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Exhaust Emissions from a 25-Passenger Organic Rankine Cycle Bus

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Emission Control Technology Division
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Background

An Organic Rankine Cycle (ORC) power system designed and built by Sundstrand Aviation was installed in a small (25-passenger) transit bus, in a program to demonstrate the feasibility of such power systems in small buses. The work was done under a grant from the U.S. Department of Transportation to Dallas (Texas) Transit Systems. The installation was accomplished by LTV Aerospace Group, who were also the overall program managers.

After the installation of the ORC power system and an extensive period of shakedown, development and optimization, arrangements were made with Sundstrand for exhaust emissions tests at the Office of Mobile Source Air Pollution Control (OMSAPC), Ann Arbor laboratory. The tests of the ORC bus reported herein were conducted over a five-week period in March and April 1973.

The emissions tests were conducted by the Test and Evaluation Branch of the Emission Control Technology Division as part of a continuing effort to stay abreast of alternative power systems development and assess the emission control potential of such systems. Transportation of the bus from Sundstrand Aviation, Rockford, Illinois, to the Ann Arbor laboratory was provided by LTV. Sundstrand provided personnel to operate the bus and interpret engine parameter data.

Vehicle Description

The bus chosen for this project was a Twin Coach model TC-25 built by Highway Products, Inc. of Kent, Ohio. The engine usually installed in this 25-passenger bus is a 413 cubic inch displacement (CID) Chrysler gasoline-fueled V-8 internal combustion engine.

The Sundstrand-designed Organic Rankine Cycle power system installed in the bus is described in Reference 1 at the end of this report. Briefly, the power system includes a monotube heater that provides supercritical working fluid (CP-25, toluene) for a turbine expander. Turbine power output goes through a reducing gear box to the three-speed automatic transmission originally installed in the bus. Liquid propane is the fuel. The engine was installed in the rear of the bus in the normal engine compartment, with the condenser mounted on the roof of the bus at the rear.

The curb weight of the "stock" bus is about 10,500 pounds. The bus as tested with the ORC power system installed weighed about 14,000 pounds (2,500 lbs. front, 11,500 lbs. rear) due to instrumentation and an increased engine weight. All testing was done with an inertia weight of 12,800 pounds to simulate the weight of the standard TC-25 bus with 20 passengers.

Test Program

The ORC bus arrived at the Ann Arbor laboratory on Friday, March 16, 1973. Vehicle preparation and checkout took several days. Testing started on March 22 and continued through April 13. However, due to several equipment and vehicle problems, only a small number of tests were completed. These were principally a modified version of the 13-mode heavy duty diesel engine Federal test procedure. This modified procedure is similar to the heavy duty diesel engine test procedure developed by the California Air Resources Board and the Engine Manufacturers Association. This procedure, which will be referred to as the Federal 13-mode procedure, is described in SAE paper number 700671, and the Federal Register of November 15, 1972, Volume 37, Number 221, Part II.

For these tests a heavy duty electric chassis dynamometer was used which had motoring capability and permitted both speed and torque control. The dynamometer is equipped with large diameter (40") rolls to minimize slippage and tire loss problems. Rear wheel horsepower was measured and engine brake horsepower was then calculated to provide the basis for determining brake specific emissions.

The heavy duty diesel procedure is a steady state procedure for testing a diesel engine on an engine dynamometer with engine load as the operating variable at each of two engine speeds, "rated" and "intermediate". The load is varied from zero to maximum torque available at each of these two engine speeds, in steps of 25% of maximum torque. Three idle periods are interspersed among these load points, for a total of 13 operating modes. Rated speed is self-explanatory; the maximum allowable engine speed. Intermediate speed is defined in the procedure as "...peak torque speed or 60% of rated speed, whichever is higher." For the ORC power system, 32,000 and 20,000 rpm were selected as the rated and intermediate speeds, respectively, since these would give approximately the same transmission speeds as the internal combustion engine. The true rated speed of the ORC turbine expander is 35,000 rpm.

The 13-mode procedure calls for continuous analysis of exhaust pollutant concentrations and measurement of engine fuel and air consumption rates for calculation of exhaust pollutant mass emissions. However, for simplicity and ease of calculation in our tests of the ORC bus, the Constant Volume Sampling technique (CVS) was employed. In the CVS method a positive displacement air pump pulls a constant volume stream consisting of all the engine exhaust plus dilution air. From this mixture a small sample is pumped into an impermeable Tedlar plastic bag for analysis at the end of the test period. The product of pollutant mole concentration times pollutant density times constant volume flow rate, in appropriate units, gives pollutant mass emissions.

