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Passenger Car Performance with the Experimental Gas Turbine VW—GT 70

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This paper describes the performance obtained by the Volkswagenwerk AG with an experimental gas turbine power plant in a passenger car. Following a brief description of the power unit and its installation in the vehicle, results of operational tests are given. The investigations cover both the road performance and the effect on the environment of this experimental turbine car. The results are compared with those from spark ignition engines of similar power. Possible solutions are indicated where the results are considered to be not yet satisfactory.

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INTRODUCTION

The possibility of using gas turbines as alternative power plants for passenger cars has been investigated by various car manufacturers. In view of the necessity to reduce the environmental pollution caused by automotive emissions, interest in gas turbines has become even greater. Due to their continuous combustion process with high excess air, gas turbines promise to have low exhaust emissions.

The work performed by the Volkswagenwerk AG on experimental gas turbines was aimed initially to acquire information on the feasibility of these unconventional power plants in passenger cars. Gas turbine vehicles were, therefore, investigated under all operating conditions characteristic for passenger cars. The results obtained are here compared with those of the conventional piston engine. The power range of the gas turbine was selected according to the requirements of the small vehicle weights considered. In its basic version, the gas turbine has a fairly simple design which should easily allow modifications. The changes found to be necessary from the analysis of the tests may, therefore, be subsequently incorporated.

The operational results obtained with the basic version of this experimental gas turbine installed in a passenger car are given in what follows. First the gas turbine and its installation in the vehicle are described. Details on the performance of the gas turbine driven passenger car and its effects on the environment are provided. From the results obtained, tasks are indicated for further development to give a gas turbine power plant to meet today's passenger car operational requirements.

GAS TURBINE AND VEHICLE

Gas Turbine

The VW-GT 70 gas turbine used in the tests was strictly experimental. It was developed in cooperation with Williams Research Corp., Michigan, USA. The design and thermodynamic cycle are described in detail in reference

