Chassis Tests) 9-mode	Test Engine (Chassis Tests) 13-mode	Reference Engine 13-mode (Engine Dynamometer)
HC	1.11	0.98	1.31
CO	3.49	8.19	12.13
NOx	13.84	13.68	14.23
Fuel	292	275	290

The chassis version test results were calculated assuming a torque of 1005 Newton-metres at 2100 RPM, 1045 at 1900 RPM and 1085 at 1600 RPM. (This was interpolated from manufacturer data.)

Figures 8-11 present a graphical digest of the 9- and 13-mode test results. Emissions and fuel consumption are plotted as a function of power output and engine RPM. These graphs present rather simple relationships for these quantities. For example, in Figure 8 one can seen that hydrocarbons are affected but very little by the power output and are only slightly affected by changing RPM. Carbon monoxide is even more interesting. For up to about 50% maximum power CO emissions are very low and not affected by engine RPM. However, from 50-100% maximum power they increase dramatically. Finally, oxides of nitrogen are almost a linear function of power and are not dependent upon engine RPM.

Figure 6
13-Mode Test Results

Mode	Condition	--Test Vehicle-- g/h HC	CO	NOx	Fuel kg/h Calc.	Meas.	kw Power	--Reference Engine-- g/h HC	CO	NOx	kg/h Fuel	kw Power
1	Idle	35.4	31.8	120.0	1.8	1.8	0.0	42.6	84.0	124.1	2.0	0.0
2	1600/2%	59.0	112.0	349.2	9.8	8.9	3.6	210.3	480.0	191.7	7.9	4.1
3	25%	61.4	92.6	635.2	16.0	14.9	45.4	85.6	201.0	624.9	15.9	51.4
4	50	62.6	119.2	1025.8	22.4	21.9	90.9	88.0	114.2	1027.4	25.7	103.2
5	75	89.2	497.0	1713.2	32.0	29.4	136.4	129.5	819.9	1733.1	37.0	153.3
6	100	87.0	4436.0	1865.6	37.0	41.0	181.8	76.7	6267.5	2051.4	48.3	196.2
7	Idle	34.4	23.6	123.6	1.8	2.2	0.0	34.9	58.6	100.7	1.6	0.0
8	2100/100%	129.2	1937.4	2847.0	50.0	49.1	221.0	118.9	3913.9	2355.5	58.5	239.0
9	/75	128.0	580.0	2491.0	44.5	40.6	165.8	142.7	535.2	1748.6	45.1	171.0
10	/50	99.4	127.6	1469.6	31.9	31.6	110.5	139.7	200.7	1019.0	33.3	113.4
11	/25	91.4	223.8	834.2	23.0	22.2	55.2	165.2	258.2	626.9	26.7	56.8
12	/2	97.6	89.4	372.0	12.0	14.6	4.4	179.9	301.4	280.2	14.0	4.6
13	Idle	41.7	31.2	162.0	2.9	1.9	0.0	31.8	49.9	86.7	1.5	0.0
WEIGHTED AVERAGED		79.8	664.9	1110.6	22.7	22.3	81.2	114.2	1060.3	1244.2	25.3	87.4
Power Specific X/kw-hr		0.98	8.19	13.68	0.280	0.275		1.31	12.13	14.23	0.290	
Fuel Specific g/kg fuel*		3.52	29.29	48.92				4.51	41.91	49.18		

*Calculated fuel for test vehicle.

Note: The Reference engine was a similar GM 8V-71 NA tested on an engine dynamometer. The test vehicle was given a chassis version 13-mode test using a CVS sampling system.

Figure 7

9-Mode Test Results

Mode	Torque	Weighting	g/hr HC	g/hr CO	g/hr NOx	Fuel kg/hr Calc.	Fuel kg/hr Meas.	kw Power
1	Idle	0.232	22.6	39.8	122.2	2.0	2.2	0.0
2	25%	0.077	69.8	100.8	729.8	19.8	19.3	52.0
3	55	0.147	80.0	114.6	1229.4	25.8	28.8	114.4
4	25	0.077	72.8	90.8	682.0	18.3	18.9	52.0
5	10	0.057	76.8	100.6	480.8	14.1	13.9	20.8
6	25	0.077	79.0	97.4	727.6	19.5	18.8	52.0
7	90	0.113	116.0	1136.4	2588.2	43.5	41.0	187.1
8	25	0.077	83.0	117.0	767.4	19.9	18.9	52.0
9	CT	0.143	23.8	5.0	72.8	0.8	0.6	0.0
WEIGHTED AVERAGE			61.4	192.2	763.2	16.1	16.1	55.1
Power Specific g or kg/kw-hr			1.11	3.49	13.84	0.291	0.292	
Fuel Specific g/kg fuel			3.81	11.94	47.40			

Test was run at 1900 rpm.