The sample bags were analyzed using the usual array of instruments: unburned hydrocarbons (HC) were measured with a flame ionization detector (FID), CO and CO_2 with non-dispersive infrared (NDIR) analyzers, and nitrogen oxides (NOx) with a chemiluminescence (CL) device. An attempt was made to run at steady speeds of 0, 15, 30, 45, and 60 mph with road load power settings. Only a few of these were successful because of power system problems.

Early in our testing of the ORC bus it became evident that it would be extremely difficult to obtain stable preselected horsepower settings due to the nature of the engine design and controls. To provide good off-design performance, the turbine is operated at a constant pressure ratio by varying the number of nozzles supplying the superheated working fluid to the turbine. Thus, changing the throttle position increases the power in steps. The test procedure, therefore, was modified to set the power by selecting rpm and the number of nozzles. Idle required 1 to 2 nozzles and was automatically cycled by the control logic.

Minor mechanical problems were encountered which interrupted testing and limited the total number of useful tests. The ORC power system became restricted to operation on 1,2,4 or 5 nozzles, therefore, several tests were run at only three power settings.

Desired load and engine speed settings were calculated prior to each test. However, when these values were adjusted for dynamometer friction losses, rear-wheel motoring losses, and transmission efficiency, the observed horsepower differed considerably from the 25, 50 and 75% hp values. Initially, it had been intended to report emissions in terms of net horsepower measured at the rear wheels as was done on the bus testing reported in Reference 2. However, the observed horsepower was highly variable from test to test unless corrected for dynamometer friction and rear wheel motoring losses. Therefore, the horsepower values used in calculating the ORC bus brake specific emissions and tabulated in the tables are those based on the turbine performance. These problems were not encountered during the later tests of the gasoline bus.

Experimental data on tire losses and automatic transmission efficiencies, obtained from industry sources, were used to back-calculate brake horsepower output.

Tests of a "Baseline" Bus

The Test and Evaluation Branch previously tested the ORC bus in its stock, as-received-from-the-factory, condition with the conventional engine installed, in order to establish baseline emissions with which the ORC power system emissions could be compared. However, these test results, reported in Reference 2, were not directly comparable due to the inertia weight and power absorption limitations inherent in the Clayton dynamometer used for those tests. Therefore, the tests of a gasoline-powered bus were repeated on the heavy duty large roll chassis dynamometer that was used for the ORC bus tests.

The second baseline bus was a Twin Coach 29-passenger city bus powered by a 413 CID Chrysler V-8 engine using gasoline. This vehicle is identical to the TC-25 except that it is three feet longer and weighs 12,000 pounds. The bus was manufactured in 1970 and the only emission control was positive crankcase ventilation. This vehicle was obtained through the courtesy of the City of Muskegon, Michigan, where it had seen extensive use in city bus service.

The gasoline bus was driven from Muskegon to the Ann Arbor facility on Tuesday, April 17, 1973. Since the vehicle had been in storage for many months and had about sixty thousand miles of city bus service it was hard to start and ran poorly. The engine was given a major tune-up at the Ann Arbor lab prior to testing.

The inertia weight set into the dynamometer was the same as that for the ORC bus, 12,800 pounds. Weights were placed in the gasoline bus to obtain the same rear wheel, rear axle, and dynamometer axle loads as the ORC bus. All emissions tests used the Constant Volume Sampling method.

Operating conditions included a simulation of the Federal 13-mode procedure, steady state tests (constant speed at road load), the LA-4 light duty vehicle urban driving cycle (as used in Federal emissions certification tests), and the Ann Arbor-1 (AA-1) Urban Bus Cycle.

The AA-1 cycle is a speed versus time trace generated in the summer of 1971 by attaching a fifth wheel to one of the buses of the Ann Arbor Transportation Authority. The cycle is not an official test cycle, but rather is used as an experimental tool for comparing buses. The cycle consists of 26 start/stop modes, and the 5.4-mile route requires 29.5 minutes to complete, for an average speed of about 11 mph. The maximum speed on the cycle is 38 mph.

The procedure for the 13-mode tests was to establish the desired engine speed by using the dynamometer to control vehicle speed. At this speed the load is controlled by the vehicle throttle setting. Bag samples of the diluted exhaust gas were taken at 2%, 25%, 50%, 75% and 100% of the maximum power at the chosen engine speed. The idle modes were run with the transmission in neutral. It had previously been determined that 2,000 rpm and 3,200 rpm were the desired intermediate and rated speeds for the Chrysler 413 engine in the bus, as reported in Reference 2. However, dynamometer speed limitations prevented running the gasoline engine bus above 2,900 rpm at the lower power settings; therefore, 2,900 rpm was used as the rated engine speed for this vehicle. To develop a valid dynamometer road load for the AA-1 bus route, LA-4 urban driving cycle, and the steady state tests, the gasoline bus was taken to a test track to obtain steady state road load data: engine speed, manifold vacuum, vehicle speed. These conditions were duplicated on the chassis dynamometer and a road load curve, Table 13, was developed. The steady state test modes on the chassis dynamometer were idle, 10, 20, 30, 40, 50, and 60 mph cruises, each maintained for five minutes to allow time for an adequate sample to be collected.