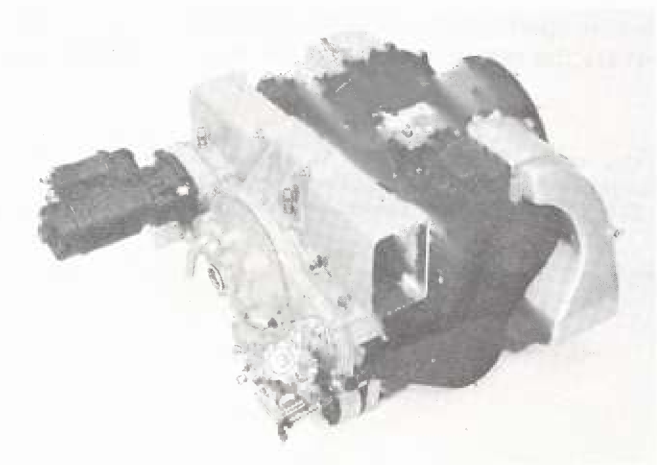

Fig. 1 Volkswagen Research Gas Turbine VW-GT 70

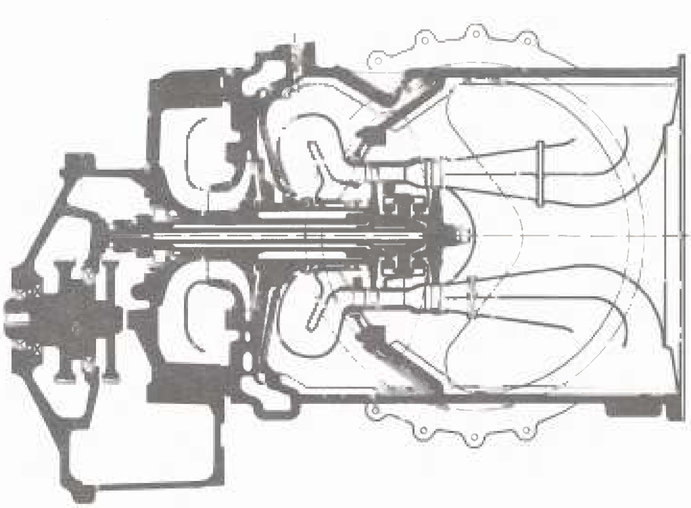

Fig. 2 Gas turbine cross section

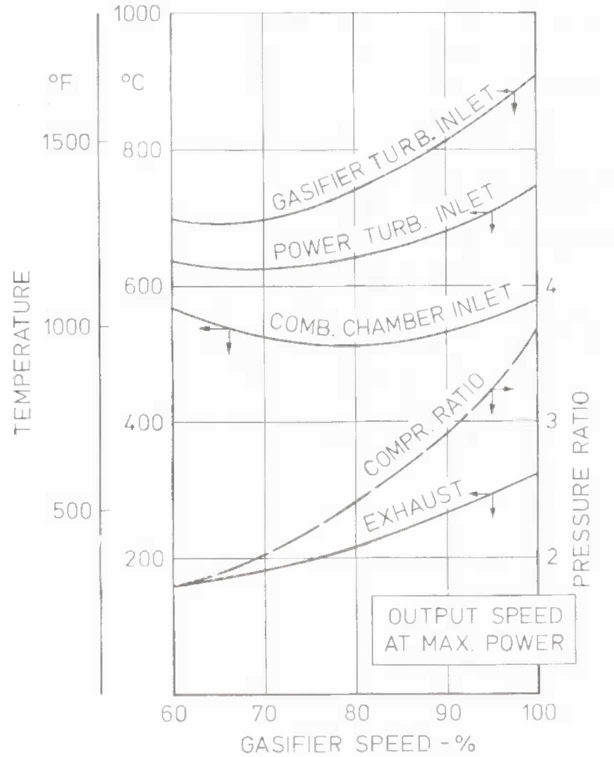

Fig. 3 Thermodynamic parameters versus speed

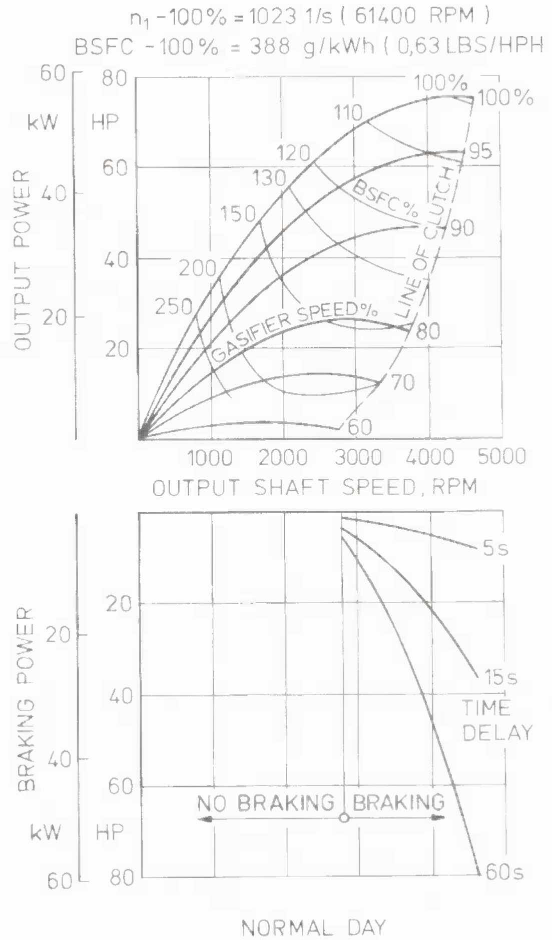

Fig. 4 Performance characteristics

(1)[1] and will only be briefly reviewed in the following.

In Fig. 1, the engine is shown. The gas turbine is of twin-shaft construction with regenerative air preheating and integral reduction gear. The power unit develops 75 hp. With its dimensions of 24 x 26 x 16 in. and its weight of 375 lb including all auxiliaries, this gas turbine fits into the rear engine compartment of various Volkswagen vehicles. The maximum output shaft speed of 4550 rpm corresponds to that of the comparable piston engine.

The cross section of the engine is shown in Fig. 2. Characteristic are the concentric shaft arrangement of gasifier and power turbine and the drive of both shafts into the common

[1] Numbers in parentheses designate References at end of paper.

Table 1

Inlet conditions	60 F, 29.5 inHg(15 C, 1 bar)
Power	75 hp (55 kW)
Pressure ratio	3.7
Airflow	1.3 lb/sec (0.59 kg/sec)
Gasifier turbine inlet temperature	1,674 F (912 C)
Gasifier speed	61,400 rpm (1023 1/sec)
Power turbine speed	50,600 rpm (843 1/sec)
Output speed	4,550 rpm (76 1/sec)
Effectiveness of regenerator	0.8

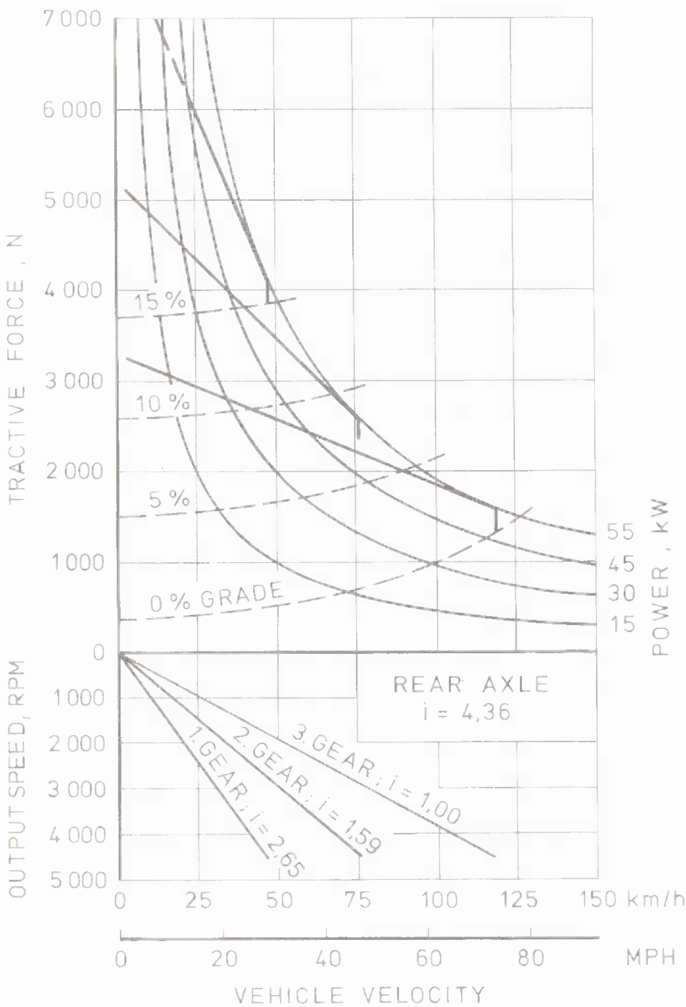

Fig. 5 Tractive force characteristics VW-GT 70 in VW Microbus

front positioned reduction gear. Power absorption by the compressor is utilized for braking by means of connecting both shafts with a simple overrunning clutch. The only equipment to improve fuel economy used on the basic version of this experimental engine is to bypass the power turbine on idling. All auxiliaries are driven off the gasifier shaft.