Figure 8

HC Emissions, Steady State

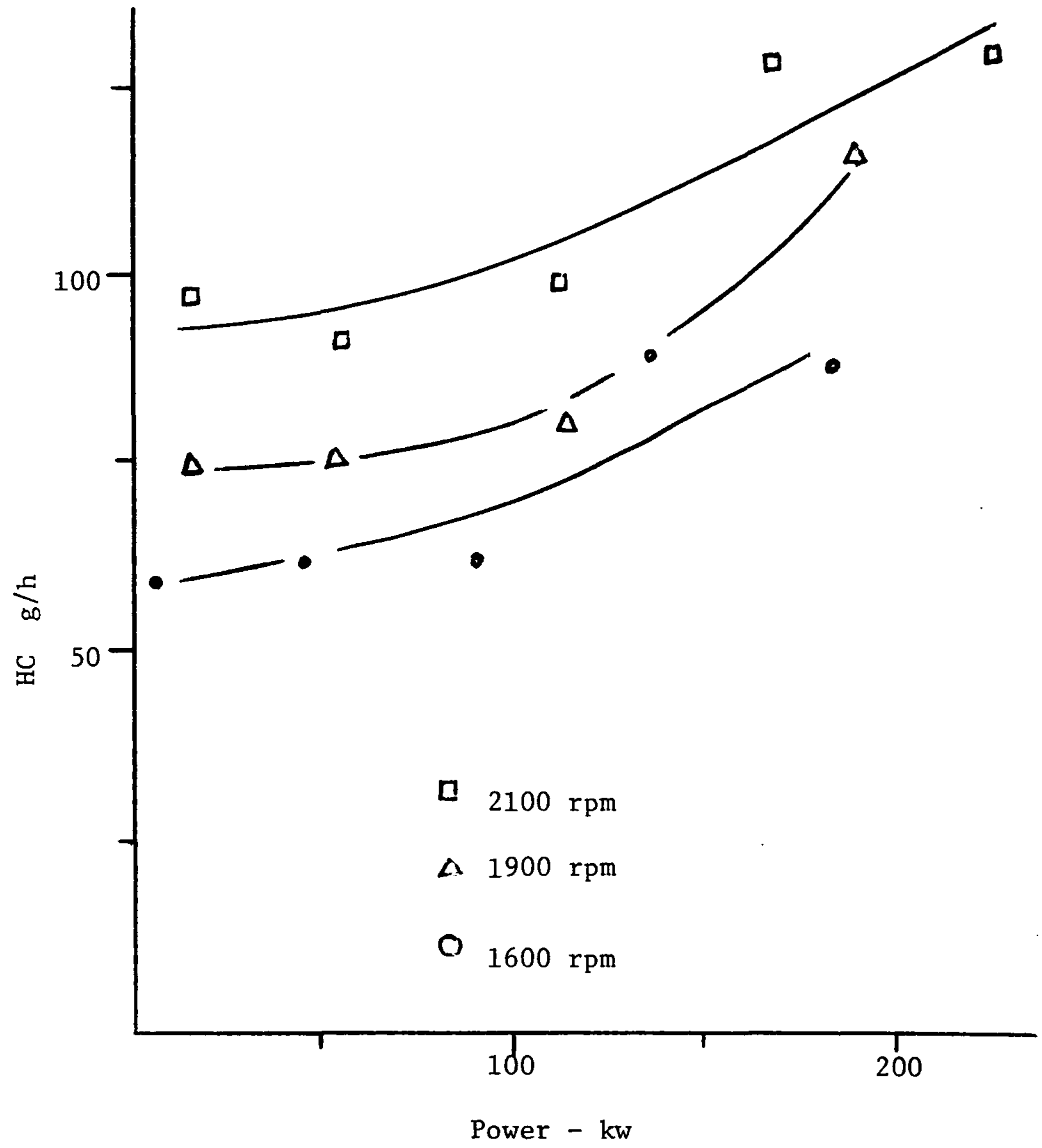


Figure 9

CO Emissions, Steady State

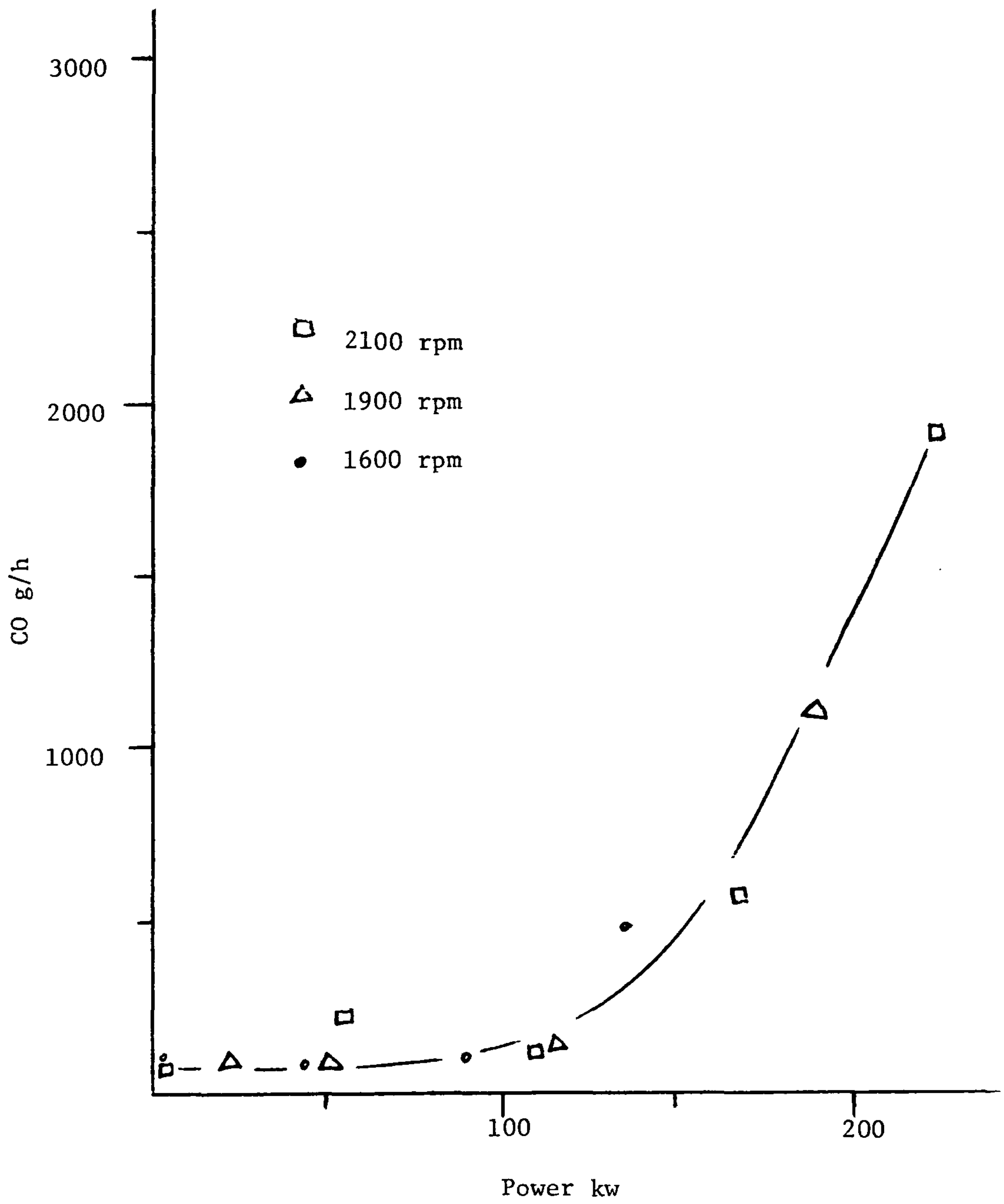


Figure 10

<u>NOx Emissions, Steady State</u>

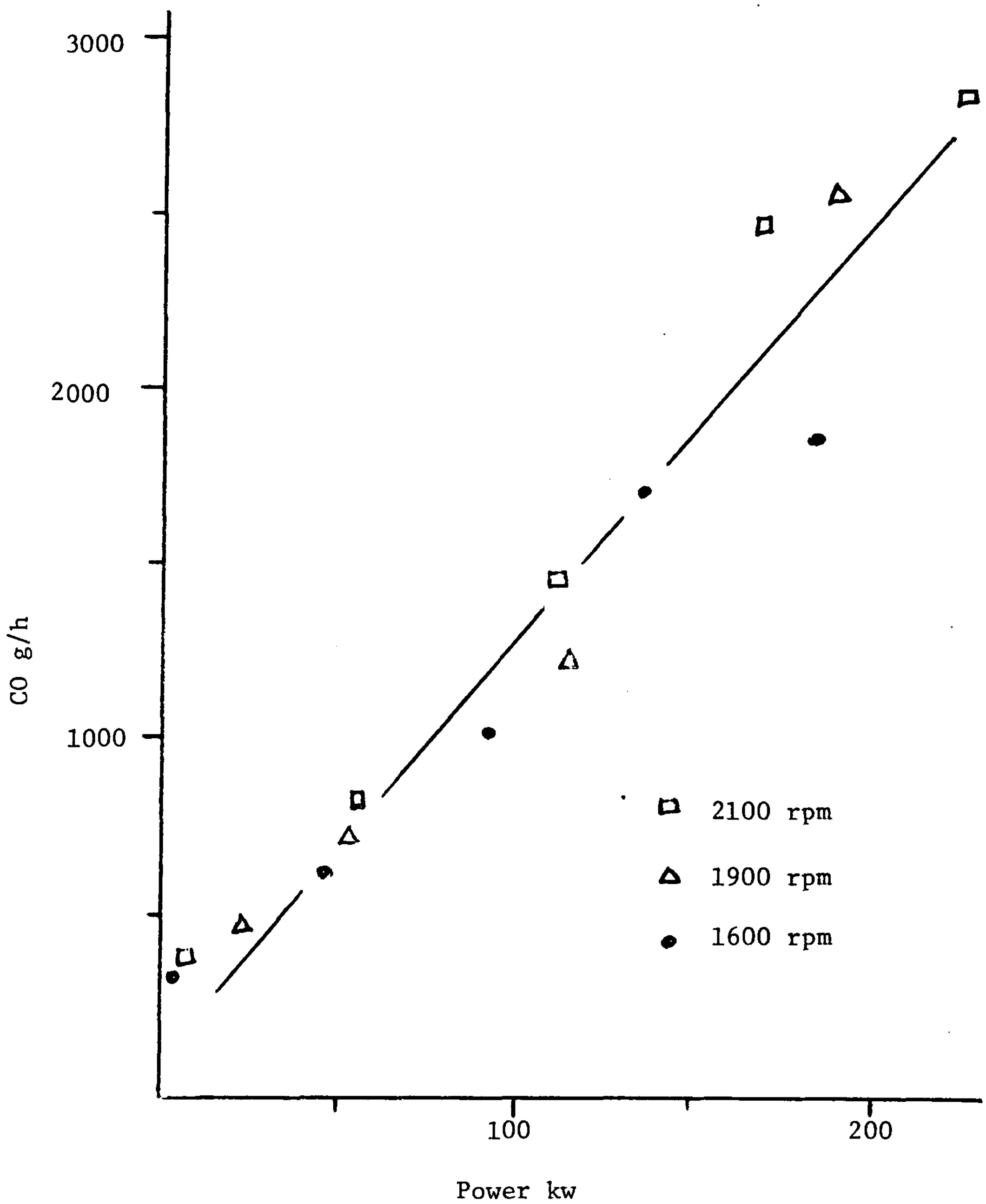
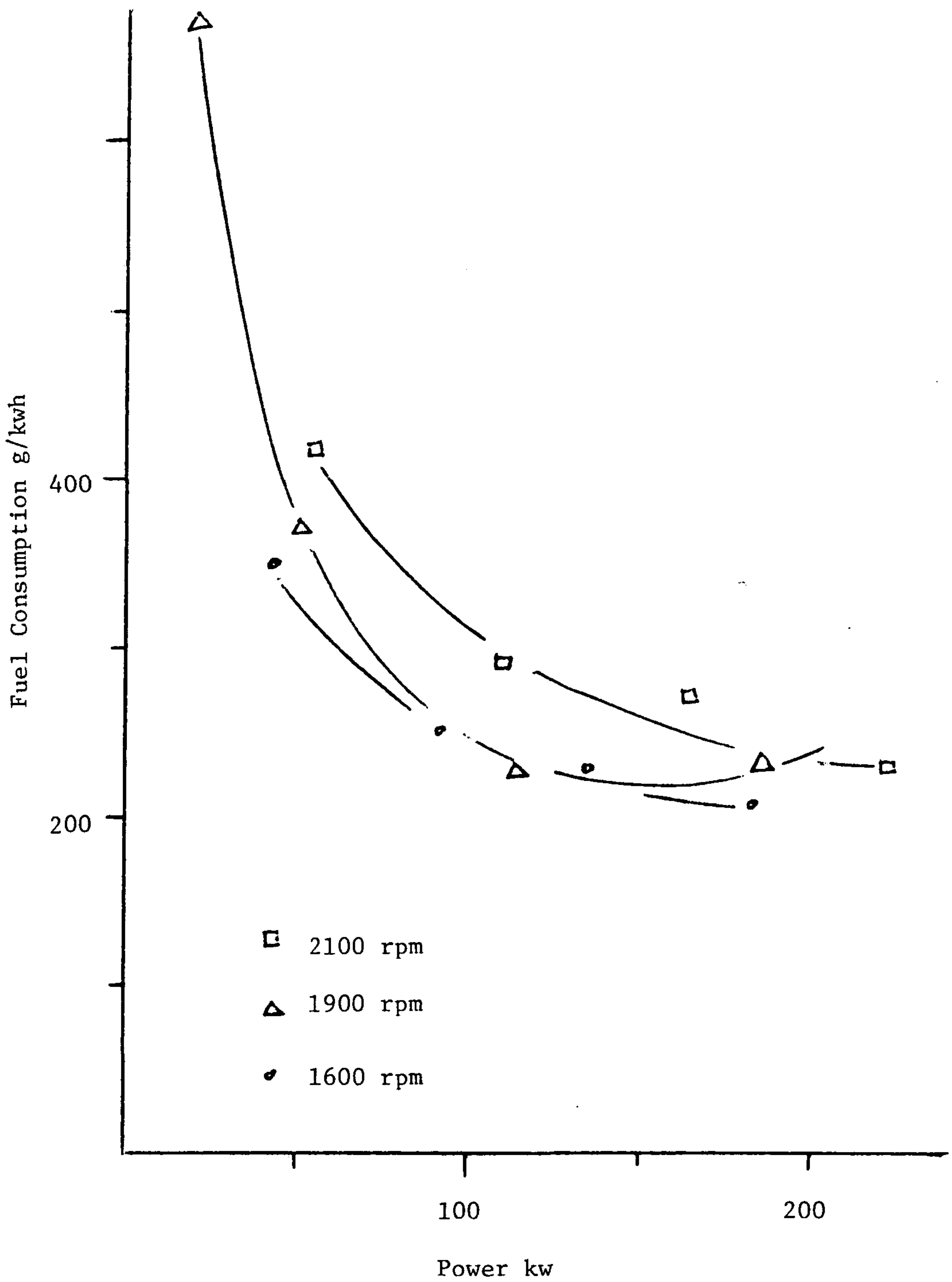


Figure 11

Fuel Consumption, Steady State



B. Driving Cycle Emissions and Fuel Consumption

The overall unweighted average emissions for three test loads and four cycle categories are as follows:

HC 2.07 g/km
CO 28.0 g/km
NOx 29.2 g/km
Fuel 67.6 1/100 km

These results are drawn from Figure 1, "Summary of Results". They do not include emissions from the linearized cycles. Emissions and fuel consumptions, by vehicle load and driving cycle, are found in Figure 3 12-15.

Hydrocarbon emissions seem to be inversely related to vehicle speed. There is no real discernable change with load. This relationship can be seen in Figure 16 where hydrocarbon emissions have been plotted as a function of average cycle speed. For this graph, the averages for each combination of cycle category and vehicle load have been plotted. Linearized cycle results are omitted.

Fuel consumption was derived from a "carbon balance" on the exhaust constituents.

Emissions were also calculated on the basis of grams of pollutant per kilogram of fuel consumed. Averages for all the transient driving cycles are listed by cycle category and load condition in Figure 17. The most interesting point about this figure is the extreme stability of NOx emissions. They vary from 47 to 57 grams per kilogram of fuel. And, except for carbon monoxide, the overall emissions agree fairly closely with those observed from the 9- and 13-mode tests.

