74-31 AEB

Exhaust Emissions Tests of the Carter Steam Car

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Technology Assessment and Evaluation Branch
Office of Mobile Source Air Pollution Control
Emission Control Technology Division
Environmental Protection Agency

Background

Jay Carter Enterprises of Burkburnett, Texas, has designed and built a steam Rankine cycle power system. This system was installed in a Volkswagen station wagon to demonstrate their approach to the Rankine cycle system. Carter Enterprises developed their system over the past six years with no financial assistance from the Government or any company.

Since their own emission tests indicated that the vehicle was close to meeting the original (1976) statutory emission levels, Carter Enterprises contacted the Alternative Automotive Power Systems Division (AAPSD) of EPA and arrangements were made for exhaust emissions tests at the Motor Vehicle Emissions Laboratory in Ann Arbor, Michigan. The tests of the steam car reported herein were conducted during separate one-week periods in March and May of 1974. The emissions tests were conducted by the Technology Assessment and Evaluation Branch of the Emission Control Technology Division at the request of AAPSD as part of a continuing effort to stay abreast of alternative power systems development and assess the emission control potential of such systems. Carter Enterprises provided personnel to operate the car and interpret engine parameter data.

Vehicle Description

The Carter Rankine cycle system is installed in a Volkswagen "Squareback" station wagon. The standard VW four-speed transaxle is used, with the steam system occupying the normal engine compartment except for a small ram-air condenser located at the front of the vehicle. An additional small forced-air condenser is at the rear of the vehicle. The expander is a four-cylinder radial, single acting uniflow engine without crossheads and is designed to operate on 2000 psi steam pressure at 1000°F with a maximum driveshaft speed of 5000 rpm. The boiler is a variable pressure monotube type fired by a modulating burner utilizing a modified spinning cup fuel atomizer. Fuel used was a blend of 50% (by volume) Indolene gasoline and 50% kerosene. The complete steam system in its present prototype configuration weighs approximately 120 pounds more than the original internal combustion engine. The dry weight of the car is 2470 pounds. Vehicle test instrumentation was neatly packaged in the vehicle dashboard. Externally the vehicle closely resembled the original vehicle.

A standard 1974 Volkswagen type 111/113 "Super Beetle" was also tested to compare steady state fuel economy.

All testing was done at an inertia weight of 2750 pounds to simulate the weight of the vehicle and two passengers.

Test Procedure

The car was tested according to conventional Federal procedure, except where the nature of the engine or unique tests required special procedures and deviations to be employed. The Federal procedures include operation of a vehicle on a chassis dynamometer using simulated road loads, with exhaust emissions analysis by the Constant Volume Sampling (CVS) method.

The special procedures used in the tests of the Carter steam car included:

1) use of an electric chassis dynamometer instead of the conventional Clayton water brake dynamometer.

2) delivery of engine cooling air as a function of vehicle speed rather than by the fixed-speed fan specified in the conventional procedures.

3) removal of one air filter from the dilution box to reduce backpressure in the car's exhaust system.

4) use of a special system for exhaust hydrocarbon analysis.

5) a deviation from the startup and warmup phases of the driving schedule.

These special procedures and the reasons for using them, are described in more detail below. Figure 1 is a schematic drawing of the test setup.

Operating Modes: The car was tested by the 1975 Federal Test Procedure (FTP) for exhaust emissions and urban fuel economy. This procedure uses the LA-4 driving schedule. For highway fuel economy the Federal Highway Fuel Economy test was conducted. Finally, for steady state data and engine/emissions mapping, the car was tested on the chassis dynamometer at idle and at various constant speeds up to 60 mph.

Dynamometer: Instead of the double-roll Clayton water brake chassis dynamometer used in most EPA testing, an electric chassis dynamometer with a large (48" dia.) roll was employed. The reason for using the electric dynamometer was that the Carter car required ram-air cooling for the steam condensor and the electric chassis dynamometer system used included a blower which delivered air flow over the car as a function of roll speed. In the normal Federal Test Procedure a fixed speed fan delivers air to cool the engine, but in the case of the Carter car the amount of cooling air would be too great at idle and low speeds, and too little at high speeds for the condensor requirements.

In addition, for steady state tests, the engine power could be determined by motoring the vehicle with the electric dynamometer. In motoring a vehicle, power flows from the dynamometer roll through the rear wheels into the engine, analogous to coasting down a hill. A Clayton water brake dynamometer is incapable of operating this way. This motoring horsepower plus the indicated horsepower gives the vehicle engine horsepower which permitted EPA to evaluate the vehicle powerplant performance.

The road load horsepower vs. speed curve that was set into the electric chassis dynamometer for these tests was identical to the curve on a Clayton dynamometer for the same inertia weight class. To confirm this, tests were conducted on a Chevrolet Vega for which Clayton dynamometer test data were available. Data on exhaust emissions and fuel economy from the electric dynamometer tests were then compared and found to be within the repeatability range of the Clayton dynamometer test results.

