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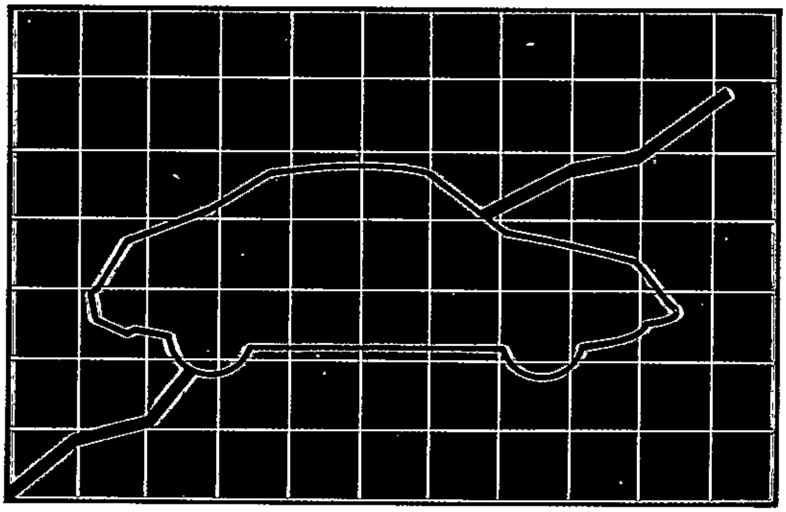
Automotive Technology Status and Projections

Volume I. Executive Summary



June 1978

Prepared for
Department of Energy
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Volume I. Executive Summary

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ABSTRACT

Results of an assessment of the status and projections of automotive technology are presented. Factors considered include fuel economy, exhaust emissions, multifuel capability, advanced materials, and cost/manufacturability for both conventional and advanced alternative power systems.

To insure valid comparisons of vehicles with alternative power systems, the concept of an Otto-Engine-Equivalent (OEE) vehicle was utilized. Each engine type was sized to provide equivalent vehicle performance. Sensitivity to different performance criteria was evaluated. Fuel economy projections are made for each engine type considering both the legislated emissions standards (0.4 g/mi HC, 3.4 g/mi CO, 1.0 g/mi NO_x) and possible future emissions requirements (0.4 g/mi NO_x).

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SECTION 1

INTRODUCTION

The need to improve air quality has led to more stringent Federal emissions standards for controlling exhaust emissions from automobiles. Early attempts by automobile manufacturers to meet these emissions standards with conventional engines led to significant fuel economy penalties. In 1975, at a time when much emphasis was being placed on developing better emissions control hardware, the Jet Propulsion Laboratory published a report (Reference 1) on an Automotive Power Systems Evaluation Study (APSES). This report made an assessment of conventional and alternative power systems and included projections of their fuel economy potential and their ability to meet the then most stringent legislated emissions standards (0.4 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x).

Since the APSES report, the impact of the oil embargo by OPEC nations has helped focus the need for energy conservation in this country, especially in the use of petroleum for transportation. This need to conserve petroleum has led to the passage of Federal fuel economy standards which require an increase from a sales-weighted-average of 18 mpg in 1978 to a sales-weighted-average of 27.5 mpg in 1985 based on the composite driving cycle. The passage of these Federal fuel economy standards has had and will continue to have a significant effect on the type of vehicles produced by the automobile industry. It is leading to the development of lighter weight vehicles and more fuel efficient conventional engines, and some reflective thoughts about emissions.

The energy crisis and the fuel economy legislation have resulted in modification of emissions standards for passenger cars. Up through 1985, the most stringent Federal emissions standards are set at (0.4 g/mi HC, 3.4 g/mi CO, 1.0 g/mi NO_x). Because of its special pollution problems, California requires that vehicles meet the (0.4 g/mi HC, 9.0 g/mi CO, 0.4 g/mi NO_x) values starting in 1982. Consideration is being given to waiving the 0.4 g/mi NO_x requirement and requiring vehicles to be certified for 100,000 miles (currently a certification for 50,000 miles is required). The 0.4 g/mi NO_x requirement has been established as a research goal by Federal legislation.

The Department of Energy (DOE) has significant programs aimed at the development of advanced alternative heat engine power systems (Brayton and Stirling). Since these advanced power systems are aimed for automotive application in the 1985-2000 period, the DOE programs have as their prime goals good energy efficiency, multifuel capability, low emissions, and competitive cost.

Because of the ever-changing automotive technology base and the evolving constraints (fuel economy, exhaust emissions, noise, etc.) on the automotive industry, it is important to continually reassess the potential of the various alternative power systems in this changing environment. The objective of the work in the Automotive Technology

Status and Projections (ATSP) task is to provide DOE with this information so that it can be used to help assess and develop a more effective DOE heat engine program in the transportation area.

The general objective of the ATSP task is to make a continuing assessment of the status of automotive technology. The study considers both current and advanced conventional engines, advanced alternative engines, advanced power train components and other energy-conserving vehicle modifications which could be implemented by the end of this century. A secondary objective is to make vehicle-level projections of the fuel economy and emissions potential of both conventional and advanced alternative power systems.

The major thrust of the ATSP task is the assessment of the potential of advanced alternative heat engine power systems (Brayton and Stirling) when compared with the evolving conventional power systems (uniform-charge Otto, diesel, stratified-charge Otto). Factors considered in the task include fuel economy, exhaust emissions, multifuel capability, use of advanced materials, and cost/manufacturability.

Since the period covered in the study extends to the end of the century, each candidate power system is evaluated for its ability to meet not only the current legislated emissions standards but also the possible future emissions requirements, including the 0.4 g/mi NO_x level. Consideration is given to the presently unregulated emissions of particulates, noise, and odor. The impacts of the Federal fuel economy standards are included as they relate to vehicle/engine size and weight.

To obtain the latest data and to learn about the latest developments in conventional and alternative power systems and advanced materials, technical discussions have been held with both domestic and foreign automobile manufacturers, automobile suppliers, and Government laboratories. This is the pattern that has been followed in providing the basis for the material in the report. In general, the technical material contained in this report is based on the information which was available as of April 1978.

SECTION 2

TECHNOLOGY STATUS REVIEW

Considerable improvements have been made recently in the fuel economy and emissions characteristics of vehicles with conventional engines (uniform-charge (UC) Otto, naturally-aspirated (NA) diesel, turbocharged (TC) diesel) and advanced conventional engines (rotary UC Otto, stratified-charge (SC) Otto, rotary SC Otto). Federal fuel economy standards have had and will continue to have a significant effect on the type of vehicles produced by the automotive industry. It is leading to the development of lighter-weight, downsized vehicles and the use of smaller, more fuel efficient engines. In addition to the downsizing trend, more emphasis is being placed on weight savings through material substitution in both drive train components and the vehicle body.

As a result of these trends and the acceptance of somewhat lower performance, a larger variety of engine systems are being seriously tried in production vehicles in the United States. This is evidenced by the recent introduction of two NA diesel engines (Oldsmobile, VW), a TC diesel engine (Mercedes-Benz) and a TC Otto engine (Buick) in passenger cars. Indications are that use of these engine types will increase in the near future. The use of turbocharging permits either greater performance or the use of a smaller engine for the same power level. Other techniques for improving the fuel economy of conventional engines are being studied (e.g., variable displacement, microprocessors, etc.). With continued development, it is expected that vehicles with conventional engines can meet the Federal fuel economy and emissions (0.4 g/mi HC, 3.4 g/mi CO, 1.0 g/mi NO_x) standards. Very encouraging fuel economy and emissions results have recently been obtained with the TC diesel in the Department of Transportation (DOT) safety vehicle program (References 2 and 3).

Developments have continued on both the pre-chamber (Honda CVCC) and direct injection (Ford PROCO and Texaco TCCS) versions of the SC Otto engines as alternatives to the diesel engine. Rotary engine developments (References 4 and 5) in both the UC Otto (Mazda and NSU/Audi) and SC Otto (Curtiss-Wright) engines have made significant improvements in the fuel consumption characteristics of these engines. Rotary engines, with their high power density, have definite weight and packaging advantages over other conventional engines.

Successful introduction of catalysts (oxidation and three-way) on conventional UC Otto engines has permitted the re-tuning of these engines for improved fuel economy while controlling emissions to current levels. It has been demonstrated that small UC Otto vehicles with three-way catalyst emissions control systems can meet strict emissions levels (0.4 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x) with little fuel economy penalty (Reference 6). To meet the same emissions levels in larger cars will result in a larger fuel economy penalty (about 10 percent).

The three-way catalyst system (Reference 7) requires closed-loop feedback control for maintaining an adequate air-fuel ratio control (near stoichiometry) for good conversion efficiency of HC, CO, and NO_x. Best results have been achieved using fuel injection systems (Volvo, Saab). Although attempts are being made to use three-way catalysts with carburetors (Reference 8), the trend is toward single-point or dual-point injection into the intake manifold. The use of electronic engine controls is increasing. This technology (Reference 9) offers new flexibility and precision in controlling engine variables to achieve both better fuel economy and lower emissions.

Considerable R&D is being directed toward finding effective control techniques for the unregulated emissions (particulates, odor, noise) from diesel engines. If legislation is enacted to control the levels of these pollutants, it will pose a problem for vehicles with diesel engines until effective controls are identified.

The Department of Energy (DOE) has significant programs (References 10 and 11) aimed at the development of advanced alternative engines (Brayton and Stirling). Since these advanced engines are aimed for automotive application in the 1985-2000 period, the DOE programs have as their prime goals the development of engines which satisfy the long-term future needs of automotive transportation (i.e., good energy efficiency, multifuel capability, low emissions, and competitive cost).

Participation in the DOE Brayton engine program has been expanded to include groups/companies which have been active in the past in the development of Brayton engines for heavy duty truck and aircraft applications. This involvement of the truck groups brings to the automotive program their extensive design and hardware experience (Reference 12). Likewise the involvement of the NASA/Lewis Research Center (LeRC) as the project manager of the DOE program brings into the program their extensive aircraft experience (Reference 13). Hence the current automotive program is now benefiting from the combined expertise and experience of groups/companies with the broadest possible backgrounds in Brayton engines.

The focal point of the DOE program has been the Chrysler Upgraded engine (References 14 and 15) which is currently undergoing development modifications and dynamometer testing. To provide a firm foundation for the next Brayton engine generation, contracts for improved system conceptual design studies have been awarded to the following four contractors: Chrysler Corporation, Williams Research Corporation/AM General, Detroit Diesel Allison (DDA)/Pontiac and Ford Motor Company/AiResearch. In the component area, considerable progress has been made in the development of low NO_x combustors for Brayton engines. The use of wide-range variable geometry for all flow-controlling elements of the engine, including the compressor, diffuser, and high temperature turbine inlet nozzles, offers the possibility of improved part-load efficiency. Characterization testing of a variable-geometry single-shaft engine is underway at DDA (Reference 16). As vehicle size and weight are reduced, the potential degradation of Brayton engine thermal efficiency due to reduced engine size requires more careful examination especially as it relates to ceramic parts.