Emissions g/kg Fuel

Test	HC	CO	NOx
9-mode	3.81	11.94	47.40
13-mode	3.58	29.78	48.23
Transient Cycles	3.63	46.4	50.86

As will be pointed out below, carbon monoxide emissions are extremely variable in their own right.

Figure 12

HC Emissions (g/km)

Category	Type	No.	Empty	Half	Full
NY-NF	Original	23	2.89		
	Lin 23	48		2.91	
	Original	41	3.42	3.08	4.01
		42	3.54		3.24
	Hand Gen.	39	4.67		2.84
		40	4.61	3.34	2.62
	Speed. Scr.	32	2.41	3.26	3.79
LA-NF	Original	07			2.08
	Lin 07	11	2.82	2.52	2.70
	Original	08	3.19	2.17	2.44
	Lin 08	12	2.44	2.60	2.89
	Original	09	2.62	1.95	2.36
	Lin 09	13	2.79	2.28	2.55
	Original	20			2.10
	Lin 20	47	1.82	1.87	1.95
	Original	54	1.88	2.33	2.58
NY-FWY	Original	44	1.31	1.54	1.44
		45	1.42	1.66	1.45
		46	1.37	1.57	1.47
	Speed Scr.	31		1.70	1.81
LA-FWY	Original	28		1.20	1.36
		52	1.02	1.02	1.11
		53	0.81	0.87	0.92
St. L-NF	Special	51	2.35	2.41	
Composite	Special	50		2.70	

Figure 13

CO Emissions (g/km)

Category	Type	No.	Empty	Half	Full
NY-NF	Original	23	13.96	--	--
	Lin 23	48	--	7.55	--
	Original	41	4.39	18.98	28.48
		42	4.64	27.13	50.18
	Hand Gen.	39	13.42	--	33.31
		40	10.05	24.84	29.55
	Spd. Scr.	32	36.87	50.13	84.12
LA-NF	Original	07	--	--	21.66
	Lin 07	11	3.88	17.31	25.90
	Original	08	6.19	16.29	17.01
	Lin 08	12	5.28	14.79	14.76
	Original	09	4.56	17.09	13.63
	Lin 09	13	3.76	9.44	20.55
	Original	20	--	--	32.41
	Lin 20	47	7.26	18.63	26.74
	Original	54	7.87	16.24	35.80
NY-FWY	Original	44	11.35	36.61	52.57
		45	8.81	42.79	29.48
		46	10.91	41.96	43.55
	Spd. Scr.	31	--	22.89	26.11
LA-FWY	Original	28	--	17.81	42.10
		52	20.54	34.58	64.26
		53	22.82	46.75	80.51
St. L-NF	Special	51	5.70	25.04	--
Composite	Special	50	--	11.09	--