The layout makes various engine modifications possible. For example, it is possible to improve part-load fuel economy by a power transfer arrangement in the common reduction gearbox. Single-shaft operation can be tested by rigid coupling of the shafts in the gearbox. The main bearing arrangement is designed to allow annular or can-type combustion chambers.

The engine performance data at full power are given in Table 1. As shown there, the VW-GT 70 operates with a turbine inlet temperature of 1674 F, a compressor pressure ratio of 3.7, and a heat exchanger effectiveness of 80 percent. The air mass flow is 1.3 lb/sec. The test result presented in Fig. 3 illustrates how the main thermodynamic parameters change with gas generator speed.

In Fig. 4, the engine performance diagram is given as measured on the test rig. Lines of constant gas generator speeds and constant specific consumptions are shown. In these performance and consumption data, all engine auxiliary losses have already been subtracted. In certain speed ranges during deceleration, the shafts of the gasifier and power turbine are linked by the overrunning clutch. In this case, the gasifier speed is not reduced to idling and the power absorption of the compressor provides a braking effect on the vehicle. The influence of the heat exchanger delays the development of the full braking power.

Vehicle Installation

The VW-GT 70 gas turbine fits into the engine compartments of the VW 1600 vehicles and the VW Microbus.

The VW 1600 automatic transmission is used in the experimental vehicles. This three-speed automatic transmission has a ratio of 2.65:1 in first gear, 1.59:1 in second gear, and 1:1 in third gear. The two-shaft gas turbine has an inherent torque factor of approximately 2. Together with the transmission, a torque increase of 5.3 is achieved at the start which is quite sufficient for drive-off. Therefore, the hydrodynamic torque converter in the standard transmission could be omitted.

For the installation of measuring equipment, the spacious VW Microbus was very convenient. The major part of the road tests was, therefore, performed with this car. It is generally driven like a passenger car and is registered as a station wagon in the USA. The tractive force characteristics of this unit are given in Fig. 5. The installation of the gas turbine in the vehicle and in the engine compartment is shown in Figs. 6 and 7. Similar modes of installation have been tested in VW 1600 vehicles.

The anchorage points of the piston engine are used for the suspension of this power plant. To prevent power losses resulting from erosion and accumulation of dirt in the compressor and heat exchangers, paper filter units were installed in the air intake ducts of the car body. Unlike the piston engine, the compressor intake ducts of the gas turbine were directly connected by a rubber flange to these body air ducts. The exhaust gases leave the gas turbine behind the heat exchangers with 300 F at idling and 630 F

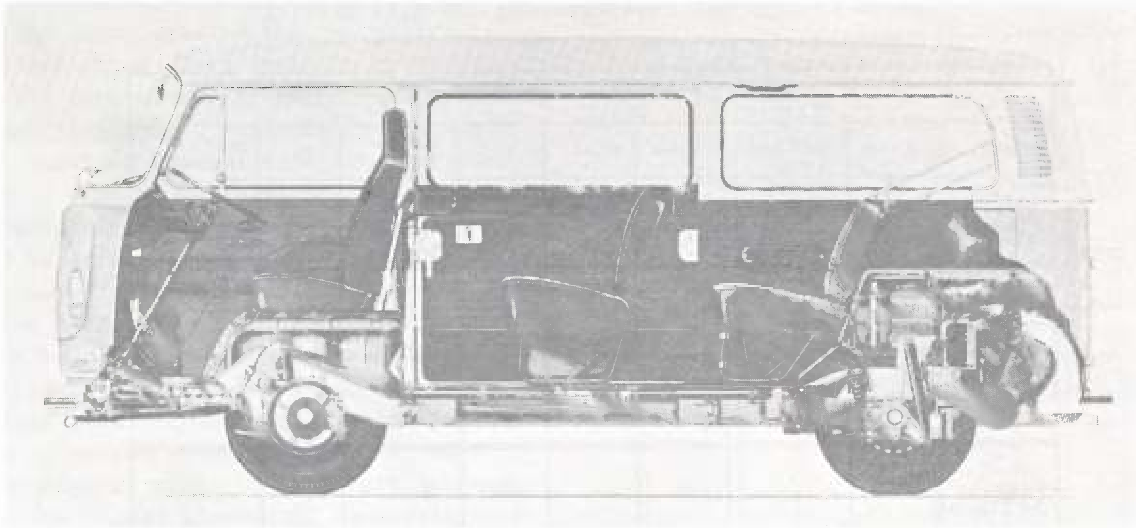

Fig. 6 Test vehicle VW Microbus with gas turbine VW-GT 70

at full load. Since the gas velocities are low, immediate mixture with ambient air is ensured. Only two short exhaust ducts of large area were fitted to the power unit. These ducts discharge the exhaust gases at an inclination toward the road and within the area of the vehicle.

PERFORMANCE CHARACTERISTICS

The problems investigated with the gas turbine test vehicles were:

1 Performance, particularly fuel economy and flexibility during transient road operation
2 Influence on the environment, particularly by noise and exhaust emissions.

The results of these investigations are detailed in the following.

Road Performance

Fuel economy. The fuel used during most of the tests was Diesel No. 2, but operation with kerosene and lead-free gasoline was also investigated.