Available information indicates that the use of ceramics is required to achieve the engine efficiency needed for passenger car application. Ceramic material efforts (Reference 17) in the DOE program include long-term durability testing, development of improved heat exchanger and structural ceramic materials, regenerator durability testing, and hot rig testing of ceramic rotors. Progress is being made in the development of ceramic regenerators (Reference 18) with several units having been tested at 1000°C (1832°F) for over 4000 hours without failure. The use of ceramics for hot stationary parts now appears feasible and some success has been achieved in the hot spin testing of ceramic rotors (Reference 19). One rotor successfully completed a 200-hour durability test whose duty cycle included turbine inlet temperatures from 1930°F to 2100°F and rotor speeds from 27,500 to 50,000 RPM. Clearly, although progress is being made, additional work on advanced ceramic materials is needed to support advanced Brayton engine development.

There are passenger car gas turbine programs outside of the United States which have made significant progress in the last 5 years. These include the programs at Volkswagen (Reference 20) and United Turbine of Sweden (Reference 21). Volkswagen, in conjunction with Williams Research Corporation, has developed a two-shaft engine (GT-150) and tested it in a Ro-80 vehicle. United Turbine has designed a three-shaft engine and is currently testing it on a dynamometer.

There is available in the literature considerable information on the fuel economy of vehicles powered by prototype Brayton engines. The fuel economy of the Ro-80 vehicle (3500 lb inertia weight) powered by the VW GT-150 (136 hp) was found to be 14 mpg for the EPA composite driving cycle. This fuel economy was a significant improvement over that found using earlier engine designs (e.g., the Chrysler Baseline and the VW GT-70), but it is still less than that for 1978 California production automobiles with conventional engines. It is expected that when the development modifications are completed on the Chrysler Upgraded engine, significant progress will be made toward demonstrating the fuel economy potential of Brayton engines in passenger cars.

Relative to exhaust emissions, the Ro-80 vehicle with the VW GT-150 engine (diffusion flame combustor) met the emissions standards (0.4 g/mi HC, 3.4 g/mi CO, 2.0 g/mi NO_x). Engines (General Motors GT-225) utilizing experimental premixed, vaporized fuel combustors have met the research goal emissions standards (0.4 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x) in vehicle tests; however, the vehicles have some driveability problems (Reference 22).

Most of the early automotive-related developments of the Stirling engine (References 23 and 24) have involved N.V. Philips Gloeilampenfabrieken of The Netherlands, either directly or through various licensing agreements, and for this reason few details are available on this work. In 1972, Ford and Philips began a joint development of the 4-215 Stirling engine. This development has continued under DOE sponsorship. The DOE Stirling engine program includes two major industry efforts aimed at developing an improved Stirling engine for automotive application. One of these development activities is being conducted by Ford Motor Company as a continuation of their 4-215 engine work (Reference 25). The other development activity is being conducted by a team composed of Mechanical Technology Incorporated, United Stirling of Sweden, and AM General (Reference 26). Advanced component technology activities are being performed by NASA's Lewis Research Center, project manager for the DOE Stirling engine program (Reference 11), through industrial contracts and in-house activities. Recently, a feasibility study was made to evaluate the use of Stirling engines in small cars (80-100 hp) (Reference 27).

There are also significant Stirling engine programs at United Stirling of Sweden, N.V. Philips, and Maschinenfabrik Augsburg-Nuremberg jointly with Motoren-Werke Manheim (MAN-MWM) in Germany. Of particular significance are the vehicle (automobile and truck) demonstrations at United Stirling (References 28 and 29).

Much of the information about automotive Stirling engines has come from the Ford 4-215 program (Reference 30). Unfortunately, very little test time has been accumulated because of the numerous technical problems encountered during this engine program. These include roll-sock seal system failure, power control instability, air/fuel control instability, system contamination, preheater leakage, heater head temperature maldistribution, and numerous other mechanical problems. Many of these problems have now been resolved and testing time is now beginning to accumulate.

In the component development area, much improvement has been made in the sliding piston rod seal as an alternative to the roll-sock seal; however, hydrogen leakage in the sliding seal is still large enough to require a hydrogen refill capability in the engine. Significant progress has also been made in the development of the ceramic rotary air preheater; however, leakage, seal wear, and durability continue to be problems.

In limited vehicle tests, vehicles with Stirling engines have not demonstrated any fuel economy advantage over vehicles with conventional engines. The best fuel economy for the Torino vehicle (4500 lb inertia weight) powered by the 4-215 engine (170 hp) has been 12.6 mpg over the EPA composite driving cycle (Reference 30). This fuel economy is considerably less than that projected from steady-state engine data. It is expected that as more data becomes available and Stirling engine operation is better understood the fuel economy can be brought closer to the projected values.

The only emissions data available for vehicles with Stirling engines was taken by Ford on the 4-215 program. This limited vehicle emissions data indicates that there should be little difficulty in meeting Federal legislated emissions standards. Although Stirling engines have not yet demonstrated their ability to meet the 0.4 g/mi NO_x level in vehicle tests, engine dynamometer tests and combustor rig tests indicate that it is likely these levels can be met.

SECTION 3

COMPARISON METHODOLOGY

In making comparisons of the various alternative power systems, it is important that these comparisons be made at the vehicle level and that a consistent methodology be followed.

Central to the comparison of vehicles with alternative power systems is the concept of an Otto-engine-equivalent (OEE) vehicle. This concept originated during the earlier APSES study at JPL. To the individual customer, the OEE vehicle should be indistinguishable in transportation function and driving behavior from the baseline vehicle. In comparison with the baseline vehicle, this concept requires the OEE vehicle to have the same passenger and luggage space, same accessories, same drag coefficient and frontal area, same operating range, and equivalent performance.

The meaning of equivalent performance requires further comment. Each alternative engine is sized to provide the same vehicle performance as the baseline system according to some performance criteria. The following four performance criteria have been evaluated during this study: 0-60 mph acceleration time, 10-second acceleration distance, 40-60 mph acceleration time, and a combination of the preceding three criteria. The combined criteria were satisfied for an alternative power system by minimizing the RMS deviation from baseline performance for the three criteria.

Vehicle performance is calculated using a vehicle computer simulation program. Appropriate power system weights and engine torque-speed characteristics are used for each alternative power system. Vehicle weight propagation effects are included in the calculation procedure to properly account for the influence of power system weight on vehicle design. This procedure assumes that each alternative vehicle is designed with the same degree of optimization. This procedure yields the appropriate engine horsepower and vehicle weight for each power system. A detailed discussion of this method for the horsepower sizing of alternative power systems is given in Reference 31.

Once the engine horsepower and vehicle weight for each OEE vehicle have been determined, fuel economy is calculated using a vehicle computer simulation program. This program uses steady-state engine map data to predict vehicle fuel economy for the city, highway, and composite driving cycles. The results of a calibration of this computer program are given in Table 1. Since the calculated fuel economies are used only in making comparisons, the accuracy demonstrated by this calibration is considered adequate. The computer program does not include engine transient effects (response time, etc.), which could be important factors for the advanced alternative power systems.

Table 1. Computer Program Calibration for 1978 Pontiac Sunbird(1)

Driving Cycle	Fuel Economy, mpg	
	Predicted	EPA Measurement
City	20.5	22
Highway	34.1	32
Combined	25.0	26

(1) Four-cylinder, 151 CID engine; four-speed manual transmission; 3000 lb vehicle inertia weight.

SECTION 4

ENGINE CHARACTERISTICS

Total power system weights for each engine type are given as a function of horsepower in Figure 1. The total power system includes the engine, all auxiliaries, transmission, battery, and cooling system. The curves for conventional engines and advanced conventional engines are representative of current weight technology. The curves for the advanced alternative engines represent projections at a time when those engines have been developed for passenger car use. These curves show the Stirling power system weights to be about equal to that of the TC diesel. The free-turbine (FT) Brayton, single-shaft (SS) Brayton, rotary UC Otto, and rotary SC Otto power systems show significant weight advantages over other engines considered in this study. The NA diesel power system is considerably heavier than other engines considered. The importance of these weight differences will be shown later.

The size characteristics of various engines are given in Table 2. Most of the data are for engines in the 100-150 hp range since size data for smaller engines is limited. This data indicates that the TC Otto and rotary engines require less volume than the other engines of the same horsepower. Most current designs of Brayton and Stirling engines are relatively bulky and do not offer any packaging advantages over the conventional engines.

A comparison of the torque-speed characteristics for some of the engines is given in Figure 2. The engine torque and speed are normalized with respect to the torque and speed at maximum power. For passenger car applications, engines with a high torque ratio at relatively low engine speed are advantageous since they exhibit better acceleration performance. These torque curves indicate that both Brayton and Stirling engines have better torque characteristics than those for conventional engines. When using the OEE vehicle concept, these characteristics require that the Brayton and Stirling engines have less horsepower than conventional engines for equivalent vehicle performance.

It is of considerable interest to compare the fuel consumption characteristics of the various engines. This is done in Figures 3, 4, and 5, where brake specific fuel consumption (bsfc) is given as a function of power fraction at the midpoint of the operating RPM range for each engine. The power is normalized with respect to the maximum power attainable at the midpoint of the operating RPM range. These data are taken from the fuel consumption maps which were used to represent each engine type in making comparison calculations. The Stirling engine with a metal heater head is compared with other gasoline engines in Figure 3. The potential advantage of the Stirling engine is clear if the predicted fuel consumption characteristics of the engine can be achieved in practice. The bsfc of the metal and ceramic Stirling engines are compared with those of the TC diesel in Figure 4. Again the potential advantage of the Stirling engine is apparent. The excellent part-load bsfc of the Stirling engine is particularly attractive. The bsfc