Figure 14

NOx Emissions (g/km)

Category	Type	No.	Empty	Half	Full
NY-NF	Original	23	21.67	--	--
	Lin 23	48	--	21.77	--
	Original	41	22.49	30.81	36.80
		42	25.20	31.74	38.78
	Hand Gen.	39	23.92	--	36.70
		40	25.53	35.13	40.66
	Spd. Scr.	32	26.82	40.19	50.46
LA-NF	Original	07	--	--	31.48
	Lin 07	11	17.02	25.25	34.18
	Original	08	18.71	25.27	26.50
	Lin 08	12	18.43	24.51	29.71
	Original	09	17.77	25.28	25.13
	Lin 09	13	18.22	23.95	31.01
	Original	20	--	--	40.62
	Lin 20	47	23.20	26.78	36.33
	Original	54	22.04	27.44	36.37
NY-FWY	Original	44	20.41	28.71	33.74
		45	19.12	29.21	37.61
		46	18.15	29.96	34.11
	Spd. Scr.	31	--	28.60	34.36
LA-FWY	Original	28	--	31.61	32.33
		52	26.87	30.66	34.91
		53	24.81	29.17	33.55
St. L-NF	Special	51	17.07	19.44	--
Composite	Special	50	--	25.04	--

Figure 15

Fuel Consumption (1/100 km)

Category	Type	No.	Empty	Half	Full
NY-NF	Original	23	55.6	--	--
	Lin 23	48	--	63.3	--
	Original	41	58.0	73.5	84.0
		42	65.8	76.3	90.1
	Hand Gen.	39	56.8	--	75.2
		40	60.8	73.1	84.5
	Spd. Scr.	32	65.7	96.4	116.6
LA-NF	Original	07	--	--	74.6
	Lin 07	11	48.6	67.2	82.2
	Original	08	53.0	65.2	64.7
	Lin 08	12	50.6	65.2	73.8
	Original	09	48.7	65.7	62.6
	Lin 09	13	56.8	67.9	76.7
	Original	20	--	--	85.7
	Lin 20	47	46.0	63.4	78.8
	Original	54	56.2	68.3	86.1
NY-FWY	Original	44	48.7	69.1	74.2
		45	48.2	69.2	76.2
		46	46.5	69.6	72.4
	Spd. Scr.	31		67.3	72.9
LA-FWY	Original	28	--	58.2	70.7
		52	57.9	66.5	80.0
		53	56.1	65.1	79.6
St. L-NF	Special	51	46.8	52.0	--
Composite	Special	50	--	62.8	

Figure 16

HC Emissions

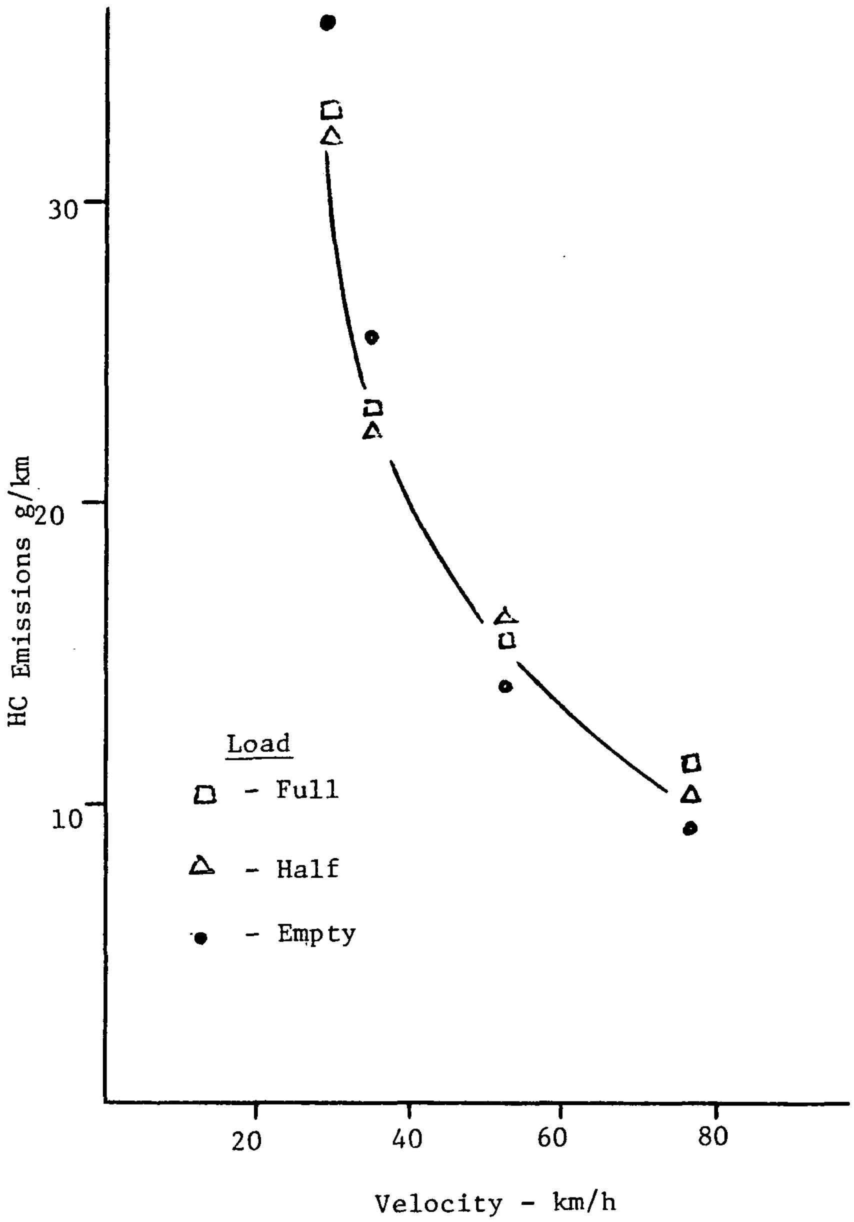


Figure 17

Average Emission Indices

Pollutant	Cycle Category	g/kg fuel Load Empty	Half	Full	Overall Average
HC	NY-NF	6.84	4.81	4.36	
	LA-NF	5.75	3.82	3.72	
	NY-FWY	3.37	2.78	2.47	
	LA-FWY	1.89	1.94	1.85	3.36
CO	NY-NF	27.5	45.2	56.9	
	LA-NF	13.7	29.4	36.9	
	NY-FWY	25.2	61.7	60.7	
	LA-FWY	44.9	60.9	93.9	46.4
NOx	NY-NF	47.6	51.7	53.6	
	LA-NF	43.3	48.5	50.3	
	NY-FWY	47.4	50.0	55.8	
	LA-FWY	53.4	57.2	51.5	50.86

C. Variability

One of the reasons for running this experiment was to see if different cycles representing the same type of operation would give the same emission levels. The standard statistical tool used for making such determinations is called analysis of variance. Under this technique, emissions are assumed to be equal to the average value, adjusted for cycle and test variability. If the cycle variation is "small", then it can be stated that the driving cycles yield identical results. "Small" is defined in terms of the test variability.

Ideally, all cycles in each category of operation should yield the same test results. This conclusion comes from the fact that they all were generated from the same input data and have all passed the same statistical "filter". It would also be expected that the test to test variability would be approximately the same for each cycle in the category.