In addition to the emissions test a simple exterior noise test was conducted using the SAE Recommended Practice J366, for full throttle acceleration only. Four runs on an open track were made in one direction only, because of nearby equipment operating. The closed throttle deceleration test was not run. Maximum engine speed attained was 2,900 rpm since the automatic transmission upshifted at that speed instead of the governed speed of 3,600 rpm.

Results and Discussion

Results of the emissions tests on the ORC bus are presented in the Appendix in Tables 1 through 4, and on the "baseline" gasoline-engined bus in Tables 5 through 12. Emissions of CO_2 are included to indicate fuel consumption. The fuel economy figures in the tables were calculated by a carbon balance equation from the mass emissions of HC, CO, and CO_2. Rolling resistance data on the gasoline bus are presented in Table 13. Table 14 shows the results of the noise tests on the gasoline bus. Figure I shows the data used to calculate brake specific emissions for the ORC bus.

Mass emissions from the 13-mode tests on the ORC bus are presented as grams per Bhp-hr, grams per minute, and grams per mile in Tables 1, 2 and 3 respectively. The variability of all emissions was greater than normally experienced. This was due to the difficulty in duplicating test conditions and adjustments to the ORC bus fuel-air mixture. The only test completed at the optimum air-fuel ratio was the test on April 12.

Using the brake specific emissions from Figure I (next page) and Table 5 to compare the two vehicles, the following table of average brake specific emissions can be calculated:

Grams Per Brake Horsepower-Hour

	HC	CO	NOx	HC+NOx
ORC Bus (4-12)	2.1	20.0	2.0	
Gasoline Bus	8.1	53.4	12.4	
'77 Cal. Std.		25		5

Thus, the ORC bus achieved improvements of 74%, 63% and 85% for HC, CO and NOx emissions. This is a considerable improvement over a vehicle whose engine easily met the current (1973) standards. In addition, the ORC bus meets the 1977 California HC, CO and NOx standards. Several important cautions must be observed however; 1) the ORC bus is a feasibility model and, although considerable improvements could probably be made, the usage deterioration to be expected cannot be predicted; 2) this comparison was made with a well used, high mileage vehicle which did not have current state-of-the-art emission improvements.

From two sets of selected data points composite brake specific emissions were calculated. These are listed at the bottom of Table 1. Since a full set of data was not available, these are only an approximation and should not be given too much weight in comparisons with full 13-mode tests of other power systems.

Emissions from the steady state cruise modes are listed in Table 4 as grams per minute and grams per mile. No horsepower readings were obtained due to equipment problems.

Mass emissions from 13-mode tests on the gasoline bus are listed in Tables 5,6, and 7 as grams per Bhp-hr, grams per minute, and grams per mile, respectively. The brake specific emissions at the bottom of Table 5 were calculated from those data points and represent composite emissions as calculated by the Federal 13-mode procedure. The brake horsepower values used in these calculations are the sum of measured dynamometer horsepower plus estimates of tire losses and transmission losses.

From experimental tire data supplied by Mr.Kenneth Campbell of Firestone Tire & Rubber Co., the rear wheel horsepower losses due to the tires would be 10.5 hp at 30 mph and 17 hp at 50 mph. This agreed with measured tire power losses at those speeds. Data supplied by Mr. Arnold Brookes of Chrysler Corporation were used to calculate overall transmission efficiencies.

In Table 8, HC and CO concentration data are presented. The gasoline bus data were calculated using those data points in the 13-mode test for which the manifold vacuum was approximately the same as required by the Federal heavy duty gasoline engine test procedure. The results are thus only an approximation and should be used cautiously.

Mass emissions, in grams per Bhp-hr, are presented in Table 9. Composite 13-mode results from the gasoline bus are presented, as well as results from an approximation of the Federal heavy duty gasoline engine procedure.

Table 10 presents the results from a single 1975 FTP on the gasoline bus. The test was run on the heavy duty chassis dynamometer with a road load power vs. speed curve and an inertia weight of 12,800 pounds.