Dilution Box: Since Rankine cycle systems are extremely sensitive to exhaust system pressure, measurements were made with a manometer of the pressure in the exhaust adapter between the car and the dilution box. Removing the first of the three dilution box filters (see Figure 1) reduced negative pressure on the vehicle exhaust to less than one-half inch of water. All tests were run without this first filter. For the steady state tests, exhaust backpressure was between -.4 and -.2 inches of water.

Sampling and Analysis: The Constant Volume Sampler (CVS) unit employed for the FTP tests had a capacity of about 400 standard cubic feet per minute (scfm), sufficient to handle the exhaust flow from the Carter car, which was about 300 scfm maximum. Bag samples of the dilute exhaust/air stream were analyzed by the standard complement of instruments: non-dispersive infrared (NDIR) analyzers for CO and CO_2, a chemiluminescence (CL) analyzer for NOx, and a flame ionization detector (FID) for unburned hydrocarbons. Because the Carter fuel blend contained kerosene a heated sample line and FID system, as described in the FTP for Diesel-powered passenger cars, was employed. Otherwise, the heavy HC fractions in the exhaust gas would condense and thus be lost to analysis, leading to errors in calculating HC mass emissions. The continuous analysis of the diluted exhaust stream with the hot FID was the source of the hydrocarbon emission values reported here for the 1975 FTP and steady state tests done in May. Equipment problems, which would have caused an unacceptable delay, prevented the use of the heated FID in March.

Added Instrumentation: Several additional pieces of equipment were used to allow evaluation of additional vehicle parameters. Since a Rankine cycle system is more sensitive than an internal combustion engine to ambient temperature changes, wet and dry bulb temperatures were continuously recorded throughout the tests. For the steady state tests, temperatures were stable to within ± 2°F during each test. For the 1975 FTP and Federal Highway Cycle tests, temperatures were stable to within ± 4°F during each test.

Air-to-fuel ratio was determined for several steady state tests by taking continuous samples from the raw exhaust stream. Since HC and CO concentrations were much lower than CO_2 concentrations, only CO_2 was measured to determine the air-to-fuel ratio.

Fuel consumption during steady state tests was measured with a burette. This gave an alternative to the carbon balance method for calculating fuel consumption.

Operating Procedures: Due to their familiarity with this unique vehicle, Carter personnel operated it during the tests. Because the time required to get underway following a cold start on the Carter car was in excess of the engine startup and idle period specified in the '75 FTP (which was developed for conventional cars), the procedure was altered to allow the driver to begin the first acceleration on the Federal driving cycle as soon as steam conditions permitted, but with the exhaust sampling beginning at the time of ignition. The time interval between the start of ignition and the first acceleration was 43 seconds on the first test and 48 seconds on the second test. For the hot start portion of the tests the times were 21 and 8 seconds. For a test of a conventional car this time interval is 20 seconds.

Results

Results of the two '75 FTP emissions tests are presented in the following tables, with pollutant mass emissions in grams per mile. The fuel economy for the entire test was calculated using the carbon balance method and is expressed as miles per gallon. The total test period is divided into three portions, with a bag sample collected during each. The Cold Transient portion, which includes engine startup, is in Bag 1. The Hot Stabilized portion is in Bag 2, and the Hot Transient, including a hot startup, is in Bag 3. The composite value for the entire test includes the standard weighting factors assigned to each bag value.

Test No. and Date	Bag	HC gpm	CO gpm	NOx gpm	Fuel Economy miles/gallon
No. 1	1	.93	1.71	.44	
May 9	2	.16	1.51	.37	
	3	.25	.70	.38	
Composite		.34	1.33	.39	12.7
No. 2	1	.95	1.05	.32	
May 10	2	.25	1.16	.29	
	3	.25	.96	.39	
Composite		.40	1.08	.33	14.9

The improved fuel economy in the second test is attributed to a modification in the gear shifting procedure.

It can be seen that pollutant emissions from the Carter steam car were below the original (1976) statutory emission standards of .41 HC, 3.4 CO and .4 NOx. Data from the individual bags show that the cold start portion of the test creates the greatest problem, particularly for hydrocarbons. Reduction of unburned HC emissions during the cold start would result in considerable improvement in the composite total HC value. It should be noted that the car was tested at essentially "zero miles," while the Federal certification process requires tests at 4,000 miles and 50,000 miles.

The vehicle was not able to accelerate as rapidly as required by the driving cycle at speeds above 20 mph, as seen in Figure 2. As a result of this, the distance travelled while collecting Bags 1 and 3 was 3% low. Recalculation of the mass emissions based on the actual mileage increased the emissions about 2% (see Table I). All pollutant emissions still met the above statutory emission standards.

In two tests over the Federal Highway Driving Cycle, the Carter car delivered 16.3 and 17.3 miles per gallon respectively.