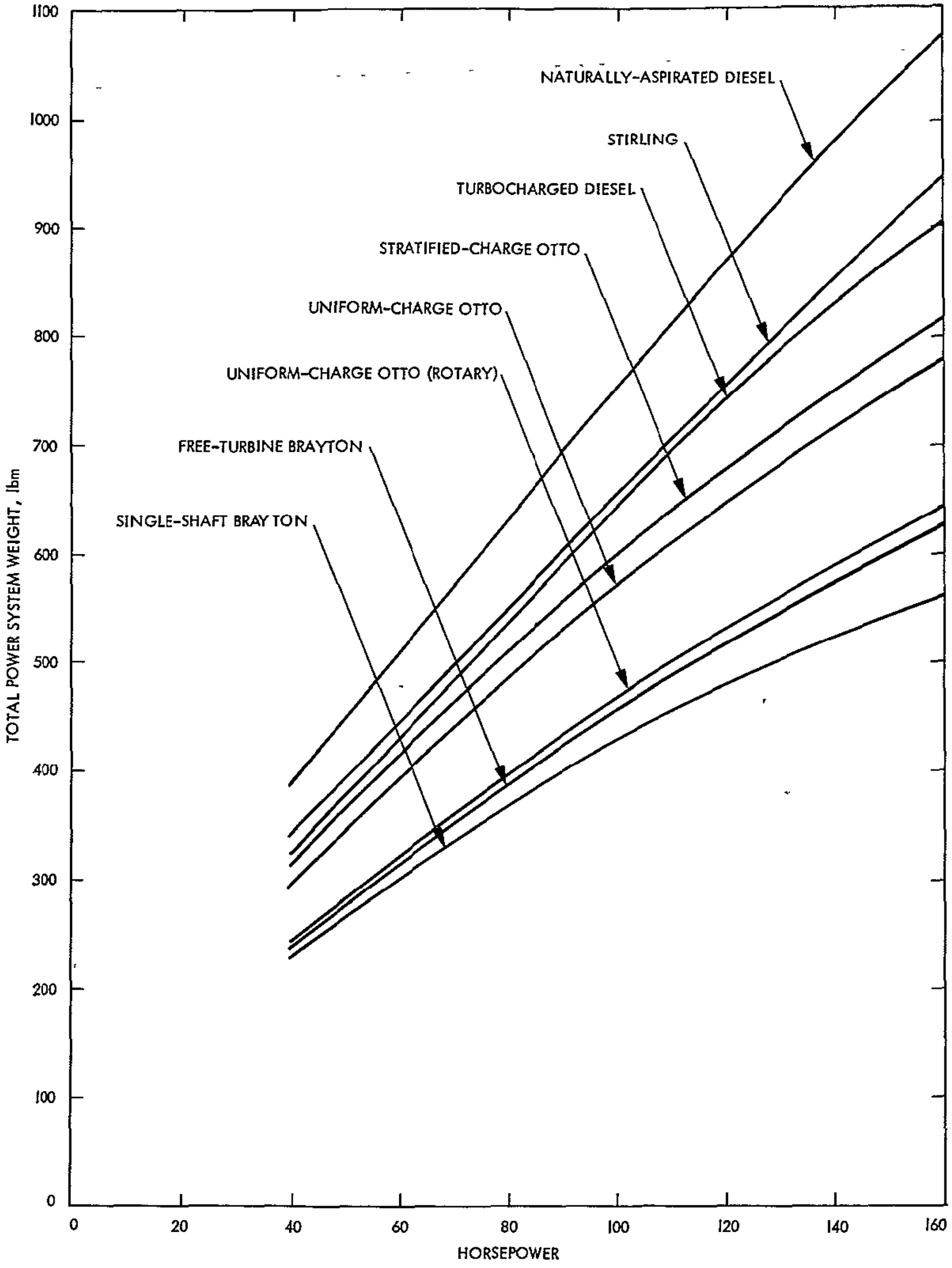

Figure 1. Total Power System Weights

Table 2. Typical Engine Size Characteristics

Engine Type	Horsepower	Engine Size, inches L	W	H
Conventional Engines				
UC Otto	130	19	25	25
NA diesel	120	32	28	30
	50	17	17	22
TC diesel	105	31	19	31
	70	17	17	22
Advanced Conventional Engines				
Rotary UC Otto	170	18	29	23
Reciprocating SC Otto	128	30	24	24
Rotary SC Otto	128	20	27	26
Advanced Alternative Engines				
FT Brayton (metal)	110	33	33	27
Stirling (metal)	170	37	26	26
	84	26	21	23

of the ceramic FT Brayton and SS Brayton engines are compared with those of the TC diesel in Figure 5. Brayton engines show potential for lower fuel consumption than the TC diesel; however, the margin is not as large as that for the ceramic Stirling, principally because of the better part-load bsfc of the Stirling. For the Brayton engines, the bsfc values given are for a 100-120 hp engine.

The influence of size effects on the bsfc of smaller Brayton engines is of considerable importance because many of the downsized passenger cars of the 1985-90 period will require engines smaller than 100 hp. The estimated effect of reduced peak horsepower on the bsfc is shown in Figure 6 for a range of horsepowers and turbine inlet temperatures. The results indicate that (1) size effects degrade the bsfc by 10-15 percent when engine horsepower is reduced from 100 to 50 and (2) that the use of ceramic components, which permit an increase in turbine inlet temperature from 1900°F to 2500°F, improves bsfc by 10-15 percent. These curves were

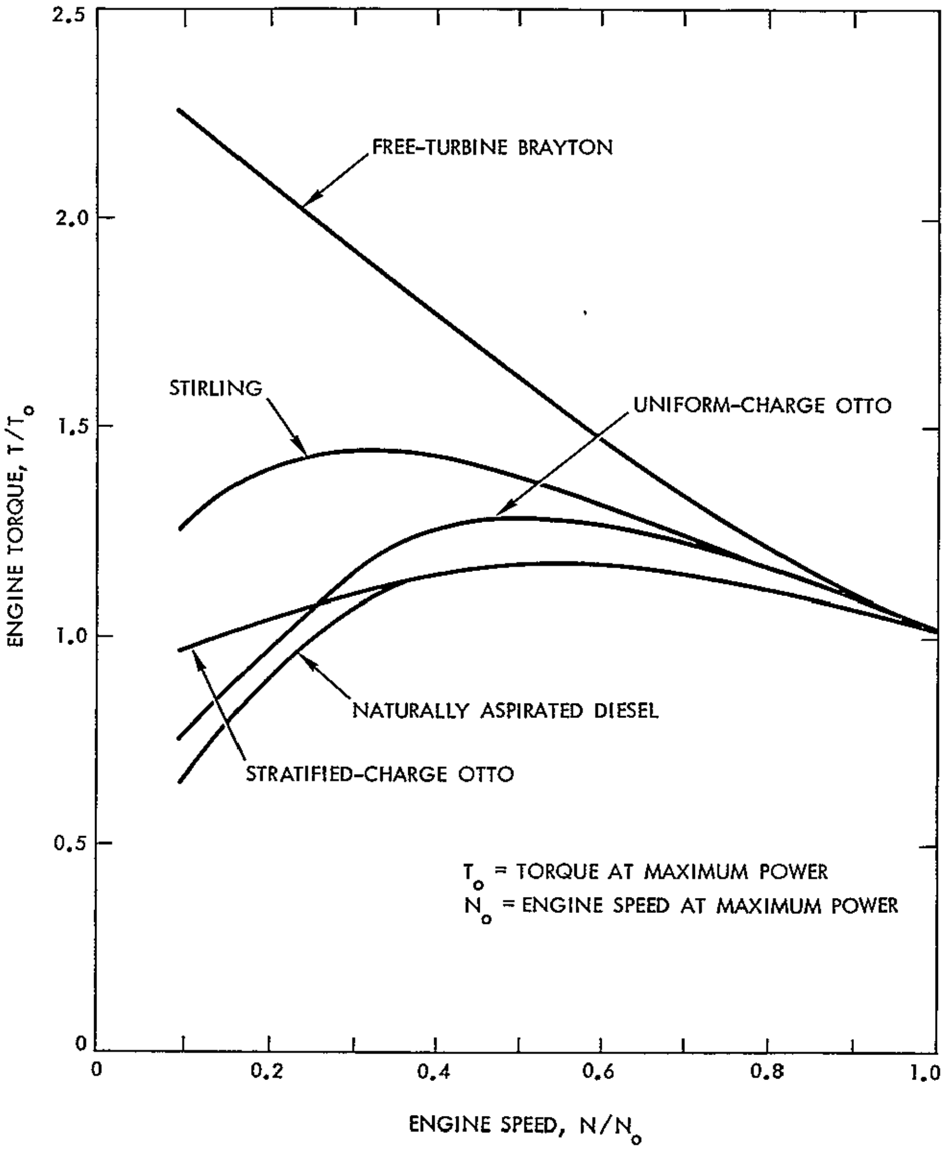

Figure 2. Typical Torque-Speed Characteristics

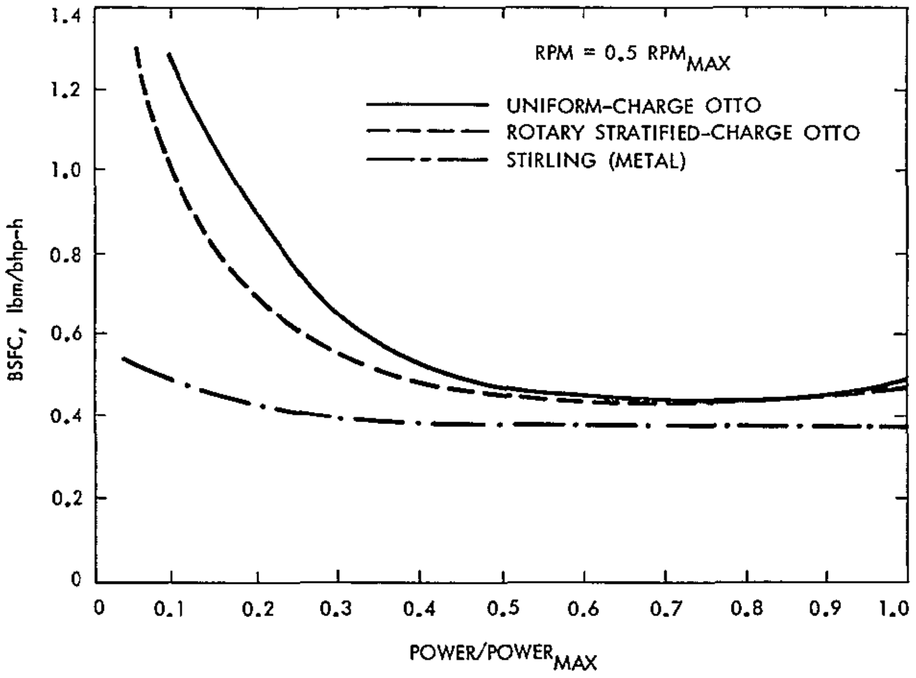

Figure 3. Comparison of Fuel Consumption Characteristics of Uniform-Charge Otto, Stratified-Charge Otto, and Stirling Engines

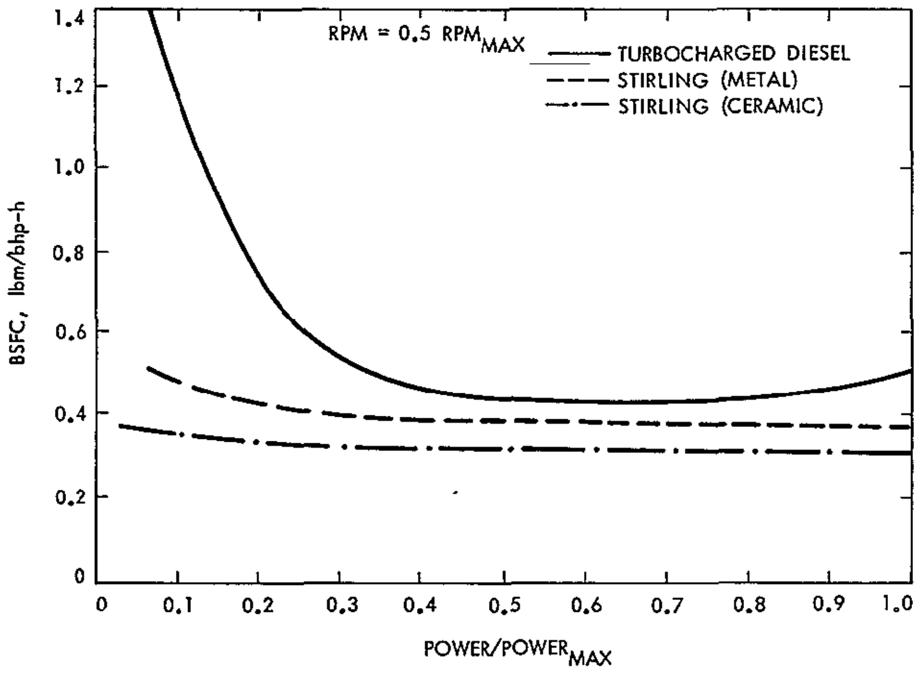

Figure 4. Comparison of Fuel Consumption Characteristics of Stirling and Diesel Engines