The Ann Arbor-1 bus route was run on the dynamometer on three different days. Composite mass emissions are listed in Table 11. In these tests the startup and first 390 seconds of the driving

Figure 1

25-Passenger Organic Rankine Cycle Bus Mass Emissions
Abbreviated Federal 13-Mode Procedure

Grams Per Minute

Test Date	Nozzles Open	Horsepower	Turbine Speed	HC	CO	CO_2	NOx
4-4*	1-2	0	Idle	.78	7.77	341	.30
	1	9.0	22000 rpm	.89	6.48	330	.29
	2	27.9	20000 rpm	.03	3.29	600	.95
	4	59.7	20000 rpm	.34	42.43	1287	3.57
	5	85.8	20000 rpm	.28	37.61	1102	3.18
	1	10.9	32000 rpm	1.16	16.46	480	.41
	2	36.9	32000 rpm	.58	33.74	1034	1.28
	4	79.6	32000 rpm	.49	36.20	1244	1.86
4-12	1-2	0	Idle	3.66	18.22	631	.46
	1-2	0	Idle	1.52	10.16	498	.46
	1	9.9	20000 rpm	1.78	7.22	432	.38
	2	27.9	20000 rpm	.57	13.70	777	.95
	4	58.4	20000 rpm	.10	12.46	1346	2.04
	1	11.6	30000 rpm	1.48	6.44	370	.34
	2	36.1	32000 rpm	.41	7.19	721	.94
	4	78.1	32000 rpm	.05	8.97	1256	1.99
	1-2	0	Idle	1.85	7.36	422	.38

$$\text{Brake Specific Emissions} = \frac{(\text{pollutant x WF})\ 60}{(\text{measured Bhp x WF})}$$

Pollutant (HC, CO, NOx) mass in grams/minute
WF = .2 x avg. idle for idle modes

$WF = \frac{.8}{n}$ n = number of power modes
n = 7 for 4-4, n = 6 for 4-12

	HC	CO	NOx
4-4 Brake Specific Emissions - grams/Bhp-hr	.99	36.8	2.34
4-12 Brake Specific Emissions - grams/Bhp-hr	2.14	19.96	1.97

*Date for 4-4 is not at optimum fuel-air ratio.

cycle are collected in one sample bag and the remaining 23 minutes of the cycle in the next two bags. In the interests of time the Hot Start tests of 5-4 and 5-8-73 were not complete 29.5 minute tests. Instead, only the startup and the first 390 seconds were run, after the complete Cold Start test had been run. The Hot Start bag data were combined with the data from the last 23 minutes of the Cold Start test to give the composite mass emissions listed in Table 11, under the assumption that the engine is operating the same at 390 seconds regardless of the type of start.

Data from the steady state tests are presented in Table 12. Fuel economy was calculated by the carbon balance method.

For the LA-4 and Ann Arbor-1 tests on the gasoline bus, a road load curve was determined using the data from column 1 in Table 13. The values in column 1 are the dynamometer horsepower readings that resulted from matching engine speed and manifold vacuum with those recorded at the test track. In column 2 are typical readings from a subsequent test on the dynamometer. The differences at each speed were a result of dynamometer non-repeatability, because engine speed and manifold vacuum were always matched with the road test values. Columns 3 and 4 apply to the 25-passenger bus in which the ORC power system was installed. The bus manufacturer's predicted road loads (for a gasoline ICE-powered bus) are listed in column 3. Sundstrand measured the values in column 4 during coastdown tests on the road with the ORC bus. The differences between columns 3 and 4 are probably due to the increased weight of the ORC bus and the increased drag due to the roof-mounted vapor condenser.

The noise data in Table 14 are from four runs, all in one direction, all on the same side of the bus. The A Scale was used; results are in decibels.

Conclusions

These tests of an ORC and a gasoline ICE bus have shown that chassis dynamometer testing for emissions from large vehicles at high loads is possible. For the gasoline bus it was possible to compare results with engine certification data. For those tests in which the two vehicles can be directly compared, the ORC bus showed considerable emissions improvement over the gasoline bus. Additional work will be necessary to reduce test variability so that conditions can be duplicated.

REFERENCES

(1) M. Reck and D. Randolf, "An Organic Rankine Cycle Engine for a 25-Passenger Bus", SAE International Automotive Engineering Congress, January 1973, No. 730212.

(2) "Exhaust Emissions from a 25-Passenger Internal Combustion Engine-Powered Gasoline-Fueled Bus", 72-7, MSAPC, Environmental Protection Agency.