For comparison purposes, the following estimates of '75 FTP exhaust emissions and urban fuel economy data for a conventional VW squareback with 4-speed manual transaxle are presented. These data are based on 1973 certification results adjusted to 1975 weighting.

HC gpm	CO gpm	NOx gpm	Fuel Economy mpg
2.2	12	2.8	22

Highway cycle fuel economy data for the conventional VW squareback are not available at this time.

Results of the steady state tests are presented in Tables II through IX with pollutant mass emissions in grams per mile. Fuel economy for the steady state tests was calculated using both a carbon balance method and a measured volume method and is expressed as miles per gallon.

During March steady state emissions testing was done to evaluate the burner, boiler, and expander performance. The steady state road load tests (Tables IV and VI) showed the Carter car's hydrocarbon (HC) and carbon monoxide (CO) levels were low enough to expect the car to meet original 1976 statutory emission standards for HC and CO; nitrogen oxide levels (NOx) however were too high. The vehicle road load curve was based on an estimate of the Clayton dynamometer road load curve. Later checks showed this estimated value to be slightly high. The excess load is expressed as a percent grade.

For comparison purposes, a standard 1974 Volkswagen was checked for fuel economy using the same test setup and road load (see Table VIII). Fuel economy (mpg) of the conventional VW was about twice as good as that of the Carter car.

A vehicle emissions map was also obtained (Figure 3). The air cooled condensers were replaced with a water cooled condenser so that power output was not limited by condenser capacity. Fuel flow rate was manually set. The car was then operated at several speeds (in fourth gear) while emission samples were taken (see Tables V and VII). The resulting emissions map, Figure 3 and Table VII, permits evaluation of vehicle emissions and performance under many operating conditions.

The Federal Driving Cycle was not attempted during the March test series because the steam car experienced some loss in power. The car was returned to Texas for corrective action and power system modifications. The corrective action included repairing valve seats and replacing a crank case o-ring. Power system modifications included installation of new piston rings, changes in fuel/air control components and addition of finless falme-quenching cold water tubing to reduce the formation of nitrogen oxides.

The Carter car was returned to EPA in May for further testing. A repeat of the steady state road load tests (Tables II and III) showed an improvement in vehicle mass emissions. HC and CO emissions were higher than measured in the earlier tests but NOx emissions were lower. The net result was that the car was able to meet the original 1976 exhaust emission levels. The road load horsepower-vs-speed curve used in these tests was identical to the curve of a Clayton dynamometer for the same vehicle inertia weight class.

The hydrocarbon mass emissions were lower for the heated FID than for the cold bag sample. This lower value may be related to the sample line and FID temperatures. Since there was no previous work indicating an optimum sample line temperature, the Diesel procedure temperature, 375°F, was used. This may have been too high a temperature for the kerosene/gasoline blend. Hydrocarbons in the heated FID sample may have been oxidized in the heated line, thus reducing the concentration observed.

Differences in fuel economy between the timed volume and carbon balance methods are small and within acceptable test variability. Part of this variability was due to the type of vehicle and test procedure. At steady speeds, the Carter car continuously changes air and fuel flow to maintain pressure, thus the fuel flow rate cycles. Emissions samples were taken over a five minute period to obtain an adequate sample. The fuel burette held insufficient fuel for this length of time; therefore, each method could have a slightly different fuel flow rate.

The vehicle did not require additional water for the boiler during testing.

Conclusions

The vehicle performed well in EPA tests. The mass emissions met the original 1976 statutory emission levels of .41 grams per mile hydrocarbons, 3.4 grams per mile of carbon monoxide, and .4 grams per mile of nitrogen oxides. The average composite result of the two EPA tests was HC .37, CO 1.2, and NOx .36 grams per mile.