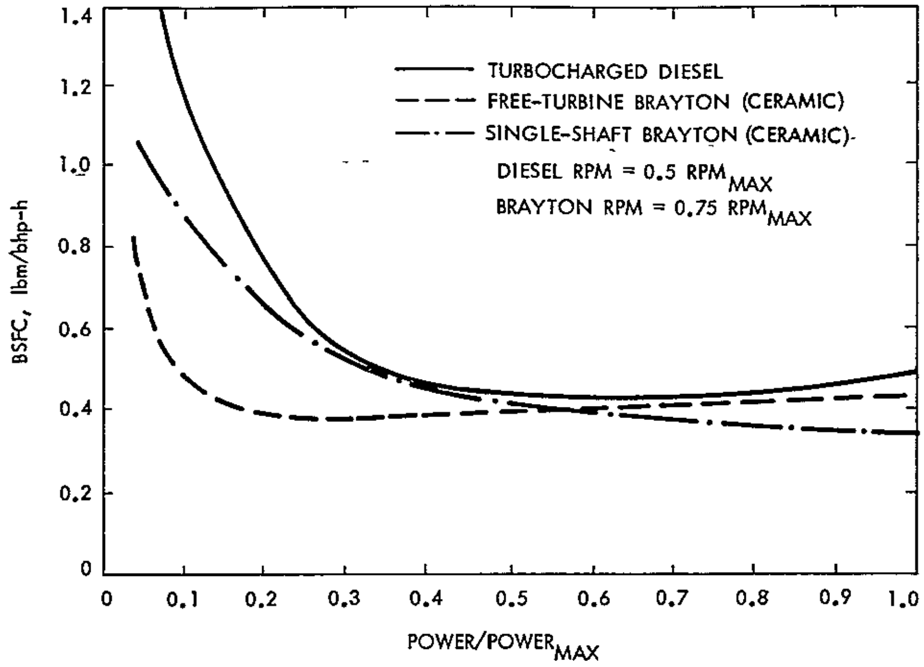

Figure 5. Comparison of Fuel Consumption Characteristics of Brayton and Diesel Engines

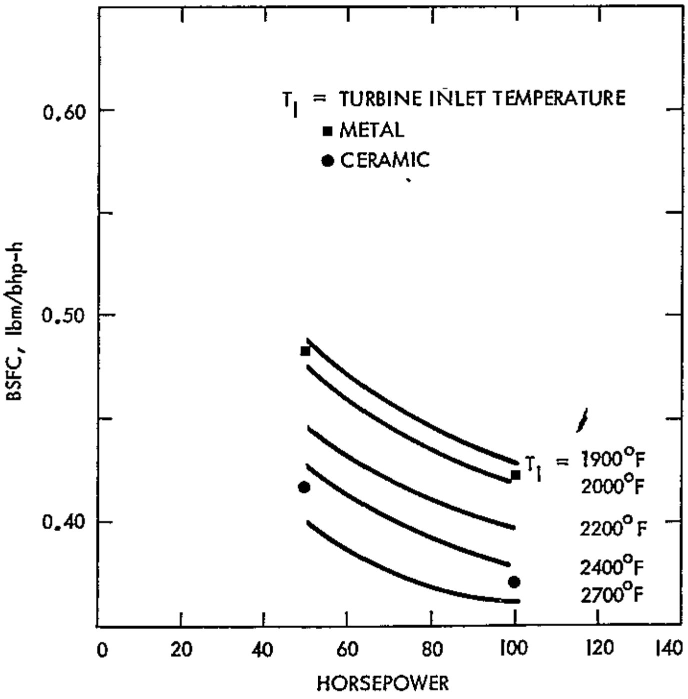

Figure 6. Effect of Turbine Inlet Temperature and Engine Size on Fuel Consumption of Brayton Engines

used in making projections for Brayton engines to account for the effects of size and turbine inlet temperature. In making projections for Stirling engines, it was assumed that the bsfc characteristics would not be degraded by size effects. The method used to account for higher operating temperatures was based on the analysis of United Stirling in Reference 28.

Idle and deceleration fuel flow rates have a significant effect on the fuel economy which can be achieved with the various engines. This is especially true in city driving, as simulated by the EPA Urban Driving Cycle, in which about 40% of the time is spent in either an idling or deceleration mode. Based on calculations made using a computer simulation program, the effect of idle fuel flow on vehicle fuel economy has been estimated, and the results are given in Figure 7.

The idle flow rates which have been used in making fuel economy projections for the various engines are given in Figure 8. The low idle fuel flow of the diesel and the high idle fuel flow for the Brayton are particularly evident. The importance of reducing the idle fuel flow in the Brayton is well known, and considerable progress has been made in reducing it. However, it still remains higher than that for other engines.

Other aspects of engine operation which are important for passenger car applications are engine transients (i.e., load variations) and accessory power requirements. Neither of these factors poses any significant problem for conventional engines. In fact, recent work on conventional engines has indicated that the effects of transients and accessories on vehicle fuel economy can be further reduced with the use of constant speed accessory drives or idle/deceleration fuel flow cutoff or modulation. DOE and the General Services Administration are jointly sponsoring an evaluation of a constant speed accessory drive to determine the potential fuel economy improvements which are possible with its use in passenger cars (Reference 32). The effect of load transients can be important for both Stirling and Brayton engines. For the Stirling engine, the following major transient effects are associated with the power level control system: (1) the power required to increase the working pressure for an increase in engine power and (2) the throttling loss which occurs when the working pressure is rapidly reduced for a decrease in engine power. For the gas turbine, the following major transient effects occur: (1) engine speed excursions into low efficiency portions of the component maps during vehicle accelerations and (2) high fuel flow and reductions in engine speed during decelerations. Using steady-state engine dynamometer fuel consumption data it is not possible to account for transient effects, and thus they are often not treated satisfactorily in making fuel economy projections.

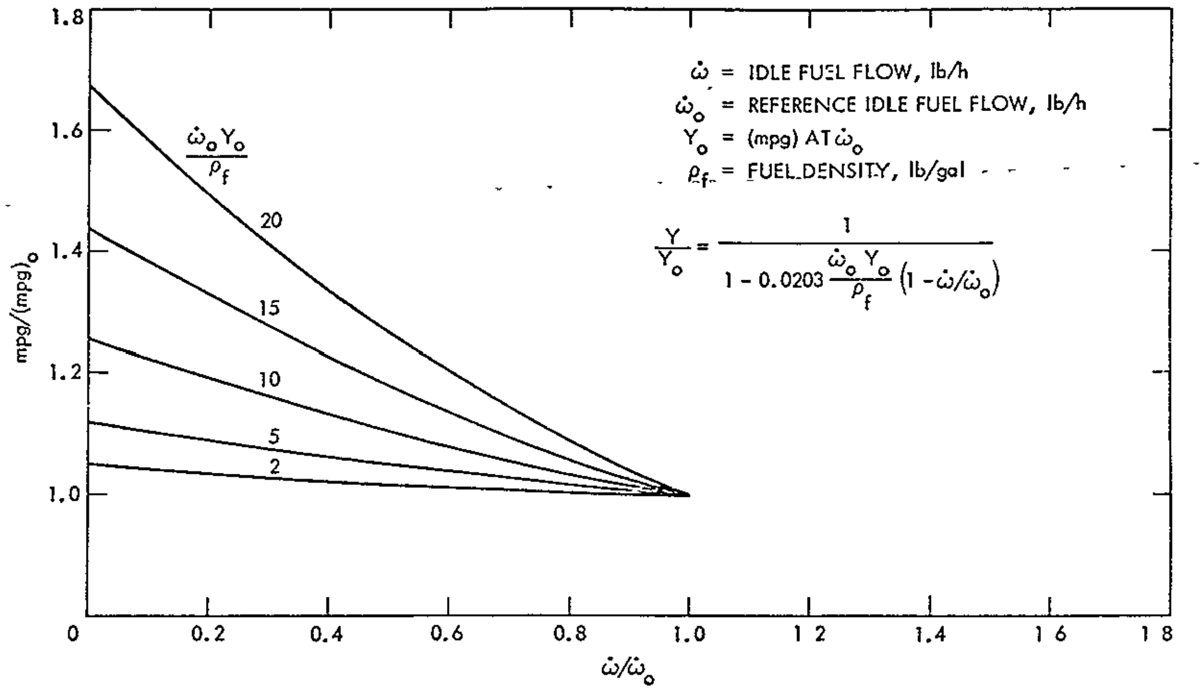

Figure 7. Effect of Idle Fuel Flow on Urban Cycle Fuel Economy

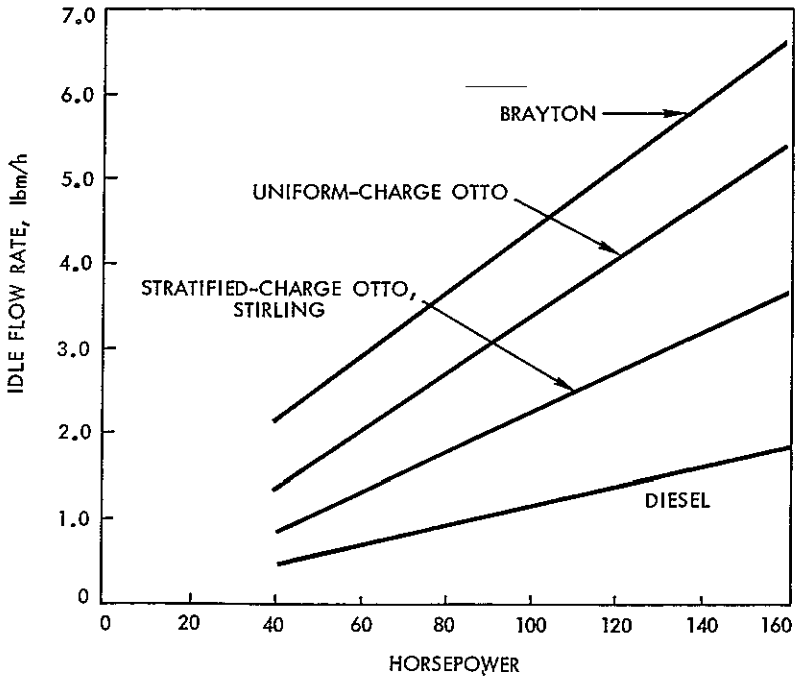

Figure 8. Idle Fuel Flow Rate Characteristics

SECTION 5

TRANSMISSION REQUIREMENTS

Except for the SS Brayton engine, which requires the use of a continuously variable transmission (CVT), all of the engines being compared can utilize the conventional manual and automatic transmissions currently available. Of course, the gear ratios, torque converter characteristics, and shift logic would need to be optimized for each of the engine types. Transmission improvements such as overdrive and torque converter lockup are applicable to the advanced conventional engines and Stirling engines, and would benefit those engines in essentially the same way that they benefit conventional engines. A summary of projected fuel economy improvements using various advanced automatic transmissions in vehicles with conventional engines is given in Table 3.