The measurements show the fuel economy at typical passenger car operating conditions. Those conditions are, in reality, a mixture of constant road load driving, frequent load changes, and lengthy idling times. In Table 2, a driving schedule is given in accordance with an EPA proposal (2). This covers 100 miles and is composed partly of the FDC corresponding

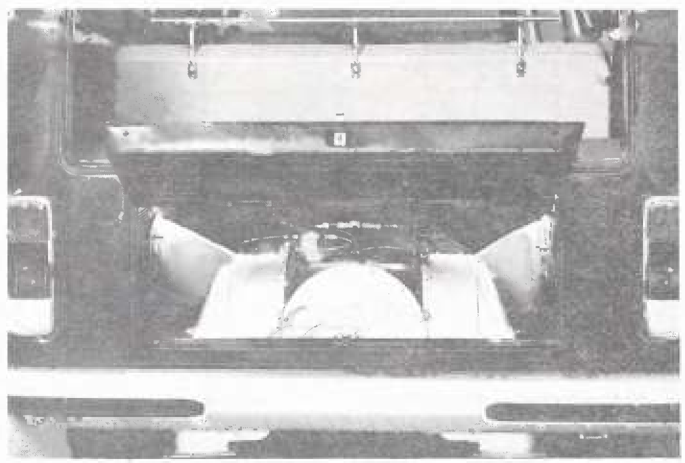

Fig. 7 Installation in engine compartment

to city traffic, partly of steady average suburban traffic and partly of fast highway driving. For the 100 miles in this mixed traffic, the experimental gas turbine vehicle consumed 8.7 gal of Diesel fuel compared with 5.3 gal of gasoline for the equivalent piston engine vehicle.

The analysis of these results reveals that the higher fuel consumption of the gas turbine is mainly due to excessive idle consumption. Of the 200 min. driving over the assumed 100 miles, 75 min. are taken up by engine deceleration and idling. Here the gas turbine consumes 2 gal of fuel, compared with 0.5 gal for the piston engine. Therefore, the improvement of idling consumption has to be one target for future development. One method investigated here was to open a bypass in the flow path be-

Table 2: Typical Passenger Car 100 Mile Driving Schedule

					VW - GT 70		PISTON ENGINE	
mode	% time	mean speed mph	minutes	miles	kg	gallons Diesel	kg	gallons Gasoline
FDC	50	19.84	100	32.8	13.9	4.49	6.5	2.35
Suburban	33	30	66	32.6	5.9	1.91	3.0	1.11
Highway	17	60	34	33.6	7.1	2.31	5.0	1.83
Total			200	100	26.9	8.71	14.5	5.29

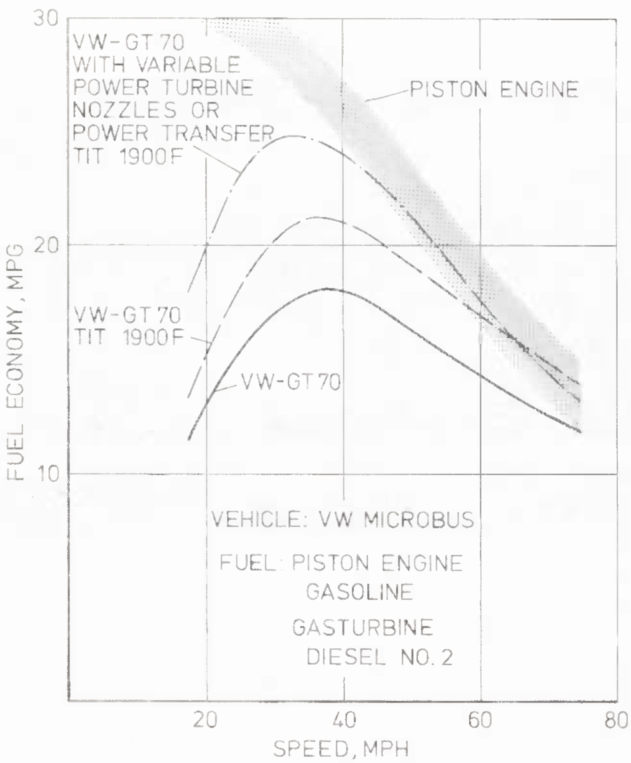

Fig. 8 Road load fuel economy

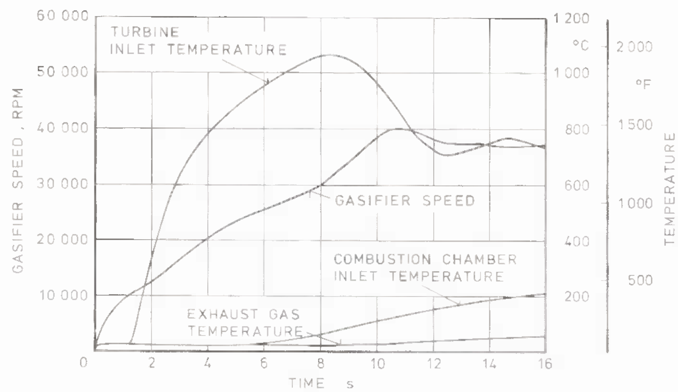

Fig. 9 Start diagram

tween gasifier and power turbine, thereby providing an increased enthalpy gradient at the gasifier turbine. This not only lowered the idling consumption to 1.4 gal, it also reduced the power output at idling. A further reduction of idling consumption can be achieved by driving the engine auxiliaries from the power turbine, and not from the gasifier shaft. This, however, adds the need for a torque converter to the drive unit.