An analysis of variance was performed for all the non-linearized driving cycles. Separate calculations were made for HC, CO, and NOx emissions as well as fuel consumption. Each load condition and cycle category was examined individually; a total of 48 of these statistical checks were made. For most (35), the cycle variability was so much larger than the test variability that one can safely assume that the results were different. Even though results may be statistically different, that does not mean that there is any practical or engineering significance to these conclusions. For example, assume two cycles that yield average emissions of 36 and 36.5 g/km. The test variability might be so low that the cycles will be deemed to be statistically different.

The reader is left to draw his or her own conclusions.

D. Linearized Driving Cycles

In order to determine if full transient operation has any effect on diesel emissions, "linearized" driving cycles were run. These driving cycles are much like the light-duty vehicle 7-mode test, with steady state cruises and constant rate accelerations and decelerations. Only emissions from the non-freeway Los Angeles category were investigated. Each linearized cycle was created to closely approximate a transient cycle. By comparing the emissions and fuel consumption between the cycle pairs, the effect of linearization should be revealed. Results are listed in Figure 18. No real pattern can be established. It does seem that hydrocarbons are slightly higher and CO is slightly lower on the linearized cycles. Certainly the difference is not very large.

E. Cold Start Emissions

Six cold start tests were run. These tests were selected to cover the range of cycle categories and load conditions. In order to minimize the effect of having a cold dynamometer gear box, the dynamometer, truck axle and truck transmission were motored prior at the start of each test. Results are listed in Figure 19; driving cycles have been listed in order of decreasing fuel consumed. (As the truck consumed fuel it would gradually warm-up; the effects of cold start operation should be

Figure 18

Linearized Cycle Emissions

Ratio of Emissions (Linear/Transient)

Item	Cycle No.	Load Empty	Half	Full	Overall Average
HC	07			1.30	
	08	0.76	1.20	1.18	
	09	1.06	1.17	1.08	
	20	1.02	0.94	1.31	
					1.10
CO	07			1.20	
	08	0.85	0.91	0.87	
	09	0.82	0.55	1.50	
	20	0.51	0.43	0.53	
					0.82
NOx	07			1.09	
	08	0.98	0.97	1.12	
	09	1.02	0.95	1.23	
	20	0.99	0.81	0.91	
					1.01
Fuel	07			1.10	
	08	0.95	1.00	1.14	
	09	1.17	1.03	1.23	
	20	0.99	0.84	0.93	
					1.04

Figure 19

Cold Start Emissions

Cycle #	Cycle Category	Load	Total Fuel	-Ratios (Cold/Hot)- HC	CO	NOx	Fuel
20	LA-NF	Full	3181g	0.93	0.84	0.94	1.05
52	LA-FWY	Half	2827	0.96	0.91	0.92	1.05
47	LA-NF	Empty	1900	0.80	1.21	1.10	1.18
54	LA-NF	Empty	865	0.83	1.36	1.03	1.22
32	NY-NF	Half	654	0.98	0.91	1.10	1.15
41	NY-NF	Half	547	0.66	1.11	1.17	1.22
		AVERAGE		0.86	1.06	1.04	1.14

most readily visible on those driving cycles that consumed the least amount of fuel.) It appears that hydrocarbon emissions are lower during cold start tests. However, this may be due to that fact the HFID sampling line, while warm, may not be stabilized for the first test of each day. As would be expected, more fuel was consumed during a cold start.

F. Tire Slip

This experiment was not planned as part of the original test sequence. It was prompted by a small quantity of tire rubber which piled up after several thousand miles of truck use. This rubber was first noticed after a series of runs under high load conditions.

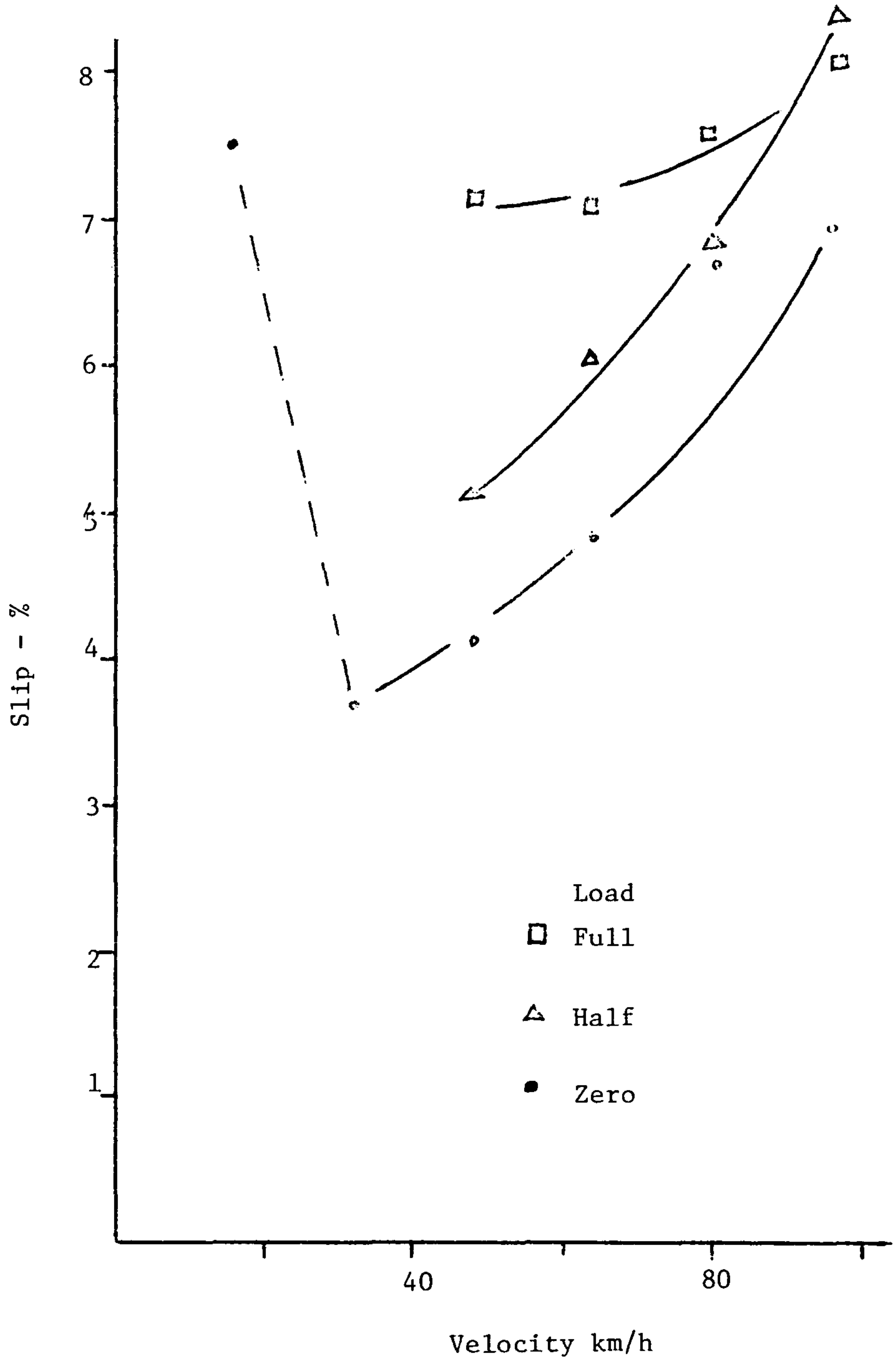
To perform this experiment, the transmission output shaft and dynamometer roll were equipped with high resolution revolution counters. The number of revolutions were then recorded by digital counters. In order to determine the "no-slip ratio", the dynamometer was used to motor the truck with transmission in neutral over the range of speed operation. This "no-slip ratio" was fairly constant with speed, having a coefficient of variation of less than 1 percent.

The experiment was run with the dynamometer in speed control. The vehicle operator used the accelerator pedal to control the amount of power. Three sequences were run at various speeds. The first sequence, called "Zero power" was run with the truck just over coming all the dynamometer friction. (While it is not really zero power, it is a very small percentage of the maximum output.) The next two runs were run at half and full power. Results are expressed in Figure 20 as a percentage change from the previously defined "no-slip ratio".