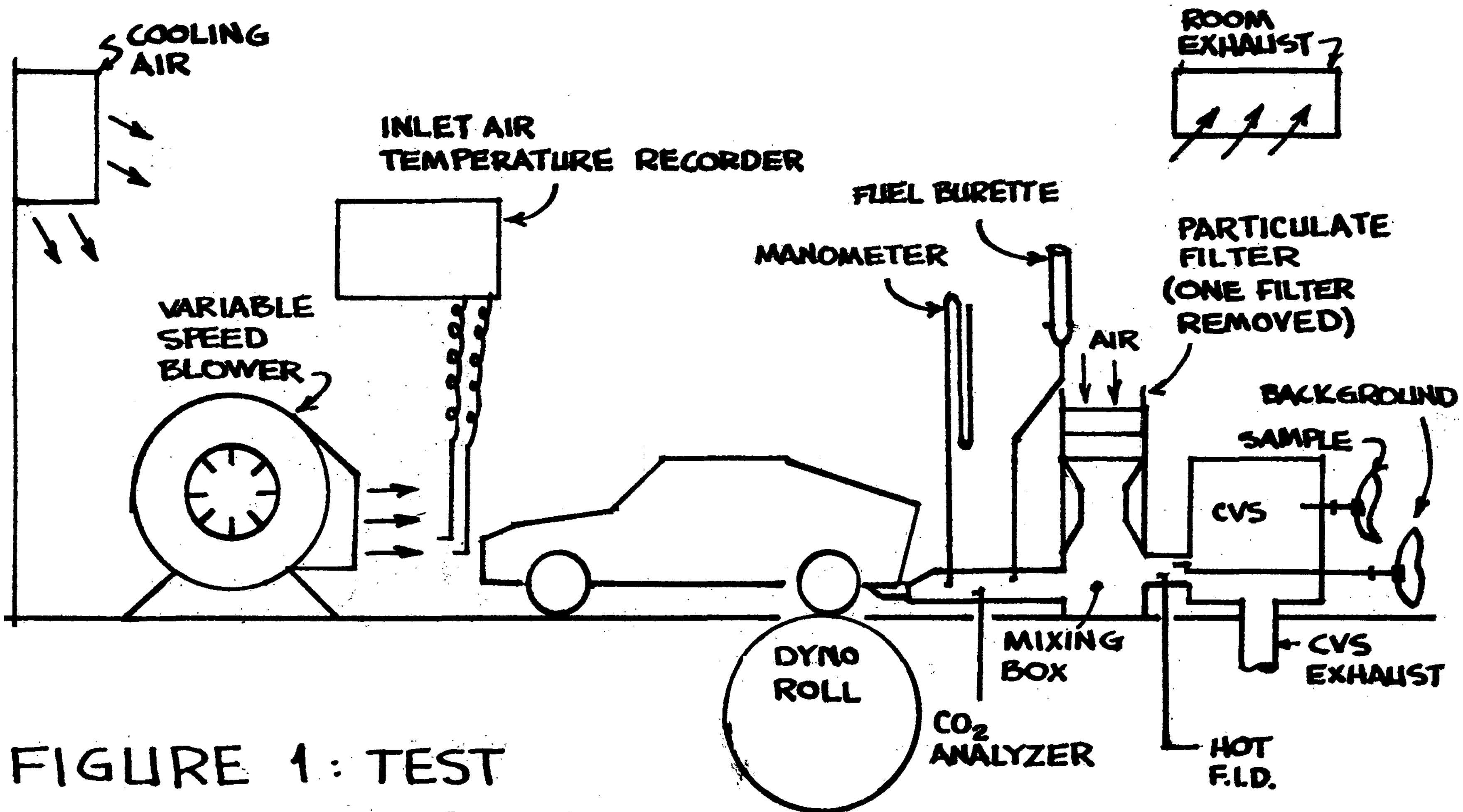

FIGURE 1: TEST SET UP

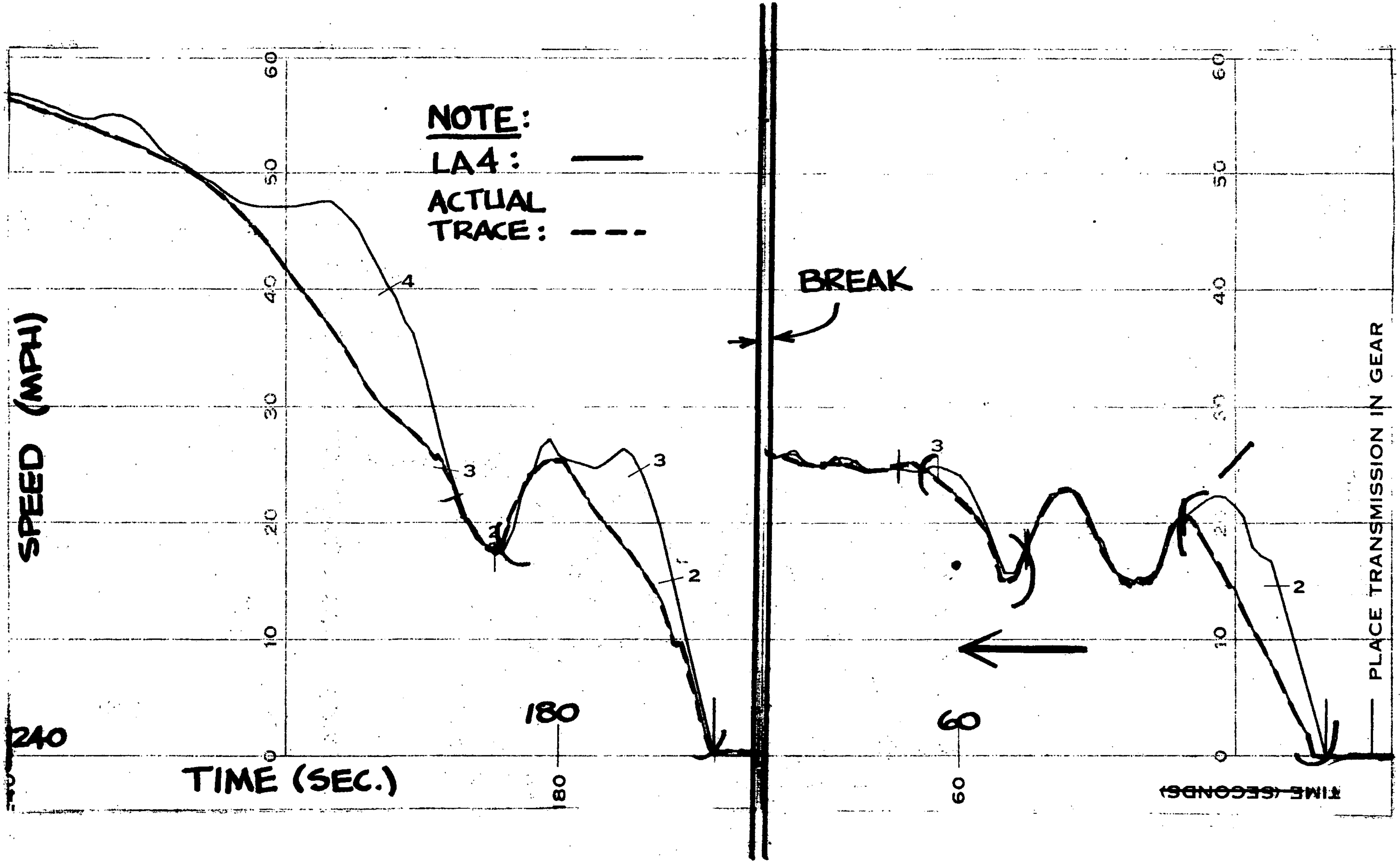

FIG. 2a.: EPA URBAN DYNAMOMETER DRIVING SCHEDULE

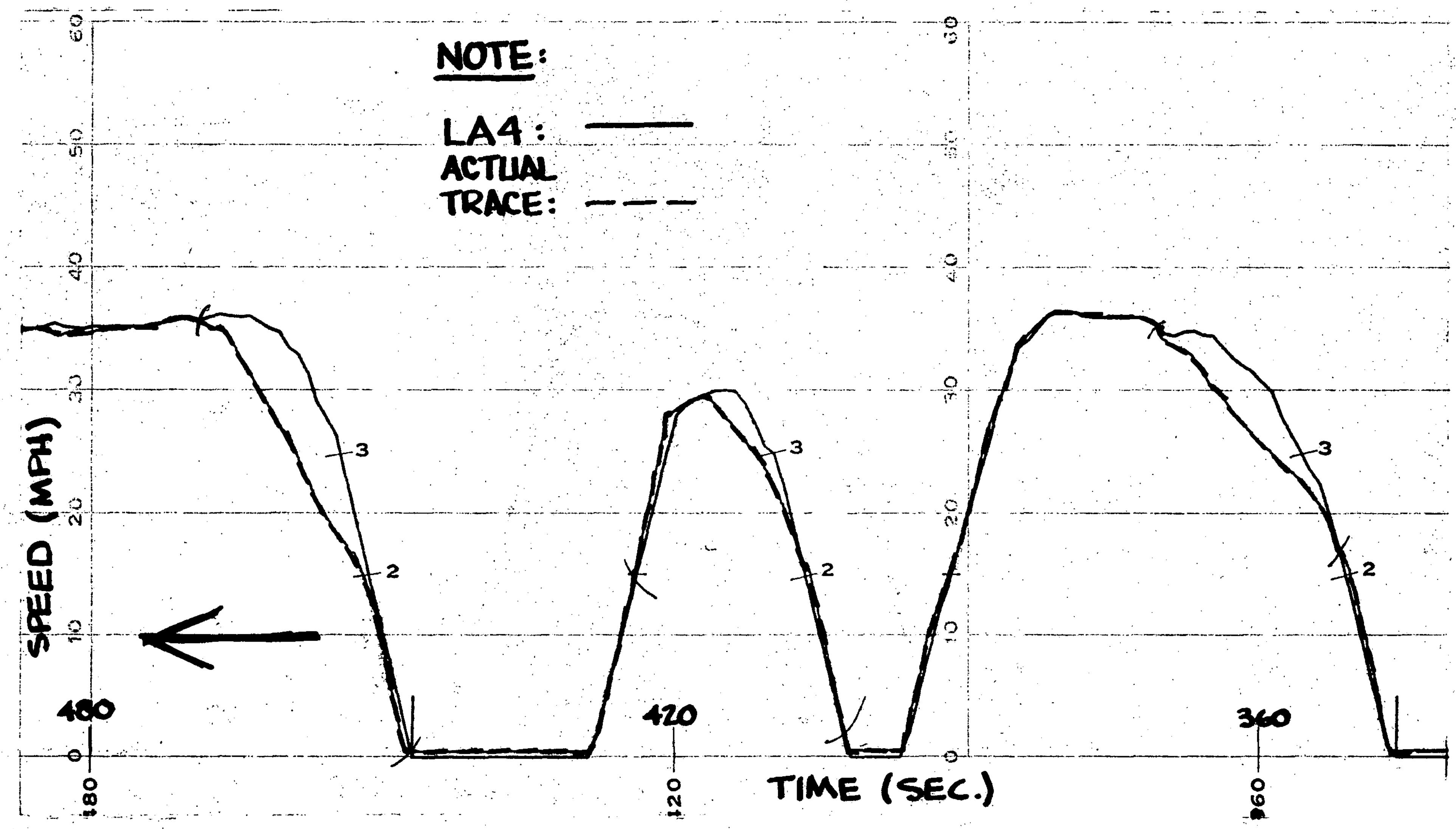

FIG. 2b.: EPA URBAN DYNAMOMETER DRIVING SCHEDULE

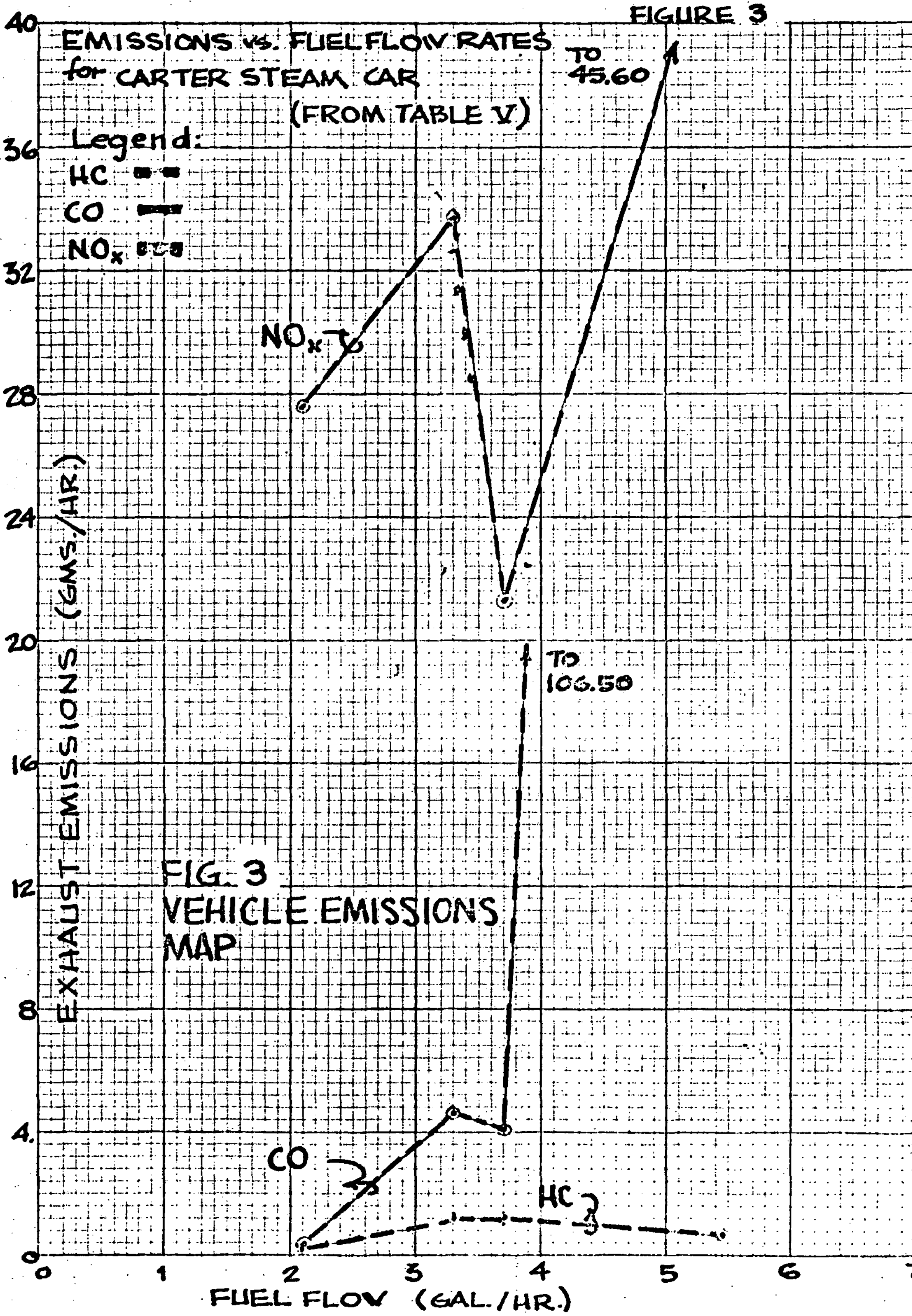

FIG. 3
VEHICLE EMISSIONS MAP

TABLE I

Carter Steam Car
Exhaust Emissions & Fuel Economy
1975 Federal Test Procedure

Test No. & Date	Bag	HC gpm*	CO gpm	NOx gpm	Fuel Economy mpg	% Miles short
No. 1 May 9	1	.93	1.71	.44		2.5%
	2	.16	1.51	.37		.5%
	3	.25	.70	.38		3.3%
Composite		.344	1.33	.39	12.7	
Composite using actual mileage		.350	1.35	.395	12.5	
No. 2 May 10	1	.95	1.05	.32		3.7%
	2	.25	1.16	.29		.4%
	3	.25	.96	.39		4%
Composite		.399	1.08	.33	14.9	
Composite using actual mileage		.408	1.10	.34	14.6	
Highway Cycle May 8					16.3	
May 9					17.3	

*The improved fuel economy in the second test is attributed to a modification in the gear shifting procedure.