Another cause for higher fuel consumption is the excessive consumption at low speeds. In Fig. 8, the fuel economy at various constant car speeds for the gas turbine car and the equivalent piston engine car is shown. At higher speeds, the fuel economy of both cars is similiar. There are still considerable differences at low speeds. In the mixed load testing described, the vehicles were driven for about 1 hr at average speeds of 30 mph. In this operation, the gas turbine consumes 0.8 gal more than the piston engine. This difference in consumption would be reduced by increasing the turbine inlet temperature to 1900 F using recent progress in materials. Devices like a power transfer unit between the two shafts or variable nozzles in the power turbine would improve the part-load fuel economy still further. This would add considerable complexity and costs to the engine and its controls.

Transient Operation

Start--The gas turbine needs 12 sec for

starting after turning the ignition key. A 1.3-kw starter motor accelerates the gasifier through the reduction gear, with the igniter working at the same time. If 10,000 rpm are reached, fuel is injected into the combustion chamber and ignition takes place. The gasifier accelerates to its idling speed of 36,900 rpm. At 30,000 rpm, the starter is disengaged and the igniter is cut off.

The time relation of gasifier speed, turbine inlet temperature, and heat exchanger temperatures are shown in Fig. 9 to explain engine operation during the start-up. In order to obtain fast acceleration, the turbine inlet temperature is raised briefly to 1900 F. Because of the time it takes for the heat exchangers to warm up, the normal preheating temperature of 1100 F is reached only after 60 sec. At a hot start, the heat exchanger is already hot and less fuel has to be injected.

A more rapid acceleration and a shorter starting time would be achieved if the maximum turbine inlet temperature shown in the diagram could be reached earlier. In developing the fuel supply and combustion system for good ignition behavior at very rich fuel air mixtures, this improvement should be possible.

Acceleration—The much criticized acceleration delay of the gas turbine was studied with particular care. In a piston engine, an increase in fuel immediately raises the output torque. In a twin-shaft gas turbine, the gasi-