A P P E N D I X

Table 1

25-Passenger Organic Rankine Cycle Bus Mass Emissions
Federal Experimental 13-Mode Procedure

Grams Per Brake Horsepower-Hour

			Date	HC	CO	CO_2	NOx	Fuel Consumption lb/Bhp-hr
1 nozzle	9.0 hp	22000 rpm	4-4*	5.96	43.3	2200	1.95	1.68
1 nozzle	9.9 hp	20000 rpm	4-12	10.8	43.7	2618	2.30	2.00
2 nozzles	31.3	23000 rpm	4-4	1.00	44.3	1113	1.20	.87
2 nozzles	27.9	20000 rpm	4-4	.07	7.09	1291	2.05	.96
2 nozzles	27.9	20000 rpm	4-12	1.23	29.44	1671	2.04	1.27
4 nozzles	59.7	20000 rpm	4-4	.33	42.67	1294	3.59	1.0
4 nozzles	58.4	20000 rpm	4-12	.11	12.81	1384	2.10	1.03
5 nozzles	85.8	20000 rpm	4-4	.20	26.28	770	2.23	.60
1 nozzle	10.9	32000 rpm	4-4	6.35	90.2	26.28	2.24	2.05
1 nozzle	11.6	30000 rpm	4-12	7.66	33.30	1865	1.76	1.43
2 nozzles	36.9	32000 rpm	4-4	.94	54.8	1681	2.08	1.30
2 nozzles	36.1	32000 rpm	4-12	.68	11.97	1201	1.57	.90
4 nozzles	74.6	27500 rpm	4-4	.26	33.44	900	1.41	.70
4 nozzles	79.6	32000 rpm	4-4	.37	27.28	937	1.40	.72
4 nozzles	78.1	32000 rpm	4-12	.04	6.90	965	1.53	.72

*Data for 4-4 is not at optimum fuel-air ratio.

Table 2

25-Passenger Organic Rankine Cycle Bus Mass Emissions
Federal 13-Mode Procedure

	Mode	Date	HC	CO	CO_2	NOx	
			Grams Per Minute				
	Start & Warm-up	4-4*	3.38	20.53	706	.648	
	Start	4-6*	4.67	23.64	627	.42	
	Start	4-13	2.96	16.00	606	.48	
	Warm-up	4-6	2.51	39.83	542	.39	
1-2 nozzles	Idle*	4-4	.78	7.77	341	.30	
1-2 nozzles	Idle	4-6	1.08	24.10	482	.41	
1-2 nozzles	Idle*	4-12	3.66	18.22	631	.46	
1-2 nozzles	Idle*	4-12	1.52	10.16	498	.46	
1-2 nozzles	Idle	4-13	1.46	8.82	518	.46	
1 nozzle	Idle	4-4	.59	6.17	613	.65	23500 rpm
1 nozzle	9.0* hp	4-4	.89	6.48	330	.29	22000 rpm
1 nozzle	9.9*	4-12	1.78	7.22	432	.38	20000 rpm
2 nozzles	31.3 hp	4-4	.52	23.18	582	.63	23000 rpm
2 nozzles	27.9* hp	4-12	.57	13.70	777	.948	20000 rpm
2 nozzles	27. *hp	4-4	.03	3.29	600	.95	20000 rpm

*Data for 3-30, 4-4, and 4-6 is not at optimum fuel-air ratio.

Table 2 cont.

	Mode	Date	HC	CO	CO_2	NOx	
4 nozzles	59.7*hp	4-4	.34	42.43	1287	3.57	20000 rpm
4 nozzles	58.4*hp	4-13	.10	12.46	1346	2.04	20000 rpm
4 nozzles	74.6 hp	4-4	.33	41.62	1120	1.76	27500 rpm
5 nozzles	85.8*hp	4-4	.28	37.61	1102	3.18	20000 rpm
Idle & Warm-up		4-4	1.03	17.86	676	.50	
1 nozzle	10.9*hp	4-4	1.16	16.46	480	.41	32000 rpm
1 nozzle	11.6*	4-12	1.48	6.44	370	.34	33000 rpm
2 nozzles	36.9*hp	4-4	.58	33.74	1034	1.28	32000 rpm
2 nozzles	36.1*hp	4-12	.41	7.19	721	.94	32000 rpm
4 nozzles	79.6*hp	4-4	.49	36.20	1244	1.86	32000 rpm
4 nozzles	78.1*hp	4-12	.05	8.97	1256	1.99	32000 rpm
5 nozzles		4-4	.38	43.74	1206	1.92	32000 rpm
Idle 1-2 nozzles		4-12	1.85	7.36	422	.38	

*Values used to calculate mass emissions in grams/Bhp-hr

Table 2 cont.