TABLE II

Carter Steam Car
Exhaust Emissions & Fuel Economy
Steady State Modes

STEADY STATE ROAD LOAD

Vehicle Speed mph	Transmission gear	Exhaust Emissions: HC Cold FID gpm	Exhaust Emissions: HC Hot FID gpm	Exhaust Emissions: CO gpm	Exhaust Emissions: NOx gpm	Fuel Flow gal/hr	Fuel Economy: Timed Volume mpg	Fuel Economy: Carbon Balance mpg
Idle	N	8.5*	6.2*	30.9*	2.88*	.632		
Idle	N	6.0*	6.6*	24.9*	2.76*	.648		
10	First	0.48	.30	3.37	0.53	1.007	9.9	10.5
10	First	0.31	.28	2.56	0.40	0.870	11.5	11.8
10	Second	0.57	.47	2.49	0.30	0.672	14.9	13.7
10	Second	0.48	.48	2.59	0.51	0.638	15.7	14.2
20	Second	0.20	.12	1.42	0.29	1.135	17.6	17.1
20	Second	0.05	.02	0.90	0.29	1.114	17.9	18.4
20	Third	0.27	.18	1.61	0.22	0.894	22.4	20.9
20	Third	0.28	.14	1.18	0.24	0.923	21.7	21.8
30	Third	0.08	.04	0.68	0.25	1.422	21.1	21.8
30	Third	0.05	.01	0.41	0.27	1.337	22.4	23.8
30	Fourth	0.11	.06	0.90	0.22	1.416	21.2	23.4
30	Fourth	0.09	.07	0.65	0.22	1.242	24.1	24.7
40	Fourth	0.03	.01	0.44	0.25	1.736	23.0	22.8
40	Fourth	0.02	.01	0.24	0.25	1.736	23.0	23.7
50	Fourth	0.01	0	0.09	0.28	2.475	20.2	20.0
50	Fourth	0.01	0	0.16	0.28	2.446	20.4	20.9
60	Fourth	0.01	0	0.07	0.34	3.567	16.8	17.4
60	Fourth	0.00	0	0.11	0.34	3.579	16.8	17.4

*grams/hour

TABLE III

Carter Steam Car
Powertrain Performance
Steady State Modes

Vehicle Speed	Transmission	Air/Fuel Ratio	Rear Wheel HP	Vapor Generator Outlet Pressure psi*	Vapor Generator Outlet Temp. °F*	Expander (engine) RPM	Expander (engine) Pressure Inlet psi*	Expander (engine) Temp. Outlet °F
0	N	36.2	0	1000	775	1500	400	165
0	N	35.0	0	1200	775	1850	350	185
10	First	35.0	.29	750	955	2500	350	200
10	First	35.0	.29	800	960	2550	375	200
10	Second	35.6	.29	950	810	1400	425	180
10	Second	33.9	.29		755	1350	410	190
20	Second	33.9	1.00	800	955	2700	425	210
20	Second	31.9	1.03	755	980	2650	425	210
20	Third	29.5	.84	875	800	1700	470	190
20	Third	31.8	.87	875	950	1800	450	210
30	Third	31.8	2.50	950	965	2500	500	210
30	Third	30.8	2.70	875	975	2500	510	220
30	Fourth	31.3	2.44	1050	800	1800	500	190
30	Fourth	30.8	2.58	1000	830	1800	550	200
40	Fourth	29.9	5.68	1100	915	2200	650	220
40	Fourth		5.52	975	925	2200	675	240
50	Fourth	25.9	9.53	1100	980	2800	775	240
50	Fourth	No data	9.73	1100	980	2800	775	240
60	Fourth	22.7	15.20	1250	980	3400	950	230
60	Fourth	No data	15.84	1300	965	3400	925	220