The transmission situation for Brayton engines is more complex than for the other engine types. Brayton engines operate at much higher RPM (50,000-100,000) and thus require a speed reduction between the turbine and vehicle drive shafts. In addition, the effective inertia is higher and thus drive shaft speed changes of the same magnitude require more power for the Brayton than for engines operating at lower RPM. Hence, it is advantageous to limit Brayton engine speed changes during both accelerations and decelerations as much as possible. For the multi-shaft free-turbine Brayton, there is no need for a torque converter since the free turbine can perform that function. This can lead to a reduction in driveline weight and packaging volume and improved efficiency. The advantages of combining the engine and transmission in a multishaft Brayton engine are discussed in Reference 21. The computer simulations of two-shaft gas turbine-powered cars, which are discussed in this report, were made using a M4 transmission.

As noted previously, the single-shaft Brayton requires the use of a CVT to match engine and vehicle driveshaft speeds. Such transmissions are not in current use on production vehicles, but a prototype model of a CVT using the hydromechanical, power-split approach is being developed under DOE contract (Reference 33). This transmission is currently being tested in a Chevrolet Nova equipped with a conventional six-cylinder engine. Development of a durable, high efficiency CVT is clearly critical to the introduction of single-shaft Brayton engines. The CVT can, of course, be used with the other types of engines and would also improve their performance and fuel economy.

Table 3. Summary of Projected Fuel Economy Improvements Using Various Advanced Automatic Transmissions

Type	Transmission				Fuel Economy Improvement, %		
	No. Gears	Overall Gear Ratio Range	Lockup	Efficiency, %	Urban	Highway	Composite
Automatic	3	3.0 to 1	No	-	0(base)	0	0
Automatic	3	3.0 to 1	Yes	-	5-10	5-10	5-10
Automatic	4	4.0 to 1	No	-	3- 5	15-20	8-11
Automatic	4	4.0 to 1	Yes	-	10-15	20-25	14-19
Continuously Variable	-	7.0 to 1	-	80-90	15-20	20-25	17-22
Continuously Variable	-	7.0 to 1	-	85-90	18-22	25-30	21-25

SECTION 6

VEHICLE FUEL ECONOMY

In anticipation of further vehicle downsizing and the use of lighter weight materials to meet the fuel economy standards, the baseline vehicles chosen for the comparisons are given in Table 4.

Following the methodology previously discussed, Otto-engine-equivalent (OEE) vehicles were established for each power system. The engine weight and torque-speed characteristics representative of each engine type were used in these calculations. In establishing equivalent performance, the combined performance criteria were satisfied by minimizing the RMS deviation from baseline performances for the 0-60 mph acceleration time, 10-second acceleration distance, and 40-60 mph acceleration time.

The results of the OEE vehicle calculations for full-sized vehicles are given in Figure 9. A constant power/weight line is shown passing through the baseline UC Otto point to aid in making comparisons. Vehicles with conventional engines (NA diesel, TC diesel) and advanced conventional engines (rotary UC Otto, SC Otto, rotary SC Otto) all require more horsepower than vehicles with the baseline (UC Otto) engine to achieve equivalent performance. Vehicles with the advanced alternative engines (FT Brayton, SS Brayton, Stirling) show definite advantages by requiring less horsepower than the baseline vehicle for equivalent performance. Vehicles with FT Brayton and SS Brayton engines show definite weight advantages, being considerably lighter than the baseline vehicle. Vehicles with rotary engines also show some weight advantage, but not as much as the Brayton vehicles. Vehicles with NA diesel, TC diesel, and SC Otto engines are heavier than the baseline vehicle. Vehicles with the advanced alternative engines require a lower horsepower/weight ratio than the baseline vehicle for equivalent performance. The results of similar OEE vehicle calculations for small vehicles are given in Figure 10. In this case the trends are similar to those for full-sized vehicles.

Table 4. Baseline Vehicle Characteristics

Vehicle Size	Horsepower	Curb Weight, lb	HP/Weight
Small	60	1750	0.0343
Full-sized	120	3200	0.0375

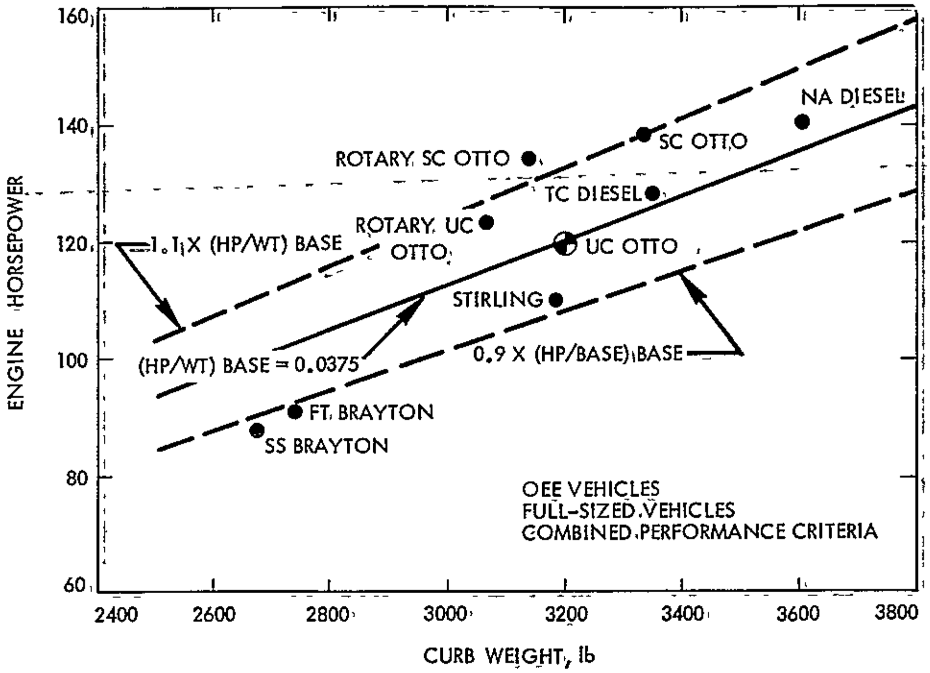

Figure 9. OEE Vehicle Results for Full-Sized Vehicles

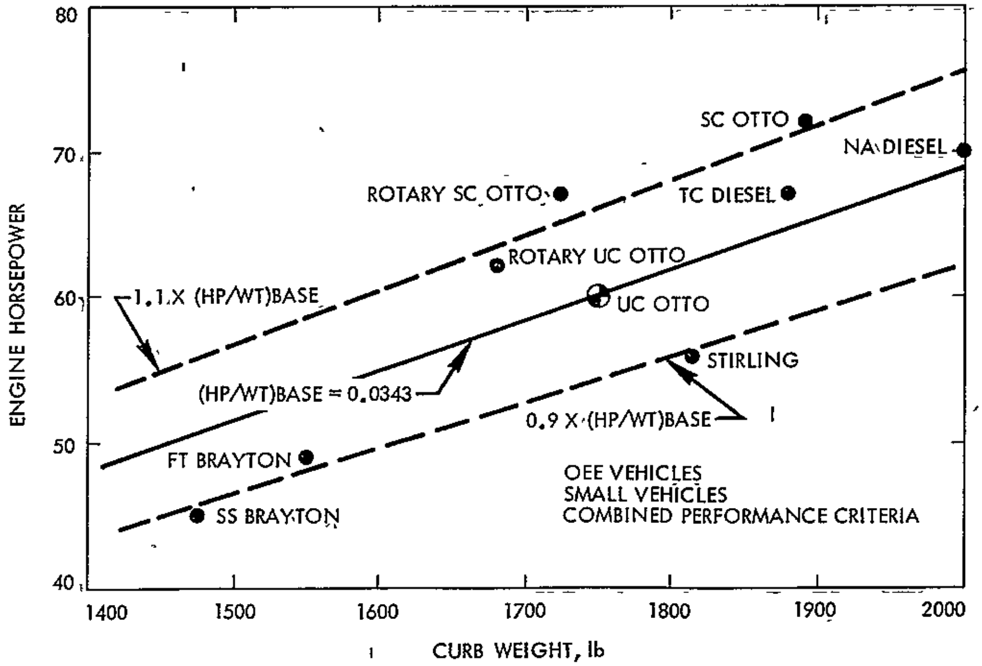

Figure 10. OEE Vehicle Characteristics for Small Vehicles

Using these OEE vehicle results and the representative fuel consumption maps for each engine type, vehicle fuel economies have been calculated using the vehicle computer simulation program. The fuel economy results for full-sized vehicles are shown plotted in Figure 11 for the composite driving cycle. Fuel economies are all expressed as gasoline equivalent mileages. The emissions constraints considered for these calculations were the Federal legislated emissions standards (0.4 g/mi HC, 3.4 g/mi CO, 1.0 g/mi NO_x). The conventional engines (UC Otto, NA diesel, TC diesel) and some of the advanced conventional engines (rotary UC Otto, SC Otto, rotary SC Otto) have one bar (cross-hatched) to represent 1978 values and another bar (open) to represent the projected 1985 values for these engines. The 1978 base for fuel economy is chosen to be the best fuel economy shown for vehicles with conventional engines.

On the composite driving cycle, vehicles with advanced alternative engines show significantly better fuel economy than vehicles with conventional engines when measured relative to the 1978 base. Relative to this base, advanced Brayton engines (ceramic) show 30 percent better fuel economy while advanced Stirling engines (ceramic) show a 40 percent fuel economy advantage. Relative to the projected 1985 base, these fuel economy advantages of vehicles with Brayton and Stirling engines are reduced by about 10 percent. The plot also shows that vehicles with SC Otto and rotary engines are projected to have fuel economies between those for the UC Otto and TC diesel.