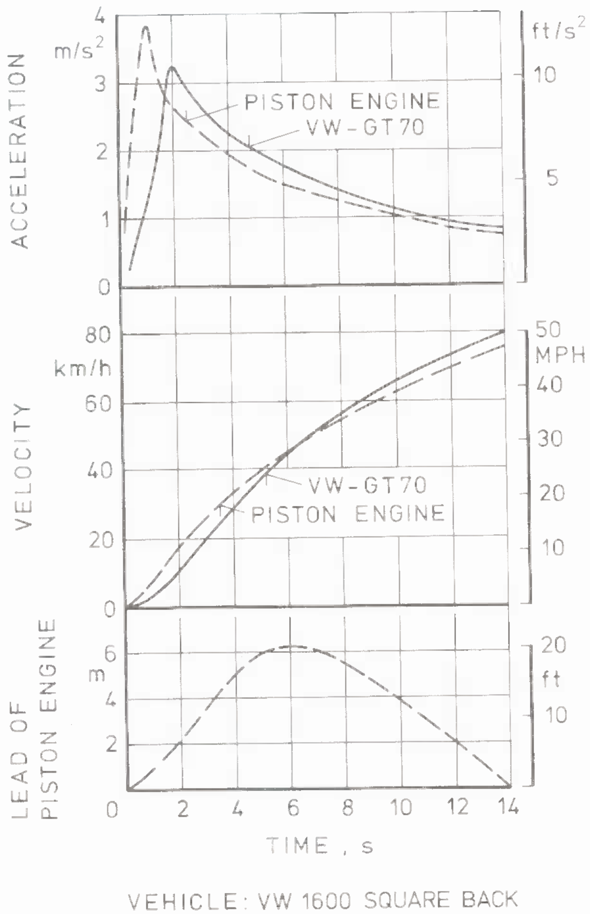

Fig. 10 Acceleration of gas turbine test vehicle

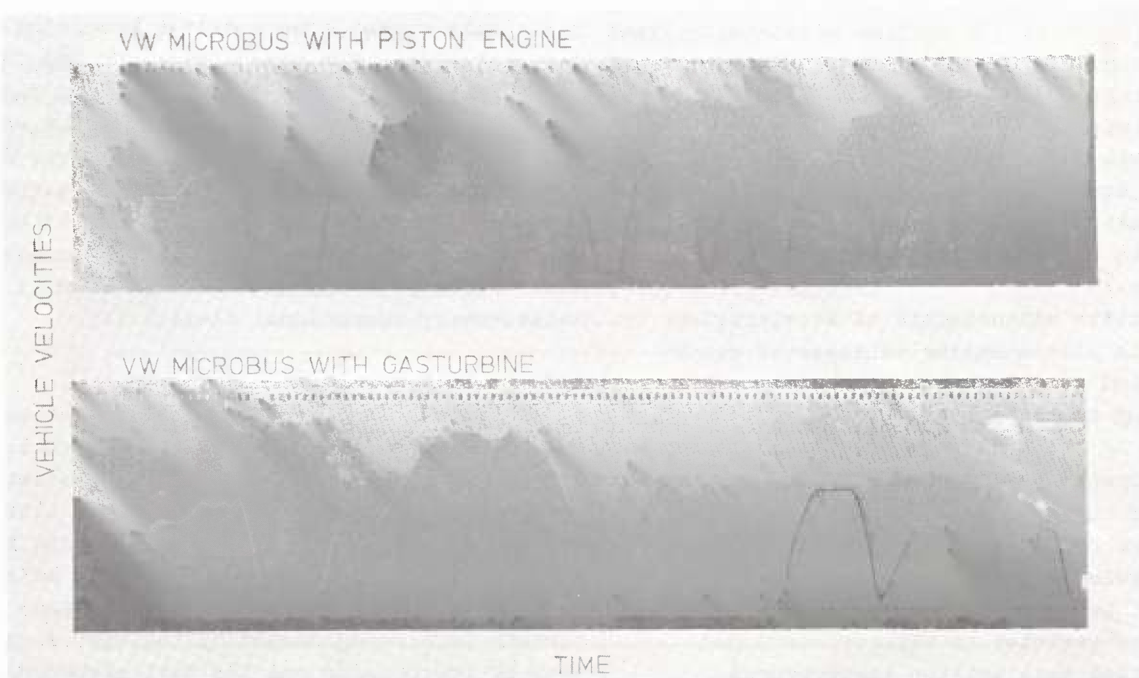

Fig. 11 Road operation schedule

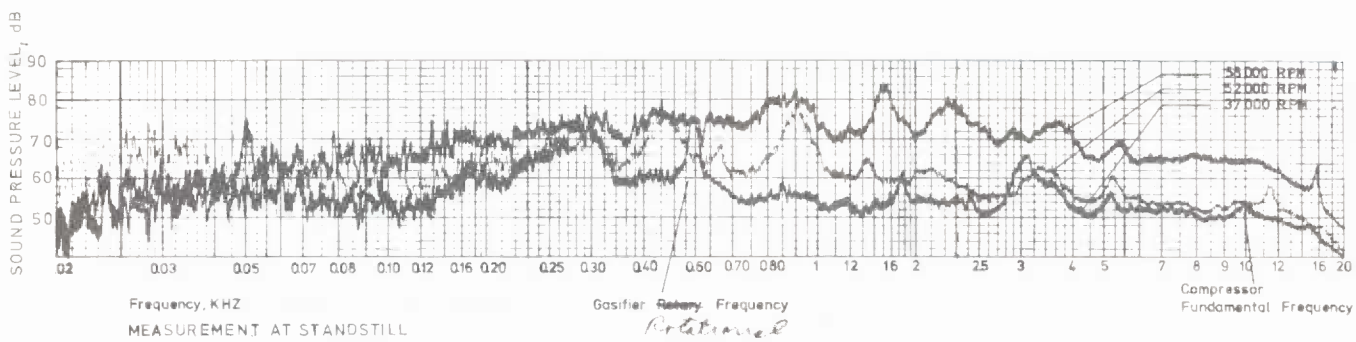

Fig. 12 Frequency analysis of exterior noise
VW Microbus with VW-GT 70

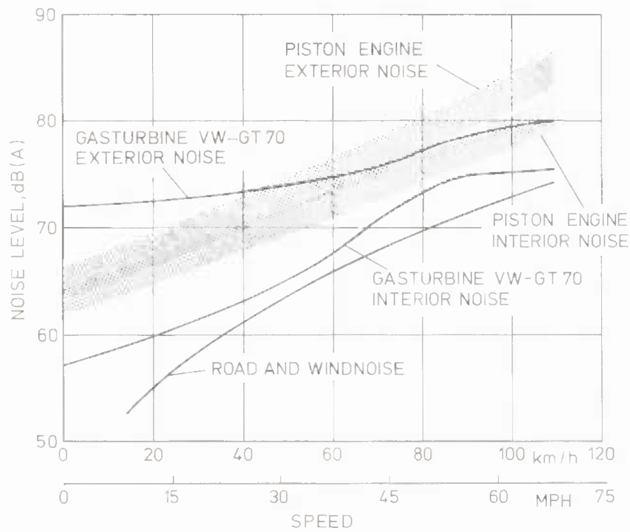

Fig. 13 Noise emission of gas turbine test vehicle

fier has to be accelerated to its maximum speed before the full output torque is available. Furthermore, due to the extremely smooth acceleration of the gas turbine, the driver believes the vehicle to be even more sluggish than it is in reality.

Comparative measurements of acceleration from zero with piston engine vehicles of equivalent power and weight gave the results in Fig. 10. According to these results, the initial acceleration of the piston engine car is higher during the first 1.5 sec. After 6 sec. both vehicles have the same speed, and after 14 sec, they have covered the same driving distance.

The acceleration of this experimental gas turbine would be improved by removal of the loads from the gasifier as already mentioned and by increased acceleration temperatures.

Deceleration—Tests to determine braking capacity showed that the performance illustrated in Fig. 4 is only available after an extended overrun period. Brief changes from acceleration to deceleration provide less braking power than shown in Fig. 4. The storage capacity of the heat exchangers keeps the preheating temperature temporarily higher, thus providing more energy to the gasifier turbine than in stationary idling. In the road tests, therefore, a servo brake operated by compressor bleed air was used. Other solutions, such as bypassing the heat exchangers or the gasifier turbine in deceleration, should also be possible.

Flexibility of Operation—The influences of transient behavior in city traffic, which is characterized by miscellaneous load changes, were evaluated. Again, the FDC was selected as a representative city traffic driving schedule. Both vehicles were driven according to this schedule. The speed traces of the first 7 FDC phases are shown in Fig. 11. They reveal that the driver of the gas turbine test vehicle already in this stage of development was able to follow the prescribed speeds and times. The only exception was the sharp acceleration at the beginning of the second phase. The improvements already mentioned should give fully satisfactory operational flexibility.