*Average

TABLE IV

Carter Steam Car
Exhaust Emissions & Fuel Economy
Steady State Modes

Vehicle Speed	Trans-mission gear	Percent Grade	Exhaust Emissions: Cold HC gpm	Exhaust Emissions: CO gpm	Exhaust Emissions: NOx gpm	Fuel Economy: Fuel Flow gal/hr	Fuel Economy: Timed Volume mpg	Fuel Economy: Carbon Balance mpg
10*	First	1.2	.08	.28	.90	1.104	9.1	9.4
9	First	1.1				1.002	9.0	
10	Second	1.2				.830	12.1	
20*	Second	1.2	.02	.07	.71	1.448	13.8	14.3
19	Second	1.1				1.390	13.7	
19	Third	1.1				1.128	16.8	
30*	Third	1.0	.02	.06	.69	1.755	17.1	17.3
30	Third	.9				1.654	18.1	
30*	Fourth	1.1	.01	.06	.58	1.679	17.9	18.8
30	Fourth	.9				1.503	20.0	
40*	Fourth	.6	.01	.06	.68	2.168	18.5	19.1
40	Fourth	.5				1.952	20.5	
50*	Fourth	.1	.01	.12	.70	2.746	18.2	18.6
50	Fourth	0				2.551	19.6	
60*	Fourth	0	.01	.34	.71	3.625	16.6	17.2
60	Fourth	0				3.235	18.5	

*Exhaust emissions for these tests only

TABLE V

Carter Steam Car
Exhaust Emissions & Fuel Flow Rates
Steady State Engine Mapping

Fuel Flow Rate Nominal	Exhaust Emissions gm/hr HC	CO	NOx	Fuel Flow gal/hr Timed Flow gal/hr	Carbon Balance gal/hr
	HC	CO	NOx		
2	.24	.36	27.65	2.019	2.127
3	1.20	4.68	33.80	3.231	3.448
4	1.20	4.08	21.50	3.771	3.750
5	.72	106.50	45.60	5.485	5.455

TABLE VI

Carter Steam Car
Powertrain Performance
Steady State Modes

Vehicle Speed	Transmission	Rear Wheel HP	Percent Grade	Vapor Generator Outlet Pressure psi*	Vapor Generator Outlet Temp. °F*	Expander (engine) RPM	Expander (engine) Inlet psi*	Expander (engine) Outlet °F
10*	First	1.21	1.2	750	1000	2400	475	240
9	First	1.01	1.1	750	1000	2450	450	250
10	Second	1.15	1.2	900	990	1425	500	260
20*	Second	2.80	1.2	850	1000	2600	525	250
19	Second	2.51	1.1	800	1000	2625	525	260
19	Third	2.51	1.1	1000	1000	1700	650	270
30*	Third	4.84	1.0	1000	1010	2500	725	255
30	Third	4.64	.9	1000	1000	2500	680	270
30*	Fourth	4.92	1.1	1150	1000	1750	850	240
30	Fourth	4.64	.9	1100	1000	1700	825	280
40*	Fourth	7.36	.6	1150	1015	2200	850	240
40	Fourth	7.00	.5	1100	990	2275	840	265
50*	Fourth	10.27	.1	1200	1000	2750	1000	230
50	Fourth	9.9	0	1150	1010	2275	900	270
60*	Fourth	13.68	0	1250	1010	3400	1000	240
60	Fourth	13.12	0	1175	1000	3350	950	270

*Exhaust emissions data for these modes are in Table IV.

TABLE VII

Carter Steam Car
Powertrain Performance
For Vehicle Emissions Map

Vehicle Speed	Rear Wheel HP	Vapor Generator Outlet Pressure	Vapor Generator Outlet Temp.	RPM	Expander (engine) Inlet Pressure psi	Expander (engine) Outlet Temp. °F	Fuel Flow Rate Nominal
20	9.00	1325	910	1150	1325	230	2
30	9.86	1040	920	1750	1010	245	2
65	3.42	625	930	3600	600	265	2
25	18.12	1800	880	1450	1800	180	3
30	19.48	1575	870	1700	1525	210	3
55	17.40	1100	870	3025	1040	230	3
30	22.89	1800	960	1750	1800	245	4
40	21.16	1440	950	2200	1425	260	4
40	30.67	1890	980	2275	1850	230	5
50	32.60	1750	960	2825	1725	240	5

TABLE VIII

Volkswagen Type 111/113
Powertrain Performance

Vehicle Speed	Trans-mission	Percent Grade	Rear Wheel HP	Fuel Flow gal/hr	Fuel Economy mpg
9	First	1.1	1.01	.620	14.5
10	Second	1.2	1.15	.424	23.6
19	Second	1.1	2.51	.820	23.2
20	Third	0.0	2.64	.552	36.2
30	Third	.9	4.64	.904	33.2
30	Fourth	.9	4.64	.746	40.2
40	Fourth	.9	7.00	1.060	37.7
40	Fourth	.9	7.00	1.050	38.1
50	Fourth	0.0	9.90	1.500	33.3
60	Fourth	0.0	13.12	1.905	31.5
60	Fourth	0.0	13.12	1.923	31.2
50*	Fourth	5.1	28.63	2.907	17.2
60*	Fourth	4.3	34.48	3.565	16.8
70*	Fourth	3.2	38.17	4.020	17.4

*Wide-open throttle

1974 Volkswagen Type 111/113 (Super Beetle)
96.6 cubic inch, single carburetor, EGR, approximately 4000 miles on vehicle