Mode	Date	HC	CO	CO_2	NOx		Nozzles Open
Idle	3-30	1.86	7.35	417	.34	21000 rpm	1
85.9 hp	3-30	.22	28.04	1208	1.89	20000 rpm	5
21 hp	3-30	.13	20.46	714	.82	16000 rpm	2
55 hp	3-30	.35	31.83	1333	2.04	18000 rpm	4
79.5 hp	3-30	.16	30.78	1371	2.26	32000 rpm	4

Table 3

25-Passenger Organic Rankine Cycle Bus Mass Emissions
Federal 13-Mode Procedure

Grams Per Mile

Mode			Date	HC	CO	CO_2	NOx
1 nozzle	9.0 hp	22000 rpm	4-4*	1.78	12.9	658	.58
1 nozzle	9.9 hp	20000 rpm	4-12	4.25	17.2	1033	.92
2 nozzles	31.3 hp	22000 rpm	4-4	1.98	87.8	2205	2.38
2 nozzles	27.9 hp	20000 rpm	4-12	2.50	59.8	3393	4.15
2 nozzles	27.9 hp	20000 rpm	4-4	.14	13.4	2433	3.87
4 nozzles	59.7 hp	20000 rpm	4-4	1.46	18.2	5558	15.42
4 nozzles	58.4 hp	20000 rpm	4-12	.46	55.6	6007	9.12
4 nozzles	14.6 hp	27500 rpm	4-4	1.01	128.6	3459	5.43
5 nozzles	85.4 hp	20000 rpm	4-4	1.19	162.3	4757	13.75
1 nozzle	10.9 hp	32000 rpm	4-4	1.84	26.2	762	.65
1 nozzle	11.6 hp	30000 rpm	4-12	2.31	10.1	579	.53
2 nozzles	36.9 hp	32000 rpm	4-4	.96	56.1	1719	2.13
2 nozzles	36.1 hp	32000 rpm	4-12	1.09	19.1	1919	2.51
4 nozzles	79.6 hp	32000 rpm	4-4	.79	58.6	2015	3.01
4 nozzles	78.1 hp	32000 rpm	4-12	.14	24.5	3430	5.44
5 nozzles	85.9 hp	20000 rpm	3-30	1.12	140.4	6047	9.44
2 nozzles	21.0 hp	17500 rpm	3-30	3.68	88.0	3071	3.52
4 nozzles	55 hp	20000 rpm	3-30	1.49	136.3	5706	8.73
4 nozzles	79.5 hp	32000 rpm	3-30	.43	84.1	3745	6.18

*Data for 3-30, and 4-4 is not at optimum fuel-air ratio.

Table 4
25-Passenger Organic Rankine Cycle Bus Mass Emissions
Steady State Modes

Grams Per Minute

Mode	Date	HC	CO	CO_2	NOx
Idle	3-26*	1.26	11.26	465.7	.48
0 mph	3-26	2.27	114.93	1082.8	1.14
15 mph	3-26	1.95	95.86	901.6	.89
24 mph	3-23*	.93	103.35	1430.4	1.67
27 mph	3-26	1.54	117.83	1363.8	1.62

Grams Per Mile

Mode	Date	HC	CO	CO_2	NOx
Idle	3-26	N/A	N/A	N/A	N/A
0 mph	3-26	N/A	N/A	N/A	N/A
15 mph	3-26	8.30	407.92	3836.2	3.81
24 mph	3-23	2.46	272.81	3775.6	4.40
27 mph	3-26	8.95	684.30	7923.3	9.38

*Data for 3-23 and 3-26 is not at optimum fuel-air ratio.

Table 5
29-Passenger Gasoline-Powered Bus Mass Emissions
Federal 13-Mode Procedure

Grams Per Brake Horsepower Hour

HP	RPM	Date	HC	CO	CO_2	NOx	Fuel Consumption lb/Bhp-hr
5.6	2000	5-7	44.58	240.08	2779	13.57	1.98
2.4	2010	5-16	164.63	685.30	5373	18.97	4.17
21.2	2000	5-7	4.40	21.94	966	11.23	.61
32.2	2000	5-16	2.71	27.72	807	18.74	.52
77.0	2000	5-7	1.93	21.77	564	8.56	.36
64.8	2000	5-16	1.86	30.35	556	15.03	.36
100.9	2000	5-7	1.04	11.76	450	7.36	.28
92.6	2000	5-16	1.33	15.25	544	14.27	.35
107.4	2000	5-7	.48	17.67	462	5.42	.30
107.1	2000	5-16	.68	20.99	507	14.10	.33
3.4	2900	5-8	475.69	179.31	3353	29.81	3.09
5.9	2900	5-16	347.71	197.07	3378	40.75	2.88
27.2	2900	5-8	59.39	52.29	802	13.17	.64
37.2	2900	5-16	42.87	75.65	809	15.34	.64
62.7	2900	5-8	3.38	44.74	650	16.77	.44
67.4	2900	5-16	1.89	39.68	617	14.97	.41
91.1	2900	5-8	1.18	22.08	576	16.78	.37
97.9	2900	5-16	1.23	35.02	633	13.97	.38
130.1	2900	5-8	.41	22.26	510	13.16	.33
127.0	2900	5-16	1.82	116.52	470	6.88	.39