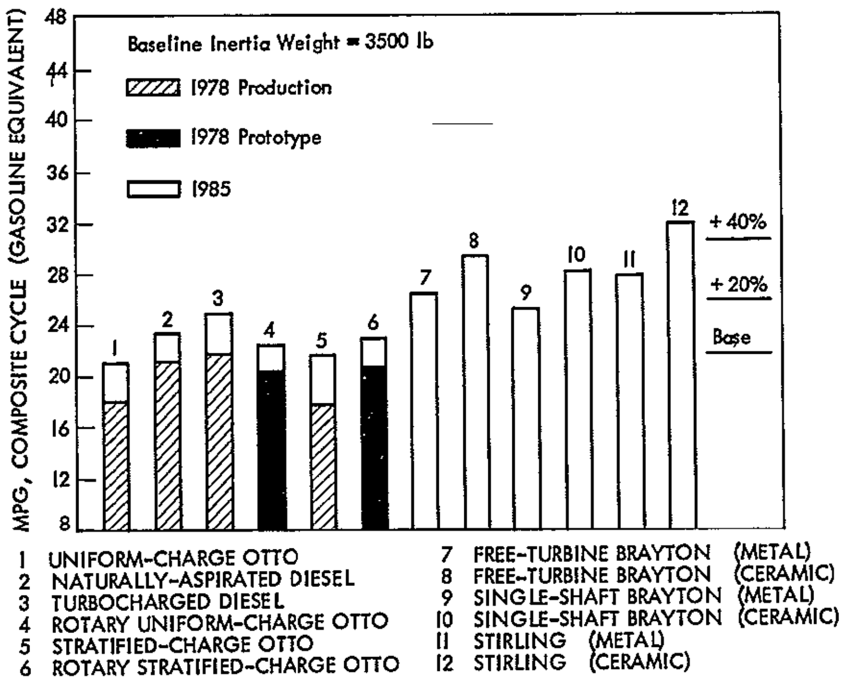

Figure 11. Composite Fuel Economy Comparisons for Full-Sized OEE Vehicles (1.0 g/mi NO_x)

Since the period for this study extends to the end of the century, it is necessary to assess the fuel economy impact of more stringent future emissions requirements, especially the 0.4 g/mi NO_x requirement. Projections of the comparative fuel economy for the various vehicles were made using one possible set of future emission standards (0.4 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x). The results of these projections for a full-sized vehicle are given in Figure 12 for the composite driving cycle. A fuel economy penalty has been imposed on vehicles with conventional and advanced conventional engines in order to meet the lower NO_x emissions requirement. The diesel engines have been dropped in this comparison since it is not expected that the diesel can meet this NO_x requirement in full-sized vehicles. Vehicles with advanced alternative engines (Brayton and Stirling) are expected to meet these emissions levels with no penalty in fuel economy. Relative to the 1985 base, the advanced Brayton engines (ceramic) show a 30 percent better fuel economy while advanced Stirling engines (ceramic) show a 40 percent fuel economy advantage.

Again using the OEE vehicle concept, computer results for the fuel economy of small vehicles are given in Figure 13 for the composite driving cycle. Both 1978 and 1985 bases are shown for vehicles with conventional engines. Vehicles with Stirling engines show significantly better fuel economy than vehicles with conventional engines. Relative to the 1978 base, advanced Stirling engines (ceramic) show a 40 percent fuel economy advantage. In this small-sized vehicle, vehicles with Brayton engines do not show the same fuel economy advantage which they show for full-sized vehicles due to their size-related penalties and relatively poor idle and part-load fuel consumption. Again vehicles with SC Otto and rotary engines are projected to have fuel economies between those for the UC Otto and the TC diesel. It is expected that the UC Otto engine with the three-way catalyst emission control system can be calibrated to meet the 0.4 g/mi NO_x emissions requirement in this weight vehicle with no fuel economy penalty. Thus, essentially the same comparison would exist between the advanced alternative engines and the conventional engines for the more strict emissions requirements.

Sensitivity studies have been made to determine the effect of different performance criteria on the fuel economy projections. The fuel economy projections which have been presented were based on equivalent vehicle performance using the combined performance criterion. This criterion was satisfied by minimizing the RMS deviation from baseline performance for the 0-60 mph acceleration time, 10-second acceleration distance, and 40-60 mph acceleration time. OEE vehicles were established by satisfying each of these performance criteria separately and calculating the vehicle fuel economy. The fuel economy projections based on the four performance criteria were all contained within a ±2 percent band. This indicates that the performance standard selected has a small effect on the fuel economy projections, at least for the performance criteria evaluated.

It is necessary to examine the sensitivity of these fuel economy projections to other assumptions made in the OEE vehicle concept which was used in this study. Two of these key items are engine weights

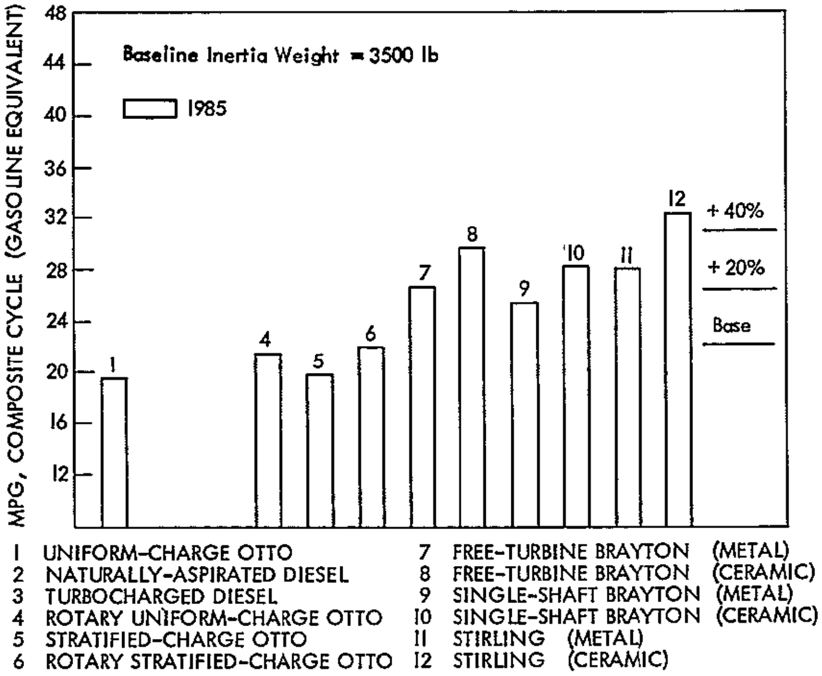

Figure 12. Composite Fuel Economy Comparison for Full-Sized OEE Vehicles (0.4 g/mi NO_x)

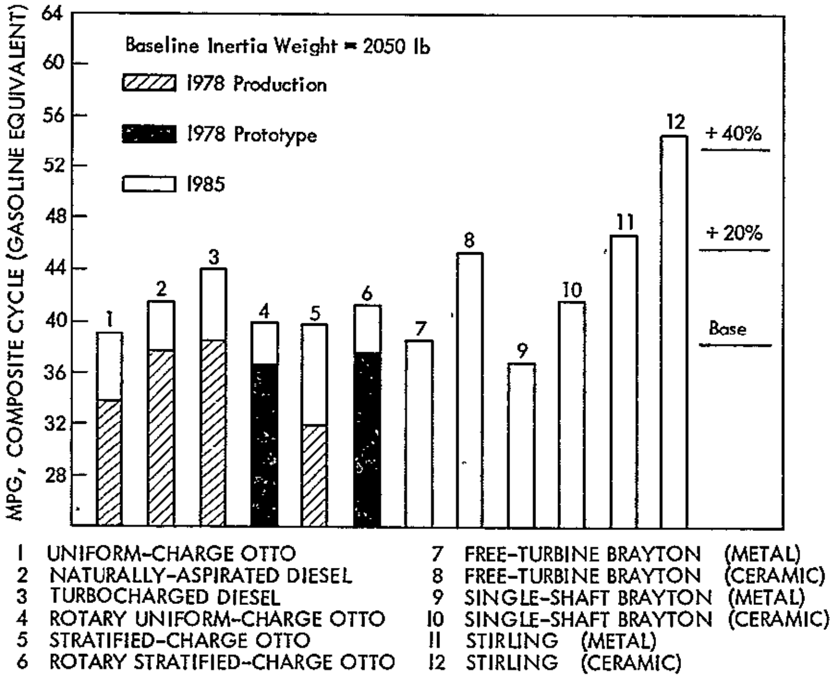

Figure 13. Composite Fuel Economy Comparison for Small OEE Vehicle (1.0 g/mi NO_x)

and engine transient response. The engine weight characteristics used to represent Brayton and Stirling engines are projections of what should be achieved with these engines as they become more developed; however, most current developmental engines fall far short of this goal. Engine weight becomes even more important since the calculation procedure for an OEE vehicle includes vehicle weight propagation effects to establish alternative vehicles which are designed with the same degree of optimization. Also, in sizing the engines to provide equivalent performance, engine transient response has been neglected. If acceleration time is measured relative to the time when the accelerator pedal is depressed, any delayed response of the engine would be included in the acceleration time. This factor could have an effect on sizing the engines for equivalent vehicle performance. To investigate these effects fuel economy calculations have been made with all engine types having the same engine horsepower and same vehicle weight. These fuel economy results for full-sized vehicles are given in Figure 14 for the composite cycle. On this basis, the advanced alternative engines (Brayton and Stirling) show less fuel economy advantage over vehicles with conventional engines. This emphasizes the importance of developing alternative engines which meet the engine weight goals and possess transient response characteristics at least comparable to conventional engines.

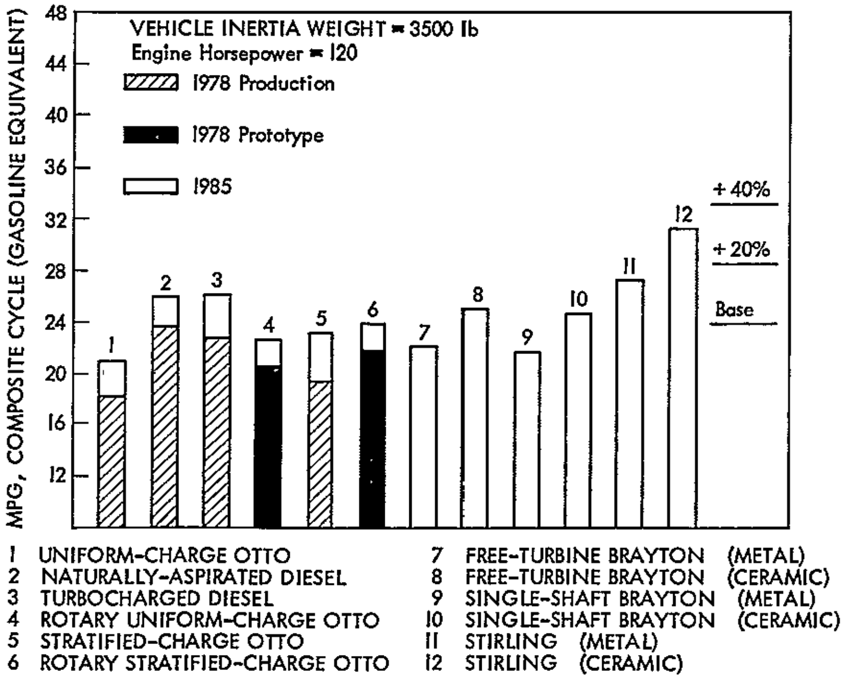

Figure 14. Composite Fuel Economy Comparison for Full-Sized Non-OEE Vehicles (1.0 g/mi NO_x)

SECTION 7

VEHICLE EMISSIONS

In this long-range study, each engine type has been evaluated for its ability to meet not only the current legislated emissions standards (0.4 g/mi HC, 3.4 g/mi CO, 1.0 g/mi NO_x), but also possible future requirements (0.4 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x). Also, the need for controlling presently unregulated emissions, such as particulates, sulfates, and odor will continue to receive attention and has been considered in assessing the emissions potential of vehicles powered by the various engines.

The emissions data for vehicles with the various engine types are shown plotted in Figures 15, 16, and 17. Boundary lines representing the emissions requirements are given to aid in evaluating each engine type. Unfortunately, little vehicle emissions data is available for vehicles with Brayton or Stirling engines, especially ones having combustor/engine control systems sufficiently optimized to control emissions to the statutory standard. Thus, in many cases their emissions potential must be inferred from steady-state combustor data and a general knowledge of pollutant formation during combustion.