These results are most confusing. Expecially the initial point on the zero load line, indicating approximately 7.5 percent slip at a rather low roll speed and power condition. This particular data point represents three replicates; these data were part of the sequence for the rest of the zero load line. The three replicates agree very closely, no explanation is available. The remaining data points seem to make more sense. They imply that as vehicle speed and load increase, the tire slip increases. These could also indicate that the tire is deforming more at higher speeds and load conditions, perhaps giving a smaller rolling radius. This would be indicated as "slip". In any event, this is an interesting topic and probably merits further consideration if chassis testing of large vehicles is to be done.

Figure 20

Tire Slip



VI. General Observations

This experiment proves that a large vehicle can be tested for emissions on a chassis dynamometer. However, in spite of this success, several problems developed during the test sequence which deserve further discussion.

Both the dynamometer setting procedure and the stability of the dynamometer calibration remain troublesome. Further work remains to be done in this area. EPA's large roll tandem axle chassis dynamometer is not a very stable piece of equipment. Its calibration curves shift and it is very difficult to set accurately. This is unfortunate, in light of the success with the track coastdown project.

Another troublesome piece of equipment is the heated flame ionization detector. While hydrocarbon emissions from diesels are not a problem, it is somewhat difficult to measure them accurately. The HFID sample line seems to adsorb and desorb hydrocarbons, thus increasing the response time of the instrument. It is uncertain exactly how much hang-up does occur. This is true even with the sample line at 175°C, the recommended temperature for such work.

Some of the emission test variability may be due to the fact that different drivers operated the test vehicle at different times in the program. Also, some slight variations in shift pattern occurred. In future programs, it is recommended that more emphasis be given to the gear shifting procedure.

Appendix A

Raw Emission Data

Run No.	Load	Cycle	Run	Distance	HC	Emissions CO	NOx	L/100 km	Fuel Used Calc.	Measured
8	Empty	34	1	0.98	2.61	13.58	24.90	49.0	407	490
			2	0.98	2.68	12.84	25.46	61.2	509	490
			3	0.98	2.61	16.72	25.84	61.8	514	510
			Ave.	0.98	2.63	14.38	25.40	57.3	477	497
9	Empty	39	1	0.97	4.69	12.47	24.18	57.6	474	480
			2	0.95	5.01	11.54	24.88	59.2	477	490
			3	0.95	4.32	16.26	22.69	53.6	432	465
			Ave.	0.96	4.67	13.42	23.42	56.8	461	478
10	Empty	40	1	1.00	4.24	11.44	25.19	59.4	504	660
			2	1.00	3.05	8.74	26.62	60.5	513	480
			3	0.98	6.55	9.97	25.79	62.6	520	380
			Ave.	0.99	4.61	10.05	25.53	60.8	512	507
11	Empty	41	1	0.88	3.68	3.66	22.47	57.5	429	449
			2	0.88	3.22	3.89	23.10	59.4	443	448
			3	0.88	3.35	5.62	21.90	57.1	426	435
			Ave.	0.88	3.42	4.39	22.49	58.0	433	444
12	Empty	42	1	0.97	3.48	3.65	24.96	65.6	540	571
			2	0.95	3.45	5.00	24.97	69.1	547	549
			3	0.95	3.70	5.27	24.67	63.6	512	532
			Ave.	0.96	3.54	4.64	25.20	65.8	534	551
13	Empty	44	1	3.59	1.35	11.02	20.58	49.7	1513	1500
			2	3.52	1.20	11.31	20.28	47.7	1424	1475
			3	3.60	1.37	11.72	20.38	48.6	1483	1490
			Ave.	3.57	1.31	11.35	20.41	48.7	1473	1488
14	Empty	45	1	3.57	1.36	9.28	19.35	48.7	1474	1420
			2	3.57	1.46	8.40	18.95	48.2	1459	1390
			3	3.57	1.43	8.76	19.07	47.6	1441	1390
			Ave.	3.57	1.42	8.81	19.12	48.2	1458	1400

Run No.	Load	Cycle	Run	Distance	HC	Emissions CO	NOx	L/100 km	Fuel Used Calc.	Measured
1	Empty	08	1	2.12	2.92	7.24	18.91	53.1	954	990
			2	2.14	3.30	5.87	18.97	54.0	980	1000
			3	2.16	3.36	5.46	18.24	51.9	949	1050
			Ave.	2.14	3.19	6.19	18.71	53.0	962	1013
2	Empty	09	1	2.09	2.99	4.32	17.52	48.4	859	980
			2	2.12	2.55	4.72	18.18	50.9	915	620
			3	2.11	2.32	4.63	17.62	46.8	837	680
			Ave.	2.11	2.62	4.56	17.77	48.7	887	811
3	Empty	11	1	1.88	2.61	4.06	17.69	49.7	792	725
			2	1.88	2.99	3.78	16.26	47.1	751	954
			3	1.88	2.85	3.80	17.12	49.1	783	825
			Ave.	1.88	2.82	3.88	17.02	48.6	775	835
4	Empty	12	1	2.04	2.54	5.99	19.12	51.8	896	1222
			2	2.09	2.33	4.86	18.18	50.4	893	1245
			3	2.08	2.44	4.98	18.00	49.5	873	1160
			Ave.	2.07	2.44	5.28	18.43	50.6	887	1209
5	Empty	13	1	2.03	2.81	3.80	17.66	56.3	969	1180
			2	2.03	2.80	3.46	17.87	55.6	957	1260
			3	2.03	2.76	4.02	19.14	58.5	1007	1153
			Ave.	2.03	2.79	3.76	18.22	56.8	979	1198
6	Empty	23	1	1.85	2.77	15.62	21.96	56.8	890	880
			2	1.87	2.89	13.51	21.06	55.0	872	883
			3	1.87	3.02	12.75	22.00	54.9	870	915
			Ave.	1.86	2.89	13.96	21.67	55.6	877	893
7	Empty	32	1	0.84	2.73	42.36	25.95	64.6	458	525
			2	0.84	2.26	33.55	27.54	65.7	466	515
			3	0.85	2.41	34.71	26.77	66.7	482	535
			Ave.	0.84	2.46	36.87	26.82	65.7	469	525

Run No.	Load	Cycle	Run	Distance	Emissions HC	Emissions CO	Emissions NOx	L/100 km	Fuel Used Calc.	Fuel Used Measured
15	Empty	46	1	3.41	1.41	10.82	18.75	49.1	1420	1420
			2	3.43	1.29	12.30	18.82	47.9	1393	1390
			3	3.43	1.41	9.60	16.89	42.4	1233	1390
			Ave.	3.42	1.37	10.91	18.15	46.5	1349	1400
16	Empty	47	1	3.81	1.45	8.81	26.64	66.3	2144	2210
			2	3.96	1.81	7.06	23.27	56.5	1897	1935
			3	3.98	1.76	6.81	23.00	54.8	1847	1970
			Cold Start Test (No Averages)							
17	Empty	47	1	3.99	1.85	7.93	24.09	58.4	1976	1965
			2	4.01	1.78	7.03	22.82	54.9	1865	1950
			3	4.01	1.82	6.83	22.68	54.7	1858	1950
			Ave.	4.00	1.82	7.26	23.19	56.0	1400	1955
18	Empty	51	1	3.72	2.35	5.70	17.71	46.8	1476	1560
19	Empty	52	1	5.21	1.07	20.69	26.90	58.2	2573	2580
			2	5.25	1.02	21.14	27.08	58.2	2587	2575
			3	5.26	0.98	19.78	26.63	57.2	2552	2560
			Ave.	5.24	1.02	20.54	26.87	57.9	2511	2572
20	Empty	53	1	5.20	0.80	24.57	25.79	56.0	2468	2525
			2	5.21	0.83	21.86	23.43	56.8	2511	2530
			3	5.23	0.78	22.03	25.20	55.6	2466	2470
			Ave.	5.21	0.81	22.82	24.81	56.1	2482	2508
21	Empty	54	1	1.84	1.56	10.67	22.79	68.6	1067	1280
			2	1.84	1.84	8.79	20.31	58.7	913	965
			3	1.80	2.10	7.87	19.30	55.6	850	890
			Cold Start Test (No Averages)							
22	Empty	54	1	1.82	1.94	7.14	22.20	56.5	871	915
			2	1.80	1.75	8.59	21.91	56.9	869	900
			3	1.82	1.96	7.88	21.93	55.3	853	935
			Ave.	1.81	1.88	7.87	22.04	56.2	865	917