Table 6
29-Passenger Gasoline-Powered Bus Mass Emissions
Federal 13-Mode Procedure

Grams Per Minute

HP	RPM	Date	HC	CO	CO_2	NOx
Idle	1075	5-7	3.26	63.87	77	.02
Idle	1075	5-16	3.16	59.96	73	0
5.6	2000	5-7	4.14	22.31	358	1.26
2.4	2010	5-16	6.46	26.90	211	.74
21.2	2000	5-7	1.56	7.76	342	3.97
32.2	2000	5-16	1.45	14.90	433	10.07
77.0	2000	5-7	2.48	27.95	724	10.99
64.8	2000	5-16	2.01	32.76	601	16.22
100.9	2000	5-7	1.75	19.78	774	12.38
92.6	2000	5-16	2.05	23.55	840	22.04
107.4	2000	5-7	.85	31.64	838	9.72
107.1	2000	5-16	1.21	37.47	905	25.17
Idle	1050	5-7	4.19	69.82	72	.03
Idle	1075	5-8	3.06	53.93	75	.04
Idle	1050	5-16	3.54	58.93	74	0
3.4	2900	5-7	27.38	10.32	193	1.18
5.9	2900	5-16	34.02	19.28	331	3.99
27.2	2900	5-8	26.92	23.7	363	5.97
37.2	2900	5-16	26.61	46.95	502	9.52
62.7	2900	5-8	3.52	46.72	679	17.52
67.4	2900	5-16	2.13	44.59	693	16.81

Table 6 cont.

HP	RPM	Date	HC	CO	CO_2	NOx
91.1	2900	5-8	1.80	33.53	875	25.49
97.9	2900	5-16	2.00	57.13	1033	22.79
130.1	2900	5-8	.87	48.28	1106	28.54
127.0	2900	5-16	3.86	246.6	996	14.56
Idle	1025	5-8	3.62	52.15	61	.08
Idle	1025	5-16	3.71	57.98	67	0

Brake Specific Emissions	HC	CO		NOx
GMS/Bhphr (5-7/5-8)	7.66	40.23		11.22
GMS/Bhphr (5-16)	8.62	66.48		13.52

$$\text{Brake Specific Emissions} = \frac{(\text{Pollutant x WF})\ 60}{(\text{measured Bhp x WF})}$$

Pollutant (HC, CO, NOx) mass in grams per minute.
WF = .2 for idle (use average of three idles)
WF = .08 for all others

Table 7

29-Passenger Gasoline-Powered Bus Mass Emissions
Federal 13-Mode Procedure

Grams Per Mile

HP	RPM	Date	HC	CO	CO_2	NOx
5.6	2000	5-7	6.48	34.89	404	1.97
2.4	2010	5-16	10.18	42.36	332	1.17
21.2	2000	5-7	2.46	12.25	539	6.27
32.2	2000	5-16	2.38	24.37	709	16.47
77.0	2000	5-7	4.30	48.38	1254	19.03
64.8	2000	5-16	3.60	58.79	1078	29.11
100.9	2000	5-7	3.17	35.98	1407	22.52
92.6	2000	5-16	3.91	44.84	1599	41.96
107.4	2000	5-7	1.92	71.61	1874	21.99
107.1	2000	5-16	2.82	87.24	2107	58.62
3.4	2900	5-8	28.79	10.85	203	1.81
5.9	2900	5-16	37.44	21.22	364	4.39
27.2	2900	5-8	29.55	26.01	399	6.55
37.2	2900	5-16	29.88	52.72	564	10.69
62.7	2900	5-8	3.99	52.80	767	19.80
67.4	2900	5-16	3.15	65.83	1023	24.82
91.1	2900	5-8	2.04	38.15	996	29.00
97.9	2900	5-16	2.95	84.35	1525	33.65
130.1	2900	5-8	.98	54.18	1241	30.03
127.0	2900	5-16	5.71	365.4	1476	21.57

Table 8

Heavy Duty Gasoline Engine Test Procedure

Emission Concentrations

Standards	HC ppm	CO%
1969-1971 California and Federal thru 1973	275	1.5
1972 California	180	1.0

Typical Federal Certification levels - Chrysler 413 engine

	HC ppm	CO%
1972 model year	85	.74
	127	.77
1973 model year	83	.59
	119	.37
	127	.77

29-Passenger Gasoline-Powered Bus (Approximation)*

	HC ppm	CO%
Test of 5-7-73	123.2	.76
Test of 5-16-73	126.6	.92

*These results were calculated using that Federal 13-mode test data for which the manifold vacuum was approximately the same as required by the heavy duty gasoline engine test procedure.