These emissions data indicate that there should be little difficulty meeting the 0.4 g/mi HC and 3.4 g/mi CO standards using conventional and advanced conventional engines. Some of the engines require the use of an oxidation catalyst, but catalyst technology is well developed and able to yield units with good conversion efficiency and adequate catalyst durability. Relative to the 1.0 g/mi NO_x standard, available data suggest that with additional development all conventional engines can meet this standard in vehicles of up to 4000 lb inertia weight. Most of the engines will require a three-way catalyst and/or exhaust gas recirculation (EGR) to reduce the NO_x emissions from current levels. The most difficult problem is with the diesel engine in the larger vehicles where the catalytic approach to reducing NO_x cannot be used and the presence of particulates in the exhaust for some operating conditions could lead to difficulties (durability of internal engine components) in using EGR. Present data indicate that for small vehicles (2250 lb inertia weight or less), the 0.4 g/mi NO_x standard can be met with conventional gasoline engines using a three-way catalyst and/or EGR. The fuel economy penalty at this vehicle weight should not be significant. Reducing NO_x emissions in stratified-charge and diesel engines which operate at overall very lean conditions requires the use of increasing amounts of EGR which has been demonstrated to result in significant fuel economy penalties. Hence for those engines the fuel economy penalty associated with NO_x emissions below 1.0 g/mi are likely to be significant for cars heavier than 3000 lb inertia weight.

The limited vehicle emissions data for vehicles with Stirling engines indicate that there should be little difficulty in meeting the Federal legislated emissions standards. Although Stirling engines have not yet demonstrated their ability to meet the 0.4 g/mi NO_x standard in vehicle tests, projections based on engine dynamometer tests

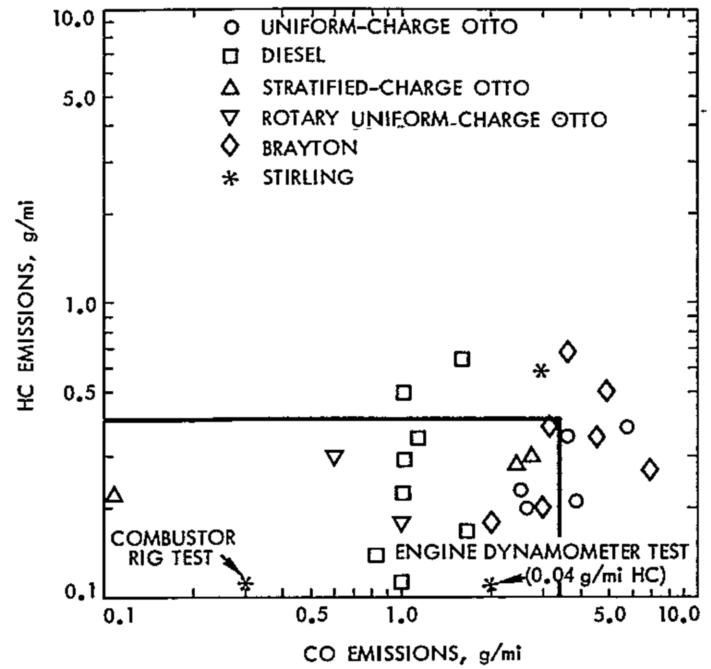

Figure 15. Urban Driving Cycle Emissions (HC, CO) for Various Engines

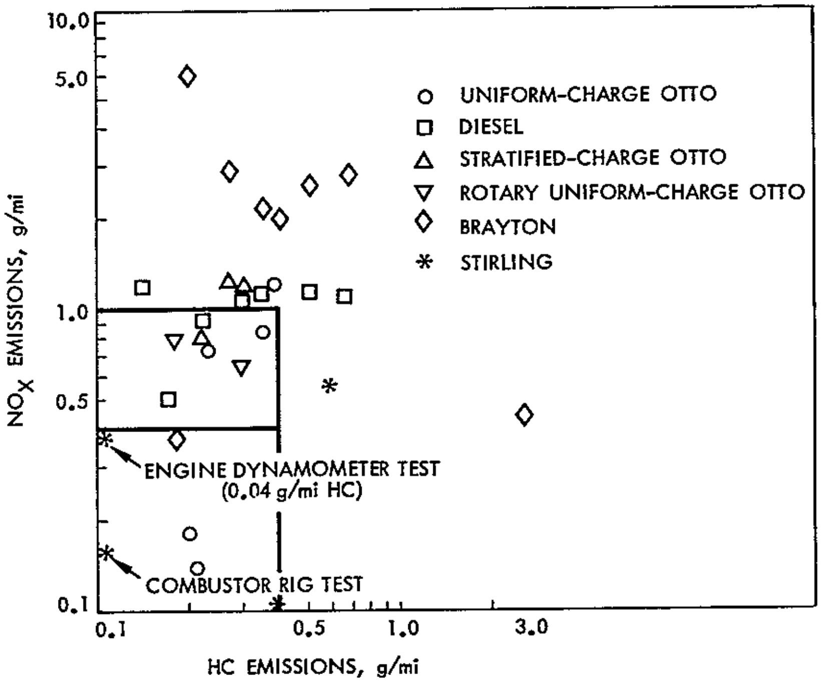

Figure 16. Urban Driving Cycle Emissions (NO_x, HC) for Various Engines

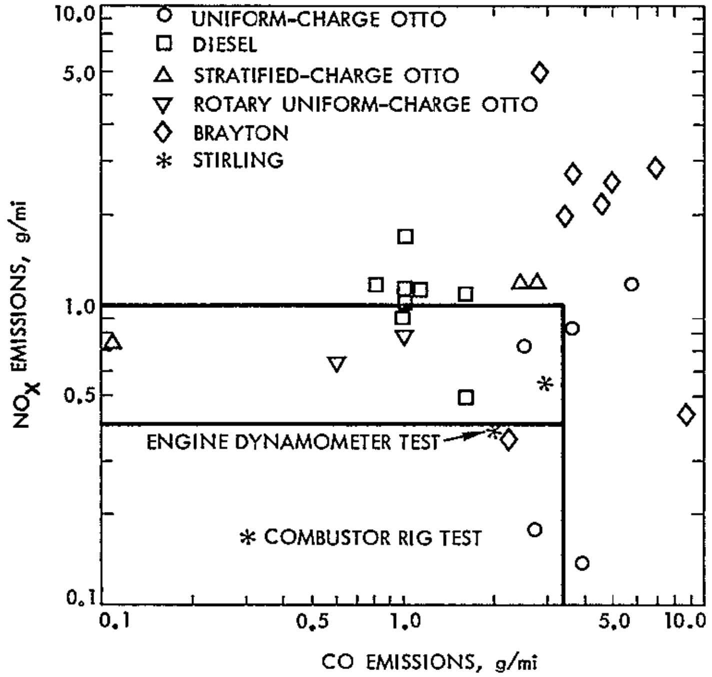

Figure 17. Urban Driving Cycle Emissions (NO_x, CO) for Various Engines

and combustor rig tests do indicate that those levels should be met. In fact, Stirling engines should have the cleanest exhaust of all engines being compared and should be able to meet the most stringest emissions requirements (0.4 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x), with relatively little additional development.

Steady-state emissions from Brayton engines are very low, but the effects of transient operation have yielded relatively high emissions levels in most vehicle tests. Using an advanced premixed, prevaporized combustor, General Motors has reported getting (0.18 g/mi HC, 2.0 g/mi CO, 0.38 g/mi NO_x) in a vehicle test; however, vehicle driveability was considered poor. The available vehicle and combustor emissions data indicate that low emissions can be achieved with the Brayton engine, but that careful combustor design and engine control (especially during transient conditions) are required. It is expected that with additional development both the Federal legislated emissions standards and the 0.4 g/mi NO_x research goal can be met by Brayton-powered vehicles.

Unregulated emissions (sulfates, particulates, and odor) are of concern for engines which use diesel fuel or distillates and/or operate at overall very lean conditions or locally very rich conditions. Sulfates result from sulfur in the fuel and can be controlled by setting strict permissible fuel sulfur regulations. This is true for all the engines which use fuels other than gasoline (the sulfur content of gasoline is already very low). Particulates (primarily smoke) result from injecting more fuel into the cylinders or combustor than can be burned in the residence time available. Smoking is most likely to occur in direct-injected and/or stratified-charge engines, such as the diesel, PROCO, and Texaco TCCS engines, and in engines using the heavier fuels. Smoking can be controlled to some extent by proper tailoring of the fuel injection system and its controls and by proper maintenance. The most difficult of the unregulated emissions to describe and to control is odor, which is primarily the result of very lean combustion. Odor is likely to be a problem with the diesel, gas turbine, PROCO, and Texaco TCCS engines.

SECTION 8

FUEL REQUIREMENTS

The fuel requirements for the various engines differ markedly, varying from the need for high quality, high octane fuel by spark-ignited, Otto cycle engines to a tolerance to low quality wide-cut distillate fuels by the Brayton and Stirling engines. The fuel requirements of the various engines are summarized in Table 5. As noted in the table most of the new engines currently being developed can operate satisfactorily on much lower quality fuel than the gasolines currently being produced. The alternative fuel capability of the new engines will become particularly important when energy resources other than crude oil are used to produce automotive fuels.

All of the fuels (gasoline, diesel oil, alcohols, and distillates) can be produced from a number of alternative energy resources, but the thermal efficiency with which a particular fuel is produced differs significantly for the various resources. In general, the automotive fuels can be produced most efficiently from crude oil (resources conversion efficiency 90 percent). The fuel conversion efficiencies for shale oil and coal are significantly lower (resource conversion efficiency 40-70 percent) than for crude oil and also show a greater variation from fuel to fuel. It is clear that engines which yield high fuel economy in a vehicle and also can use wide-cut distillate fuels will be particularly attractive from an overall energy efficiency (resource-to-wheels) point-of-view. Brayton, Stirling, and direct-injection, stratified-charge engines fall into the high energy-use-efficiency group using the alternative resources, but the conventional diesel engine does not because of its requirement for relatively high quality fuel (cetane number in a narrow range). From this same point-of-view, the long-term use of alcohol fuels does not appear attractive unless the fuel is produced from a renewable energy resource, such as biomass, in which case the overall energy efficiency is not critical as long as the cost of the alcohol fuel is competitive with that of other fuels.

Table 5. Fuel Requirements for Various Automotive Engines

Engine Type	Fuel Requirement	Fuel
Uniform-charge Otto Honda CVCC Ford PROCO	High volatility; high octane number, 90-95	Gasoline, alcohols
Diesel	Cetane number 40-65	Diesel oil
Direct-injected stratified-charge Texaco TCCS C-W rotary Spark-assisted diesel	None(1)	Wide-cut distillate
Brayton	None	Wide-cut distillate
Stirling	None	Wide-cut distillate

(1) The fuel injection and ignition systems for these engines can be designed to use fuels with a wide range of characteristics, but the systems must be specially engineered with the characteristics of the fuel to be used in mind.

SECTION 9

MATERIALS REQUIREMENTS

Materials technology always plays an important role in determining the attractiveness and ultimate feasibility of various automotive engines for a number of reasons: (1) material property limitations set the maximum temperatures and thus the peak thermal efficiency which can be attained; (2) material cost ($/lb) and availability can be important factors in determining economic viability; (3) material preparation and component fabrication must be such that automation is possible to permit mass production. A summary of material requirements for the various engines is given in Table 6. For each engine, major individual components are listed along with the maximum temperature (°F) the component would experience and the type of material from which the component would be fabricated.