Run No.	Load	Cycle	Run	Distance	Emissions HC	CO	NOx	L/100 km	Fuel Used Calc.	Measured
23	Half	08	1	2.12	2.22	18.27	24.74	63.8	1147	1160
			2	2.11	2.32	14.95	25.80	67.5	1208	1225
			3	2.12	1.97	15.65	25.28	64.4	1158	1170
			Ave.	2.12	2.17	16.29	25.27	65.2	1171	1185
24	Half	09	1	2.03	1.89	19.48	25.34	66.3	1141	1120
			2	2.06	1.95	17.67	25.15	65.0	1135	1145
			3	2.04	2.02	14.12	25.36	65.7	1136	1150
			Ave.	2.04	1.95	17.09	25.28	65.7	1137	1138
25	Half	11	1	1.82	2.88	18.39	26.20	70.0	1080	1090
			2	1.82	2.39	17.95	26.98	70.8	1093	1075
			3	1.82	2.30	15.59	22.58	60.8	938	1090
			Ave.	1.82	2.52	17.31	25.25	67.2	1037	1080
26	Half	12	1	2.00	2.80	16.64	25.31	66.5	1128	1140
			2	2.01	2.55	13.87	24.08	64.4	1098	1095
			3	2.00	2.44	13.86	24.15	64.6	1095	1110
			Ave.	2.00	2.60	14.79	24.51	65.2	1107	1115
27	Half	13	1	2.03	2.54	10.34	25.31	67.8	1167	1185
			2	2.04	2.21	9.47	23.51	67.7	1171	1180
			3	2.01	2.10	8.52	24.49	68.2	1162	1180
			Ave.	2.03	2.28	9.44	23.95	67.9	1167	1182
28	Half	28	1	10.46	1.23	17.26	32.48	58.7	5206	5040
			2	10.49	1.21	18.29	31.81	58.1	5168	5565
			3	10.49	1.15	17.88	30.54	57.9	5150	5510
			Ave.	10.48	1.20	17.81	31.61	58.2	5175	5372
29	Half	31	1	3.06	1.86	24.43	29.28	69.7	1808	1990
			2	3.20	1.55	20.46	28.41	66.3	1799	1830
			3	3.20	1.68	23.78	28.10	65.8	1785	1790
			Ave.	3.15	1.70	22.89	28.60	67.3	1797	1870

Run						Emissions			Fuel Used	
No.	Load	Cycle	Run	Distance	HC	CO	NOx	L/100 km	Calc.	Measured
30	Half	32	1	0.80	3.22	52.22	38.62	94.8	643	685
			2	0.80	3.36	48.05	40.86	97.0	658	670
			3	0.80	3.21	50.11	41.10	97.4	661	690
			Ave.	0.80	3.26	50.13	40.19	96.4	654	682
31	Half	32	1	0.80	3.22	46.79	44.08	110.6	755	1010
			2	0.82	3.22	53.06	39.37	100.7	701	710
			3	0.77	3.14	86.63	35.11	93.3	611	630
			Cold Start Test (No Averages)							
32	Half	34	1	0.92	3.59	24.40	36.65	83.8	654	660
			2	0.92	3.53	29.18	35.24	81.3	634	685
			3	0.93	2.85	13.36	20.34	53.5	422	430
			Ave.	0.92	3.32	22.31	30.74	72.9	570	592
33	Half	40	1	0.97	4.00	22.76	33.84	70.4	579	650
			2	0.93	3.18	26.70	36.10	76.6	604	625
			3	0.94	2.83	25.07	35.45	72.4	577	615
			Ave.	0.95	3.34	24.84	35.13	73.1	587	630
34	Half	41	1	0.85	2.04	20.99	36.08	89.5	645	820
			2	0.87	2.63	18.27	31.71	77.7	573	600
			3	0.88	2.75	11.31	25.62	63.9	477	570
			Cold Start Test (No Averages)							
35	Half	41	1	0.88	3.20	16.96	30.91	73.6	549	555
			2	0.87	3.15	20.85	31.14	73.3	541	545
			3	0.88	2.88	19.14	30.38	73.7	550	545
			Ave.	0.88	3.08	18.98	30.81	73.5	547	548
36	Half	42	1	0.93		25.07	33.53	81.6	643	665
			2	0.95	N/A	27.79	32.29	77.1	621	650
			3	0.93		28.52	29.40	70.2	554	655
			Ave.	0.94		27.13	31.74	76.3	606	657

Run No.	Load	Cycle	Run	Distance	HC	Emissions CO	NOx	L/100 km	Fuel Used Calc.	Measured
37	Half	44	1	3.38	1.55	42.95	31.06	77.1	2210	2295
			2	3.41	1.64	35.35	29.41	70.8	2047	2090
			3	3.43	1.42	31.52	25.66	59.4	1728	2085
			Ave.	3.41	1.54	36.61	28.71	69.1	1995	2157
38	Half	45	1	3.38	1.87	46.89	31.81	74.5	2135	2060
			2	3.38	1.62	43.80	29.18	70.2	2012	2030
			3	3.41	1.48	37.69	26.64	62.9	1819	2030
			Ave.	3.39	1.66	42.79	29.21	69.2	1989	
39	Half	46	1	3.32	1.79	50.64	30.57	71.4	2010	2030
			2	3.33	1.52	38.95	30.69	70.4	1988	2030
			3	3.30	1.41	36.28	28.62	67.0	1875	2030
			Ave.	3.32	1.57	41.96	29.96	69.6	1958	2030
40	Half	47	1	3.96	1.82	19.06	27.73	66.6	2236	2230
			2	3.96	2.01	17.80	25.74	60.1	2018	2235
			3	3.96	1.78	19.02	26.87	63.4	2129	2225
			Ave.	3.96	1.87	18.63	26.78	63.5	2128	2230
41	Half	48	1	1.84	2.95	8.15	22.37	65.2	1017	1035
			2	1.87	2.99	7.13	21.51	62.6	995	990
			3	1.85	2.78	7.38	21.38	62.0	973	1010
			Ave.	1.85	2.91	7.55	21.77	63.3	994	1012
42	Half	51	1	3.67	2.41	25.04	19.45	52.0	1618	1630
43	Half	50	1	9.27	3.84	10.82	28.07	71.1	5000	5140
			2	9.37	3.69	11.58	27.11	65.6	4916	5035
			Ave.	9.32	3.77	11.20	27.59	68.4	4958	5088
44	Half	52	1	4.89	0.98	31.51	28.14	69.5	2882	2955
			2	5.02	1.05	31.05	29.00	66.7	2839	2845
			3	4.99	0.97	32.50	29.51	66.1	2797	2795

Cold Start Test (No Averages)