Effects on Environment

Noise. In order to assess the noise behavior of the gas turbine, the external and internal noise at different car speeds was recorded. The frequency spectrum was also analyzed. The compressor intake air and the reduction gear were identified as the main sources of noise. The noise of all other components is already damped by the heat insulation of the housing and the heat exchangers. The high-frequency noises of the compressor intake were reduced by installation of sound

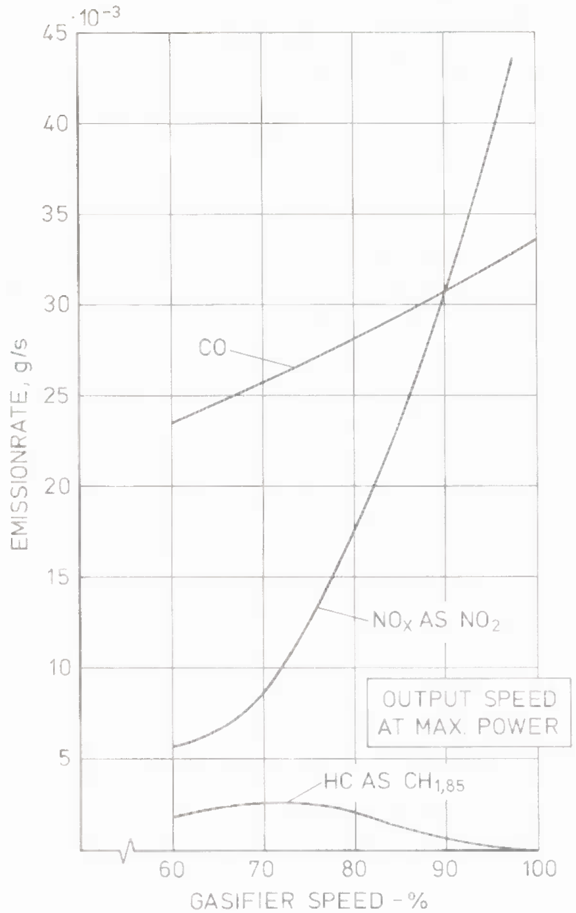

Fig. 14 Stationary pollutant mass emissions of VW-GT 70

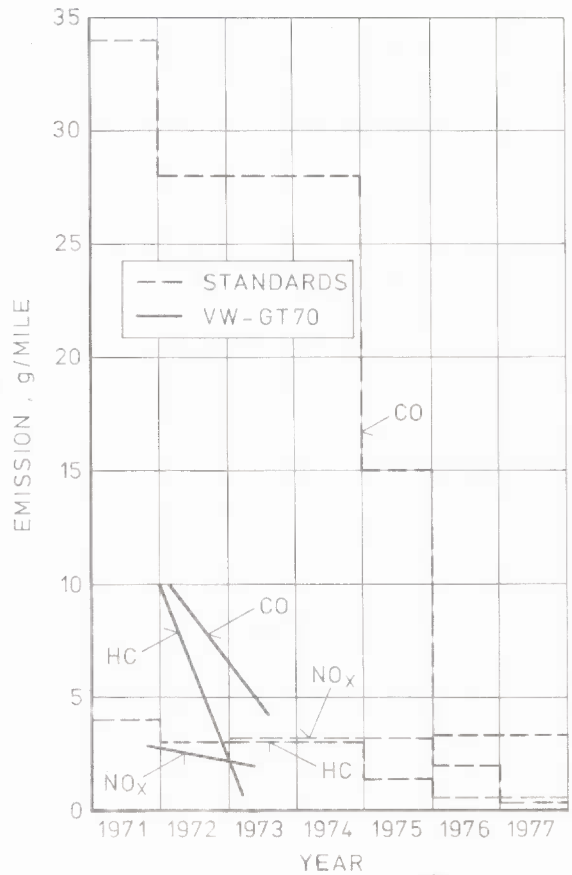

Fig. 15 U. S. Federal Automotive Emission Standards and gas turbine test vehicle emission

absorbent fiberglass matting in the air intake ducts of the car body. The noise of the reduction gear was lowered by sound insulation of the gearbox with a ceramic fiber and silicone rubber layer.

In Fig. 12, the narrow band frequency analysis of the external noise at various gasifier speeds is given. The noise emission of the gas turbine is concentrated at 1000 Hz; piston engines generally emit at 125 Hz. The sound pressure peaks are caused by the fundamental frequencies resulting from the rotational frequencies times the number of rotor blades. In some cases, they are inaudible and are not shown in the spectrum.

Table 3: Results of unsteady State Emission Measurements with the VW-GT 70

Driving schedule	NO_x	CO	HC	Vehicle	Fuel	Remarks
	gm/mile	gm/mile	gm/mile			
7- mode California cycle	1,7	3,3	0,7	VW-Microbus	JP-4	Continuous Analysis according to [4]
US - 1372 sec Federal Driving cycle	2,15	4,5	0,35	VW 1600 Square back	leadfree gasoline	Measured at EPA [3] with a CVS System
US - 1372 sec Federal Driving cycle	2,6	4,9	0,5	VW Microbus	JP-4	Continuous Analysis[5]