Material requirements for the various engines are markedly different. In general, those for the continuous combustion engines, such as the Brayton and Stirling, are much more demanding than those for the conventional Otto and diesel engines. The Brayton and Stirling engines require the use of high temperature superalloy and ceramic materials because some of their components are subject to high temperature, combustion gases and/or the hot working medium continuously when the engine is operating. For the conventional engines, on the other hand, the critical engine surfaces are subject to high heat loads intermittently and/or can be cooled with relative ease. Thus cast iron, low alloy steels, and aluminum alloys can be used in the conventional engines even though the peak combustion gas temperature is 3000-4000°F.

Most of the materials technology needed for the metal Brayton and Stirling engines is available, having been developed in connection with aircraft Brayton engines. The exception is the ceramic cellular material needed for the regenerator in the Brayton engine and the air preheater in the Stirling engine. Ceramic core material (magnesium aluminum silicate (MAS) and aluminum silicate (AS)) is now available which seems satisfactory for the regenerator/air preheater components. Hence components and even complete metal Brayton and Stirling engines for testing and development can be fabricated using materials which are currently available. The present cost of the high temperature materials and the manufacturing processes used to form some of the key engine components combine to make the cost of the Brayton and Stirling engines considerably higher than conventional engines.

Material requirements for some of the key components in the ceramic Brayton and Stirling engines are very severe and satisfactory materials are not yet available to meet them. In the case of the ceramic Brayton engines, the most critical component is the ceramic turbine rotor, which not only is subject to high temperature (2500°F), but also high stress and thermal shock. For the ceramic Stirling engine, the critical components are the heater head and the air preheater. The heater head is a tubular heat exchanger unit which is in contact with 2500°F combustion gases on one side and 2000°F, high pressure hydrogen on the other side. Little work has been done to date to fabricate such a unit from ceramics. The air preheater for the ceramic Stirling engine is subject to higher temperature combustion gases than the regenerator in a ceramic gas turbine (2700°F compared with 2000°F) and presently there is some doubt as to whether the materials being developed for the Brayton regenerator will be suitable for the Stirling engine application. Considerable R&D work is needed in ceramic materials characterization and processing before components for either the ceramic Brayton or Stirling engine will be available for developmental testing and subsequently production engineering.

Table 6. Summary of Material Requirements for Conventional and Advanced Automotive Engines

	Metal Parts	Ceramic Parts
Engine	Component/Temp.(1)/Material	Component/Temp.(1)/Material
Conventional		
Uniform charge, stratified charge, reciprocating and rotary	Piston/650/cast iron low alloy steel, or aluminum alloy	None
	Block/350/cast iron	
Brayton (metal)	Compressor/350/aluminum alloy impeller	Regenerator/1500/MAS or AS
	Shafts/stainless steel	
	Combustor/1900/superalloy	
	Turbine/1900/superalloy	
	Housings/cast iron	
Brayton (ceramic)	Compressor/350/aluminum alloy	Turbine/2500/SiC or Si_3N_4
	Shafts/stainless steel	Regenerator/2000/MAS or AS
	Housings/cast iron	Combustor/2500/SiC liner
Stirling (metal)	Combustor/1800/superalloy	Air preheater/2000/MAS or AS
	Heater head/1400/superalloy	
	Cylinder block/stainless steel	
	Pistons/1400/superalloy	

Table 6. Summary of Material Requirements for Conventional and Advanced Automotive Engines (Continuation 1)

Engine	Metal Parts	Ceramic Parts
	Component/Temp.(1)/Material	Component/Temp.(1)/Material
Stirling (ceramic)	Cylinder block/stainless steel	Combustor/2500/SiC
	Cycle coolers/stainless steel	Heater head/2000/SiC or Si_3N_4
	Swashplate drive/cast iron	Pistons/2000/SiC or Si_3N_4
		Cycle regenerator/2000/SiC
		Air preheater/2700/MAS, AS, or SiC

(1) All temperatures given in °F.

SECTION 10

COST AND MANUFACTURABILITY

Comparisons of the projected costs of various alternative automotive engines with those of the conventional gasoline engine are both difficult and uncertain for several reasons. First, the projected cost of an alternative engine, such as the Brayton or Stirling, is highly dependent on a number of assumptions which must be made concerning material and labor costs and capital investments for facilities and machinery. The validity of the assumptions is very uncertain, especially for those engine components which utilize advanced materials and fabrication techniques for which there is no prior experience in a mass production industry such as the automobile industry. Second, none of the advanced engines has reached the stage of production engineering at which manufacturability and cost-effective design are emphasized. Third, the unit cost of producing the baseline conventional gasoline engine is not known with much certainty outside the automobile industry making it difficult to set the reference engine cost. Selling prices of replacement gasoline and diesel engines are available and dealer price differentials between various engine options are known, but the relationship between those prices and the production costs is uncertain.

The engine cost results are summarized in Table 7 which gives the variable cost, selling price, price difference, and price increase factor for the various automotive engines. The baseline engine is the conventional carbureted gasoline engine with an oxidation catalyst. Cost projections are given for both 100 hp and 150 hp engines for each type. Extrapolation of the result to smaller 50-60 hp engines is probably not valid because the cost of the 100 hp engine was itself already inferred from that of the 150 hp engine and thus was not based on a complete new costing of a totally different (smaller block) engine.

The Brayton and Stirling engine results are limited to engines using metallic components except for a ceramic core regenerator or air preheater. The engine cost projections indicate that both the Brayton and Stirling engines would have higher cost than the conventional gasoline engine at the same horsepower. The projected price increase factor would be about 1.4 for the Brayton engine and 1.55 for the Stirling engine. The estimated price difference between the Brayton engine and the conventional gasoline engine is $500-600 (1977 dollars) for a full-sized car. This difference is only about 10 percent of the current selling price of a car of that size and does not seem to preclude, on an economic basis, the introduction of the gas turbine, especially if other characteristics of the engine, such as performance and smoothness/quietness, are found to be attractive by automobile buyers. The cost difference between the Brayton and diesel engine is estimated to be $300-400.

The cost difference between the Stirling engine and the conventional gasoline engine is estimated to be about $800 (1977 dollars) for engines in the 100-150 hp size range. This relatively large cost differential for the Stirling engine will thus need to be justified by

Table 7. Summary of Cost Projections for Various Automotive Engines

Engine	Variable Cost, $	Selling Price, $	Price Differential, $	Price Increase Factor
Gasoline - carbureted with catalyst				
100 hp	400	1403	0	1.0
150 hp	485	1555	0	1.0
Gasoline - fuel injected with 3-way catalyst				
100 hp	420	1474	71	1.05
150 hp	500	1617	62	1.04
Diesel - turbocharged				
150 hp	606	1786	169	1.13
Brayton (metallic) - 2 shaft				
100 hp	651	2002	599	1.43
150 hp	711	2108	553	1.36
Stirling (metallic)				
100 hp	770	2208	805	1.57
150 hp	875	2399	844	1.54

improved fuel economy, lower emissions, and greater fuel versatility. Even though the initial cost picture for the Stirling engine appears to be less favorable than for the Brayton engine, it does not seem to preclude its eventual introduction if its excellent fuel economy potential can be realized.

SECTION 11

PRESENT STATUS AND PROJECTED AVAILABILITY

A summary of the present status and projected availability of various alternative automotive engines is given in Table 8. There is clearly considerable speculation and uncertainty in preparing such a broad forecast. Probably the most uncertain assumption is that R&D work in ceramics will lead to the materials technology required for the ceramic Brayton and Stirling engines in about 5 years. In nearly all other areas, most of the technology base is presently available for the design and fabrication of components and laboratory engines. The remaining work to be done involves extensive engineering design and testing of prototype components/engines and manufacturing/production oriented activities leading to mass production.

The forecast indicates that by 1985 a number of alternative automotive engines can be developed and ready for production. Which of these engines would warrant large-scale production depends on the outcome of the extensive development programs which will be carried out between now and 1985. Engines using critical ceramic components are not projected to be available before 1990 at the earliest.

Table 8. Summary of the Present Status and Projected Availability of Various Alternative Automotive Engines

Engine	Present Status	Availability of Required Component Technology	Prototype Development	Production for Market
Diesel	Production	–	–	–
Diesel (turbocharged)	Prototype	Now	Now	1980
Stratified charge (direct injection)				
Reciprocating (TCCS)	Laboratory testing	Now	1980-85	1985
Rotary (C-W)	Laboratory testing	Now	1980-85	1985
Brayton (metal)				
2-shaft	Laboratory testing	Now	1980-85	1985
Single-shaft	Engineering studies	Now (except for CVT)	1980-85	1985
Brayton (ceramic)				
2-shaft	Materials R&D	1985	1985-90	1990
Single-shaft	Materials R&D	1985	1985-90	1990
Stirling (metal)	Laboratory testing	Now	1980-85	1985
Stirling (ceramic)	Materials R&D	1985	1985-90	1990

SECTION 12

CONCLUSIONS

Based on the comparisons of the potential of the various engine systems, the following general conclusions can be drawn relative to their fuel economy, emissions, multifuel capability, and cost.

FUEL ECONOMY

- Projected fuel economies of Stirling vehicles are up to 40 percent better than 1978 baseline (1.0 g/mi NO_x) and up to 40 percent better than the projected 1985 baseline (0.4 g/mi NO_x).
- Projected fuel economies of Brayton vehicles are up to 30 percent better than 1978 baseline (1.0 g/mi NO_x) and up to 30 percent better than the projected 1985 baseline (0.4 g/mi NO_x) in full-sized vehicle, but offer little advantage in small-sized vehicles.
- Ceramic materials are needed to show any significant fuel economy advantage for Brayton vehicles.
- Baseline vehicle fuel economies will likely continue their improvement with new lighter weight engine designs and continued work on turbocharging.

EMISSIONS

- Advanced continuous combustion power systems (Brayton and Stirling) should meet the emissions research goal (0.4 g/mi NO_x) and the currently legislated emissions standards in both small and large vehicles.
- Conventional UC Otto vehicles with three-way catalyst emissions control should meet the legislated emissions standards (1.0 g/mi NO_x) with no fuel economy penalty. These vehicles should meet the 0.4 g/mi NO_x research goal in small cars with little fuel economy penalty.
- Diesel vehicles should meet the legislated emissions standards. This probably requires the use of advanced emissions control techniques on larger vehicles.
- Unregulated emissions (particulates, odor, and noise) will present problems for diesel vehicles if new emissions regulations are passed.

MULTIFUEL CAPABILITY

- Advanced continuous combustion power systems (Brayton and Stirling) should perform well using a wide range of fuels.
- Some advanced conventional engines under development have demonstrated limited multifuel capability.

COST

- The estimated price difference between the Brayton engine and the conventional gasoline engine is $500-600 (1977 dollars) for a full-sized car.
- The cost difference between the Stirling and the conventional gasoline engine is estimated to be $800 (1977 dollars) for engines in the 100-150 hp size range.

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