Table 9

Heavy Duty Gasoline Engine Test Procedure

Grams Per Brake Horsepower-Hour

Standards	HC	CO	NOx	HC + NOx
1974 Federal & '73-'74 California		40		16
1975-76 California		30		10
1977 California		25		5
Typical 1974 Federal Certification levels Chrysler 413 engine (two tests)		14.7		14.05
Federal 13-mode procedure 29-Passenger Gasoline Bus Test of 5-7 & 5-8-73	7.7	40.2	11.2	18.9
Test of 5-16-73	8.6	66.5	13.5	22.1
1974 Federal Heavy Duty Gasoline Engine Test Procedure* 29-Passenger Gasoline Bus Test of 5-7 & 5-8-73	5.1	57.8	8.0	13.1
Test of 5-16-73	5.5	61.6	15.9	21.4

*These results were calculated using that Federal 13-mode test data for which the manifold vacuum was approximately the same as required by the heavy duty gasoline engine test procedure.

Table 10

29-Passenger Gasoline-Powered Bus
1975 Federal Test Procedure (Cold Start) Mass Emissions

Grams per Mile

Date	HC	CO	CO_2	NOx	Fuel Economy	
5-11	7.75	171.12	1028.8	15.34	5.31	6.70

* Test cycle fuel economy: $\frac{\text{miles X carbon wt. fraction x fuel density}}{\text{sum of carbon wt.fraction bags 1,2,3 emissions}}$

** Weighted fuel economy : $\frac{\text{carbon wt. fraction x fuel density}}{\text{sum of carbon wt. fraction x emissions gm/mi}}$

Table 11
29-Passenger Gasoline-Powered Bus
Ann Arbor-1 Bus Route, CVS Procedure Mass Emissions

Grams Per Mile

	Date	HC	CO	CO_2	NOx	Fuel Economy (mi/gal)
Cold Start	5-4*	19.17	286.18	1398.1	15.71	4.65
Hot Start	5-4*	17.28	280.91	1287.4	15.08	4.97
Cold Start	5-7	18.13	285.94	1164.8	17.27	5.30
Cold Start	5-8*	22.19	277.71	1289.3	24.60	4.93
Hot Start	5-8*	21.04	283.82	1219.1	24.19	5.12

* Cold start and hot start used same bag data after first 390 seconds

Table 12

29-Passenger Gasoline-POwered Bus Mass Emissions
Steady State Modes

Grams Per Minute

Mode	HC	CO	CO_2	NOx	
Idle	3.52	62.40	77.	0	
10 mph	2.08	46.61	192.	1.26	
20 mph	1.76	18.35	274.	4.11	
30 mph	1.67	13.13	404.	9.10	
40 mph	1.81	34.95	511.	11.35	
50 mph	2.26	43.03	752.	19.94	
60 mph	2.03	41.92	988.	26.46	
Grams Per Mile					
Idle	N/A	N/A	N/A	N/A	Fuel Economy MPG
10 mph	12.71	284.62	1171.	7.67	5.35
20 mph	5.45	56.70	848.	12.69	9.30
30 mph	3.38	26.51	816.	18.37	10.22
40 mph	2.79	53.99	789.	17.53	10.05
50 mph	2.83	53.98	944.	25.02	8.55
60 mph	2.11	43.31	1023.	27.42	8.08

Table 12 cont.

Grams Per Brake Horsepower Hour

Mode	HC	CO	CO_2	NOx	HP
Idle	N/A				
10 mph	22.28	499.0	2053.	13.44	5.6
20 mph	7.21	75.06	1123.	16.83	14.6
30 mph	2.78	21.86	673.	15.15	36.0
40 mph	2.03	39.36	575.	12.78	53.2
50 mph	1.88	35.88	627.	16.63	71.9
60 mph	1.21	24.97	590.	15.81	100.4

Table 13

TC-25 and TC-29 Bus
Rolling Resistance Values

	TC-29 Gasoline Bus		TC-25 ORC Bus	
MPH	Road Test (HP)	DYNO Road Load HP	Predicted HP	Experimental HP
10	3.1 (1)	5.8 (2)	3 (3)	7.5 (4)
20	8.9	14.5	9	16
30	21.7	26.3	20	27
40	41.5	49.2	37	
50	64.9	75.6	65	
60	94.4	105.9	104	

1) EPA road test
2) typical road load for Ann Arbor Bus route and LA-4
3) bus manufacturer's predicted values
4) Sundstrand Aviation measured values in road tests

Table 14

TC-29 Gasoline-Powered Bus
Noise Tests
Per
SAE RP J 366

Full Throttle Acceleration

Run No.	Noise Level, EPN Decibels
1	92.5
2	93.7
3	94
4	93.5