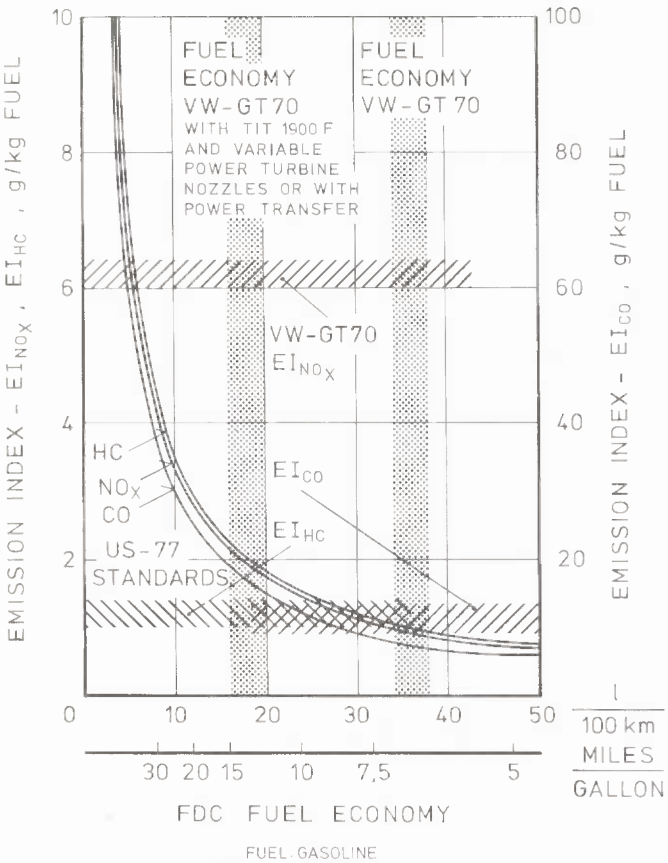

Fig. 16 Influence of emission index and fuel economy on FDC emissions

The measured noise levels inside the car and the measured noise levels of the passing car are shown in Fig. 13. According to these measurements, the exterior noise of the gas turbine vehicle at maximum speed was 80 dB(A). At idling, the gas turbine vehicle emitted still more noise than the piston engine car. It can be seen from the diagram that the noise in gas turbines does not increase very much with speed. The noise emitted during an accelerated passing maneuver, according to DIN 45 636, reached 74 dB(A). The noise level within the car is low under all operating conditions. This and the lower mechanical vibration make a trip in the gas turbine car quite comfortable.

Simple damping of the high-frequency air noise already resulted in these low interior noise levels. Reduction of the exterior noise is much more difficult. Solutions may be found by encapsulating the engine.

Exhaust emissions. The emissions of the pollutants HC, CO, and NO_x, which are all restricted by U. S. legislation, were investigated. The results shown were obtained with the original combustion system, which was not optimized for low pollutant formation.

In Fig. 14, the pollutant mass emissions at steady-state operation are shown. As the gasifier speed increases, the fuel flow rises. Nevertheless, since combustion improves with load, there are practically no HC emissions at high loads. The CO mass emissions rise only slightly. Increasing combustion zone temperatures and raising fuel flow lead to a ten fold NO_x emission at full load as compared to idling.

To evaluate unsteady-state emission performance, the VW-GT 70 was installed in various test vehicles and operated through various driving schedules. In Table 3, results of measurements taken by both Volkswagen and EPA (3) are tabulated. The evaluation procedures used are described in references (3-5). In Fig. 15, the FDC mass emissions are compared with the U. S. automotive emission standards. The comparison shows that this experimental gas turbine car already meets the proposed emission standards up to 1976. In contrast, the piston engines will have to be cleaned up by expensive equipment. With regard to the proposed standards for 1977, however, the NO_x emission is still much too high.

In Fig. 15, some early results show very high CO and HC values. In these cases, the deceleration fuel flow was reduced in one step

Table 4: Analysis of VW-GT 70 Mass Emissions in the FDC

	% of Cycletime	% of Cycle Mass Emission		
		NO_x	CO	HC
Gasifier Acceleration	15	42	11	3
Gasifier Deceleration	25	17	36	59
Idling	50	23	43	35
Constant Road Load	10	18	10	3

so that the combustion chamber operated temporarily close to the lean stability limit. A change in this fuel flow mode brought considerable emission improvements. All information in Fig. 15 is in terms of the 1975 U. S. Federal Test Procedure, and the 1975 and 1976 standards are the interim standards.

For future development, it is of interest to know which part of the emissions can be influenced by the amount of fuel consumption and which part by changing only the combustion system itself. In Fig. 16, the relationship between fuel economy and emission index in the FDC is illustrated. The VW-GT 70 in its present stage is shown in the diagram.

Assuming that the devices already mentioned for improving fuel economy will be incorporated, it will be seen that, without modifying the combustion system, this gas turbine would emit only 1.5 gm of NO_x per mile.

The analysis of the FDC in Table 4 illustrates the tasks of future developments toward a combustion system with smaller mean emission indices. It can be recognized that, for CO and HC, the amount of emission during idling and deceleration is decisive. The idling emissions only depend upon the fuel flow and the combustion system, whereas the emissions during deceleration are determined by the matching of gas turbine, combustion system, and control system. With regard to NO_x emission, acceleration is most important, but other operational modes also contribute significantly.

CONCLUSIONS

The experience with the VW-GT 70 showed that a gas turbine power plant running under the low part-load conditions and frequent load changes typical of a passenger car use is quite feasible even in the small engine power range under consideration. Although not all technical problems have been solved with this experimental engine, it appears that solutions can be found by appropriate further development. In comparing the results of the experimental gas turbine car with those of the piston engine car, it must be admitted that road performance of gas turbines in this low power range do not show definite advantages over the spark-ignition engine. This is not the case with regard to the effects on the environment. Here the gas turbine appears to offer a power plant with much less exhaust emissions than the unmodified spark-ignition engine.

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