Run No.	Load	Cycle	Run	Distance	HC	Emissions CO	NOx	L/100 km	Fuel Used Calc.	Measured
45	Half	52	1	4.97	1.10	34.12	31.15	67.3	2836	2810
			2	5.04	0.99	36.15	30.52	66.2	2828	2800
			3	5.04	0.98	33.48	30.30	65.9	2816	2795
			Ave.	5.02	1.02	34.58	30.66	66.5	2827	2802
46	Half	53	1	5.10	0.98	44.56	30.27	66.6	2829	3015
			2	5.04	0.85	51.16	29.83	67.2	2872	2890
			3	5.09	0.79	44.52	27.40	61.6	2659	2900
			Ave.	5.08	0.87	46.75	29.17	65.1	2787	2935
47	Half	54	1	1.80	2.30	15.86	28.37	69.0	1053	1090
			2	1.80	2.33	16.86	28.04	70.4	1074	1115
			3	1.80	2.37	16.01	25.92	65.6	1001	1085
			Ave.	1.80	2.33	16.24	27.44	68.3	1043	1097
48	Full	07	1	1.93	2.03	27.79	32.84	78.1	1278	1280
			2	1.93	2.17	16.48	30.29	72.2	1182	1310
			3	1.96	2.05	20.72	31.32	73.4	1220	1325
			Ave.	1.94	2.08	21.66	31.48	74.6	1227	1305
49	Full	08	1	2.06	2.84	22.74	33.24	77.3	1350	1400
			2	2.04	2.30	21.32	33.67	76.9	1330	1440
			3	2.09	2.17	4.54	12.58	39.8	705	860
			Ave.	2.06	2.44	16.20	26.50	64.7	1128	1233
50	Full	09	1	2.04	2.76	4.41	13.64	42.7	739	820
			2	2.03	2.22	10.51	33.10	76.7	1320	1410
			3	2.08	2.10	25.97	28.65	68.4	1206	1445
			Ave.	2.05	2.36	13.63	25.13	62.6	1088	1225
51	Full	11	1	1.80	2.69	24.24	33.84	81.9	1250	1360
			2	1.80	2.71	27.55	34.52	82.4	1258	1340
			Ave.	1.80	2.70	25.90	34.18	82.2	1254	1350

Run No.	Load	Cycle	Run	Distance	Emissions HC	CO	NOx	L/100 km	Fuel Used Calc.	Measured
52	Full	12	1	1.98	2.60	20.83	32.01	76.4	1283	1395
			2	2.01	2.59	20.35	32.43	76.4	1302	1400
			3	1.98	2.46	20.46	28.60	68.5	1150	1385
			Ave.	1.99	2.55	20.55	31.01	73.8	1245	1393
53	Full	13	1	1.98	2.50	14.72	30.27	78.3	1315	1435
			2	2.00	3.45	15.13	31.00	80.0	1357	1530
			3	2.00	2.72	14.44	27.86	71.8	1218	1330
			Ave.	1.99	2.89	14.76	29.71	76.7	1297	1432
54	Full	20	1	3.81	2.25	32.63	41.98	88.5	2859	2785
			2	3.98	2.03	31.97	39.17	81.2	2740	2880
			3	3.96	2.02	32.62	40.72	87.5	2938	2810
			Ave.	3.92	2.10	32.41	40.62	85.7	2846	2825
55	Full	28	1	9.99	1.47	38.88	30.67	67.6	5726	4710
56	Full	31	1	3.06	1.86	25.64	34.19	72.3	1876	1945
			2	3.11	1.79	25.08	34.34	72.5	1912	1960
			3	3.06	1.77	27.61	34.56	73.9	1917	1945
			Ave.	3.08	1.81	26.11	34.36	72.9	1902	1950
57	Full	32	1	0.79	4.36	81.75	50.38	116.2	758	810
			2	0.76	3.57	76.73	51.23	117.6	758	800
			3	0.77	3.43	93.89	49.77	116.0	757	805
			Ave.	0.77	3.79	84.12	50.46	116.6	758	805
58	Full	34	1	0.90	3.56	55.89	41.85	93.7	715	740
			2	0.90	3.14	49.88	43.71	93.5	714	700
			3	0.84	3.12	51.89	42.61	91.3	650	720
			Ave.		3.27	52.88	42.72	92.8	693	720

Run					Emissions				Fuel Used	
No.	Load	Cycle	Run	Distance	HC	CO	NOx	L/100 km	Calc.	Measured
59	Full	39	1	1.05	2.62	38.95	34.44	72.1	642	650
			2	1.05	3.01	32.17	37.22	75.5	672	665
			3	1.03	2.88	28.82	38.44	78.0	681	655
			Ave.	1.04	2.84	33.31	36.70	75.2	665	657
60	Full	40	1	1.00	2.55	21.59	38.58	76.8	651	835
			2	1.06	2.79	34.76	42.15	88.2	793	835
			3	1.03	2.51	32.31	41.24	88.5	773	825
			Ave.	1.03	2.61	29.55	40.66	84.5	739	832
61	Full	41	1	0.85	4.97	29.20	37.48	86.1	621	680
			2	0.84	3.68	30.91	38.10	87.1	620	695
			3	0.87	3.38	25.34	34.83	78.7	581	680
			Ave.	0.85	4.01	28.48	36.80	84.0	607	685
62	Full	42	1	0.92	3.42	69.10	37.99	89.6	699	755
			2	0.93	3.31	42.43	40.20	93.0	733	755
			3	0.93	2.99	39.02	38.15	87.6	691	725
			Ave.	0.93	3.24	50.18	38.78	90.1	708	745
63	Full	44	1	3.33	1.48	60.78	34.83	79.5	2245	2160
			2	3.33	1.43	50.65	34.52	74.9	2115	2180
			3	3.35	1.40	46.28	31.87	68.1	1934	2135
			Ave.	3.34	1.44	52.57	33.74	74.2	2098	2158
64	Full	45	1	3.28	1.33	34.67	38.76	82.2	2286	2450
			2	3.25	1.48	29.53	38.45	77.2	2128	2100
			3	3.27	1.55	24.23	35.62	69.2	1919	2090
			Ave.	3.27	1.45	29.48	37.61	76.2	2111	2213
65	Full	46	1	3.15	1.74	49.19	35.38	76.2	2035	2100
			2	3.17	1.50	45.14	37.04	77.6	2086	2085
			3	3.19	1.17	36.31	29.91	63.4	1715	2090
			Ave.	3.17	1.47	43.55	34.11	72.4	1945	2092

Run No.	Load	Cycle	Run	Distance	Emissions HC	CO	NOx	L/100 km	Fuel Used Calc.	Measured
66	Full	47	1	3.81	2.12	32.52	37.34	82.1	2652	2670
			2	3.90	1.91	24.28	35.68	76.9	2543	2715
			3	3.90	1.81	23.43	35.98	77.3	2556	2710
			Ave.	3.87	1.95	26.74	36.33	78.8	2584	2698
67	Full	52	1	4.46	1.29	50.21	35.61	79.4	3003	2965
			2	4.47	1.04	74.38	34.42	80.7	3059	2990
			3	4.62	0.99	68.19	34.71	80.0	3134	3060
			Ave.	4.52	1.11	64.26	34.91	80.0	3065	3005
68	Full	53	1	4.46	0.91	80.99	33.07	78.6	2972	3010
			2	4.60	0.93	78.74	34.57	81.0	3159	3110
			3	4.54	0.91	81.81	33.00	79.2	3049	3100
			Ave.	4.53	0.92	80.51	33.55	79.6	3060	3073
69	Full	54	1	1.77	2.72	35.27	36.52	87.1	1307	1360
			2	1.80	2.64	35.92	37.60	89.1	1360	1390
			3	1.80	2.78	36.22	34.98	82.2	1255	1375
			Ave.	1.79	2.58	35.80	36.37	86.1	1307	1375

Appendix B

Driving Cycle Identification

Cycle No.	Identification No.
07	152 778 878 5
08	210 620 459 3
09	211 939 981 9
11	Linear 07
12	Linear 08
13	Linear 09
20	213 884 237 5
23	155 897 487
28	131 162 575 9
31	203 708 236 5
32	212 012 741 3
34	210 952 317 5
39	WYSOR I
40	WYSOR II
41	123 667 645 7
42	179 960 930 5
44	741 286 985
45	209 279 083 3
46	137 610 363
47	Linear 20
48	Linear 23
50	ROSSOW I
51	Linear
52	786 981 11
53	153 913 507 1
54	210 620 459 3